DEVELOPMENT OF TECHNIQUES TO PREDICT PRODUCTION LINE EFFICIENCY

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SUMMARY

This industrial based research project was undertaken for British Leyland and arose as a result of poor system efficiency on the Maxi and Marina vehicle body build lines. The major factors in the deterioration of system efficiency were identified as:

a) The introduction of a 'Gateline' system of vehicle body build.

b) The degeneration of a newly introduced measured daywork payment scheme.

By relating the conclusions of past work on payment systems to the situation at Cowley, it was concluded that a combination of poor industrial relations and a lack of managerial control had caused the measured daywork scheme to degenerate into a straightforward payment for time at work. This eliminated the monetary incentive to achieve schedule with the consequence that both inefficiency and operating costs increased.

To analyse further the cause of inefficiency, a study of Marina gateline stoppage logs was carried out. This revealed that poor system efficiency on the gateline was caused more by the nature of its design than poor reliability on individual items of plant. The consideration given to system efficiency at the design stage was found to be negligible, the main obstacles being:

a) A lack of understanding pertaining to the influence of certain design factors on the efficiency of a production line.

b) The absence of data and techniques to predict system efficiency at the design stage.

To remedy this situation, a computer simulation study of the design factors was carried out from which relationships with system efficiency were established and empirical efficiency equations developed. Sets of tables were compiled from the equations and efficiency data relevant to vehicle body building established from the gateline stoppage logs.

Computer simulation, the equations and the tables, when used in conjunction with good efficiency data, are shown to be accurate methods of predicting production line system efficiency.

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INTRODUCTION

CHAPTER ONE

HISTORICAL BACKGROUND

The world's first true motor car was built in Vienna by chemist, electrician and mechanic, Siegfried Marcus in 1875. The popularity of the internal combustion engine as a source of power for transportation rapidly spread, many of the world's brilliant minds being directed towards the design and production of the motor car.

The early vehicles mostly resembled their predecessor, the horse-drawn carriage, and likewise possessed the originality and grandeur that only the wealthy could afford. This new toy was not for the likes of the man in the street.

In 1903 the Ford Motor Company was born, Henry Ford bringing to the motor industry the concept of the car as a vehicle for the masses. This concept materialised in 1908 with the launching of the Model 'T', bringing with it mass production and product standardisation facilitated by the introduction of the flow line production system. This new production technique significantly reduced the production costs of the motor car by minimising floor area, production facilities and manpower for a given output.

Prior to the introduction of the flow line, a static system of build prevailed, materials and tools being manually conveyed to the assembly which remained stationary until completion. Increases in output were achieved by duplicating the facilities.

Contrary to this, the principle of the flow line system is one of product mobility, the motor car in its various stages of assembly being conveyed through a series of work stations. The total work content of the assembly is divided up into a number of equal portions, an operator being assigned to each portion. The production capacity of the flow line is a function of the magnitude of each portion, and thus for a given capacity the total work content can be divided accordingly. This eliminates duplication of facilities. The number of stations is determined by considering the number of operators, facilities required and the sequence of assembly. On some lines where the assembly is small in size, it is only possible to have one operator per station; however, on vehicle assembly it is quite feasible to have as many as four to a station. In this case, it is the production facilities and enforced sequence of operations that dictate the number of stations.

Other savings attributed to the flow line system include a reduction in operator walking time, all facilities and materials required by the operator being placed at the station where he works, less cycle time variation and a reduced operator learning period, the last two advantages being the result of the shorter cycle times associated with flow line. All these savings contributed to reducing the production cost of the motor car sufficiently to rapidly increase its popularity as a convenient form of transport.

The success of the Model 'T' drew attention to the advantages of the flow line production system with the result that many other concerns, both in and out of the motor industry, listened to and applied the teachings of Henry Ford.

Since these mass production pioneering days, technological progress coupled with a strive for better working conditions, the latter being influenced by the rise to power of the trade union movement, has brought about new assembly techniques adopting a high degree of mechanisation and automation. This facilitated the use of lower cycle times therefore maximising production output from a single assembly line and eliminated strenuous and difficult manual operations. Evidence of this is prevelent in the motor industry where an increase in output and product sophistication has produced an additional impetus in this direction.

Despite these vast changes to the working environment, the flow line system of assembly has remained, the merits of which, until recently, have rarely been challenged. The introduction of mechanisation and automation coupled with the use of short cycle times has CREATED efficiency problems associated with equipment breakdowns and a reluctance of today's educated worker to perform the menial monotonous tasks associated with high intensity assembly lines.

These problems were non-existant in the flow line early days with little or no mechanisation and an abundance of labour hungry for work. Working conditions were poor but generally accepted without grievance. Operator welfare was not a facet of management in the early twentieth century.

In recent years, however, problems associated with labour turnover, labour relations, absenteeism, productivity and reliability of plant and equipment have in many instances become so severe that management has been forced to take action. Due to the large number of interrelated factors, such as the delegation of responsibilities, the choice of payment systems and the many facets of system design aimed at improving both behaviour and efficiency problems, the solution is difficult to find. In addition, the correct combination of these factors relates only to one particular situation which in itself is influenced by such things as the product being manufactured, industrial relations and the social climate.

Decisions as to the system design to be adopted are, therefore, complex ones and have in the past appeared to be influenced more by intuition than scientific fact. For example, poor system efficiency, although of prime concern, is prevalent in mass production environments, highlighting the lack of understanding of the influencing factors. This indicates that research concerned with the factors that influence system efficiency is inconclusively or inadequately presented to provide industry with the information it requires, a deficiency which this research work endeavours to eliminate.

CHAPTER TWO

BEHAVIOURAL PROBLEMS

This problem area is one of great interest and concern to both the production engineer and the social scientist and research in this area has, in recent years, gathered much momentum. There is a growing body of opinion that the boring, mindless repetitious work associated with today's high intensity assembly lines is unacceptable in an educated and prosperous society (1). The basis for this hypothesis is the increase in petty disputes, absenteeism, labour turnover, poor quality of work and sabotage, all of which appear to be most severe in mass production environments such as the motor industry.

Mullins (2) maintains, as do many others, that the flow line system has just about reached the limit of its development, not because of limitations in technology but because of the increasing difficulty in finding the operators to devote themselves to the meaningless tasks of the assembly line. This problem is most acute in the Swedish Motor Industry where both Volvo and Saab, faced with mounting labour turnover and absenteeism, are trying to humanise the production process.

Automation, often suggested as the solution to labour problems, unfortunately is not the complete answer, many operations in the motor industry being too complex to economically automate. In addition, complex automated equipment is all to often susceptible to breakdowns culminating in poor efficiency (3).

The basis of the projects being implemented at Volvo and Saab is to reduce labour turnover and the incidence of absenteeism by providing the operators with a more varied and stimulating working environment. To achieve this, the traditions of the flow line system have been abandoned in favour of small work groups. The major feature, however, is not the formation of these work groups but the system of self organisation operated within them. It is this autonomous working environment that supposedly induces greater job satisfaction. In addition, a greater variety of work is aimed at with the implementation of job rotation and job enlargement.

Volvo have led the world in the strive for a happier working environment and have, over the last ten years, implemented a number of experiments concerned with job enrichment, job enlargement and job rotation (4). One such experiment is with team-leader groups at the truck plant in Göthenberg. This is a form of job enlargement in which the worker follows the same body along the assembly line carrying out various jobs until the body moves over to another assembly line. There are about 20 team-leader groups, with 3 to 9 men in each. The aims of the system are to give the individual a greater say in decisions made and to improve the teamwork spirit through small, tightly-knit groups. The group chooses a team spokesman who represents the group and liaises with supervisors.

The most adventurous and recent projects launched by Volvo have involved the setting up of two completely new plants, an engine factory at Skövde (5) and a car assembly plant at Kalmar (6).

In the car assembly plant, the work of assembling the many components into finished cars is divided up between a number of work teams, each having a responsibility for a special section of the car, such as the electrical system, steering and controls, instrumentation, brakes and wheels.

Within the work team, which consists of 15 to 25 men, the members themselves agree on how the work should be distributed and they themselves decide when and how job rotation should be carried out.

The movement of car bodies between and within the teams is done on self-propelled carriages. Work on the car body can either be done on the move or when stationary and with the help of a tipping device the body can be turned so that work on the underbody can be carried out as comfortably as possible.

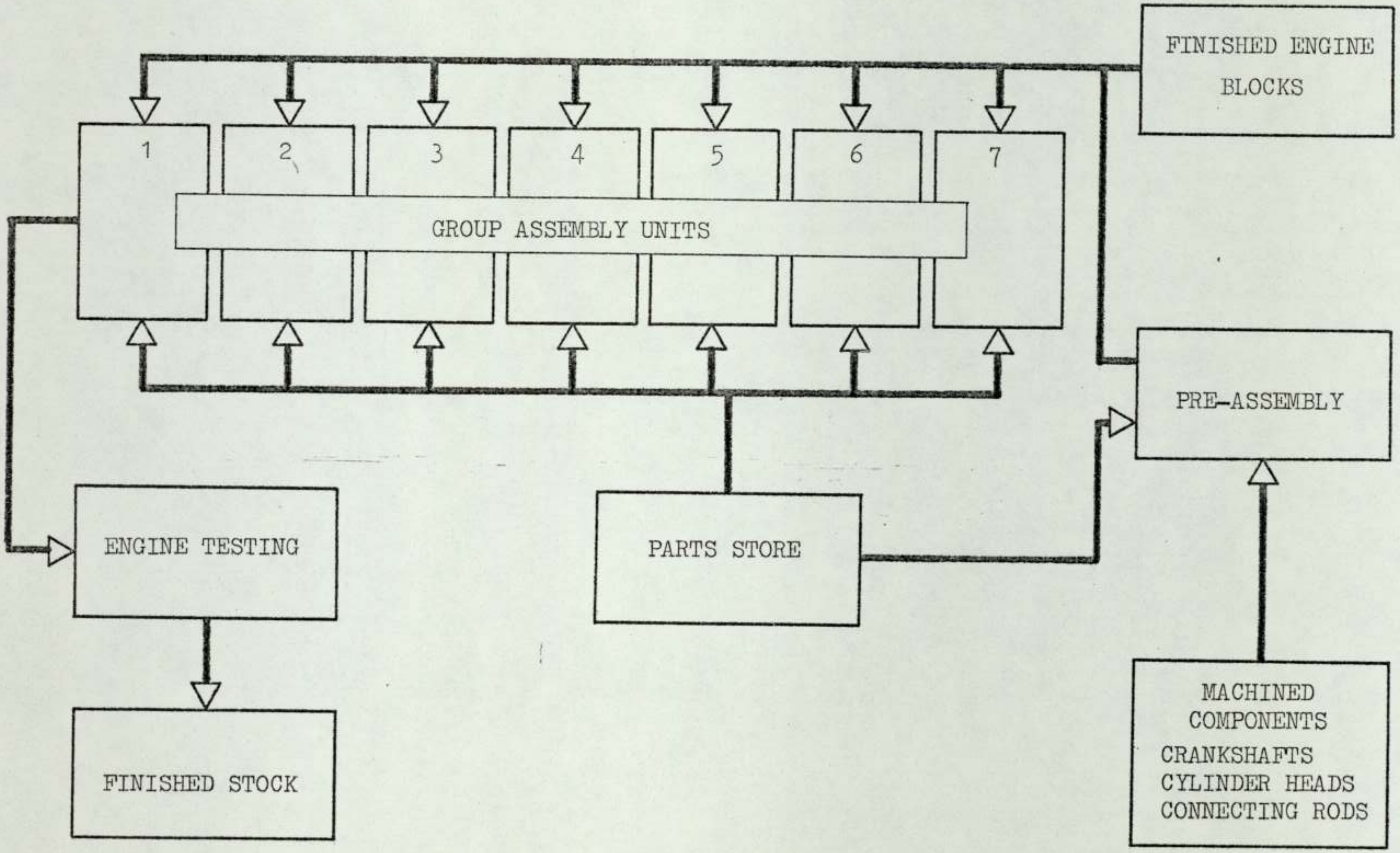
Between each work region is space for arranging buffer stocks of bodies. These buffers make it possible to vary the work rhythm and allow short pauses and relaxations. The team itself takes care of the transportation of materials within its area and is given greater responsibility for the quality of the car.

The layout of the new engine plant at Skövde is again based on group orientated work. Buffer stocks of work pieces are located between each individual operator and each working group. This will allow the individual to take a pause in his work when he feels like it and it will also enable both the individual and working team to have more control over their own rate of work. Each team is responsible for both direct and indirect job tasks such as quality control, material handling and tool changes.

Saab have been more cautious than Volvo and have restricted their experimentation to the new engine plant at Soedertaelje (1,3,7,8). Like Volvo, Saab have adopted an autonomous work group system, seven such groups being involved on engine assembly at Soedertaelje. Each group consists of four fitters whose responsibility it is to assemble the complete engine. It is up to them how they organise themselves with the alternatives of assembling the entire engine individually or working in groups of two or four. The engine plant is shown in diagramatic form in figure 1.

Although these experiments are still in the early stages, both Volvo and Saab say that they are encouraged by the results so far, both labour turnover and absenteeism having declined. These comments are to be expected in view of the large sums of money that both Volvo and Saab have invested in job enrichment experiments. The results are certainly not conclusive, operator behaviour being influenced by many factors. For example, the Swedish economy is at present going through a difficult patch with the result that a degree of insecurity could be motivating the workers in the motor industry to hold onto their jobs. In addition, at this stage in the experiments, increased job satisfaction could be as a result of change, not the nature of the change, i.e. the 'Hawthorne' effect.

FIGURE 1. SCHEMATIC OF SOEDERTAELJE ENGINE PLANT



Despite uncertainty over the long term effects of group working and greater worker involvement in decision making, other concerns both inside and outside of the motor industry are watching with interest the progress of the Volvo/Saab experiments and in some instances experimenting for themselves. Examples of the latter can be found at Fiat and the Philips Company in Holland.

Fiat, faced with considerable industrial unrest culminating in frequent petty disputes and a high incidence of absenteeism, are looking to group assembly, job rotation and job enlargement at their Termoli Engine and Cassino Car Plants, as a solution (9,10).

One of Fiat's prime objectives is to try and take as many operations as possible out of the actual line and treat them more as pre-assembly operations that are arranged not only to provide variety and increased interest but also improved working positions for the operatives.

One approach that is under assessment at the new Fiat plant at Cassino is the use of a number of identical assembly lines, each moving more slowly than a conventional line, with the operatives on the new lines performing work at one station that normally would be performed at two or more stations of the conventional line.

At the Termoli plant, engines are being assembled on a system known as the 'island principle'. Instead of the assembly line consisting fundamentally of a conveyor which carries the basic assembly between work stations where items are added in sequence, the 'island principle' allows for the shunting of assemblies into side areas where what would otherwise be a series of 'line' operations can be carried out before the product is returned to the continuously moving main conveyor for transfer to the next 'island'. This principle is shown in diagramatic form in figure 2.

Whereas this arrangement alleviates many of the human problems, the very nature of the items being assembled necessitates that certain disciplines must be retained and there is a limit to what can practicably be included in the work cycle at each pitch. Thus, while there is more variation within the cycle than would be the case with normal 'line' assembly, each operator is restricted to repeating the cycle without any possibility of a complete change of content, as long as he is assigned to one particular 'island'.

This restriction does not apply to another example of the 'island principle' that is to be tried out in the Turin factory for the later stages of the car body assembly and trimming. A layout of the arrangement is shown in figure 3.

Because of the longer cycle times, it is necessary to employ a small team of operators at each set of identical stations or 'islands' and greater variation of duties performed can be obtained by permitting the operators within each team to change round and divide up the work as they wish.

FIGURE 2. ENGINE ASSEMBLY ON THE 'ISLAND PRINCIPLE'

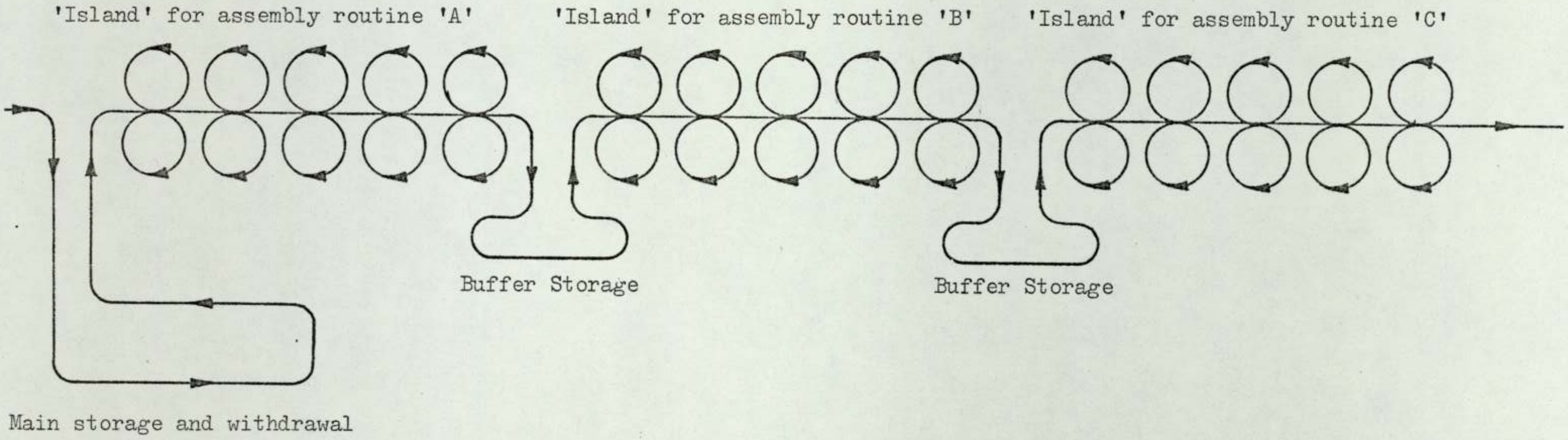
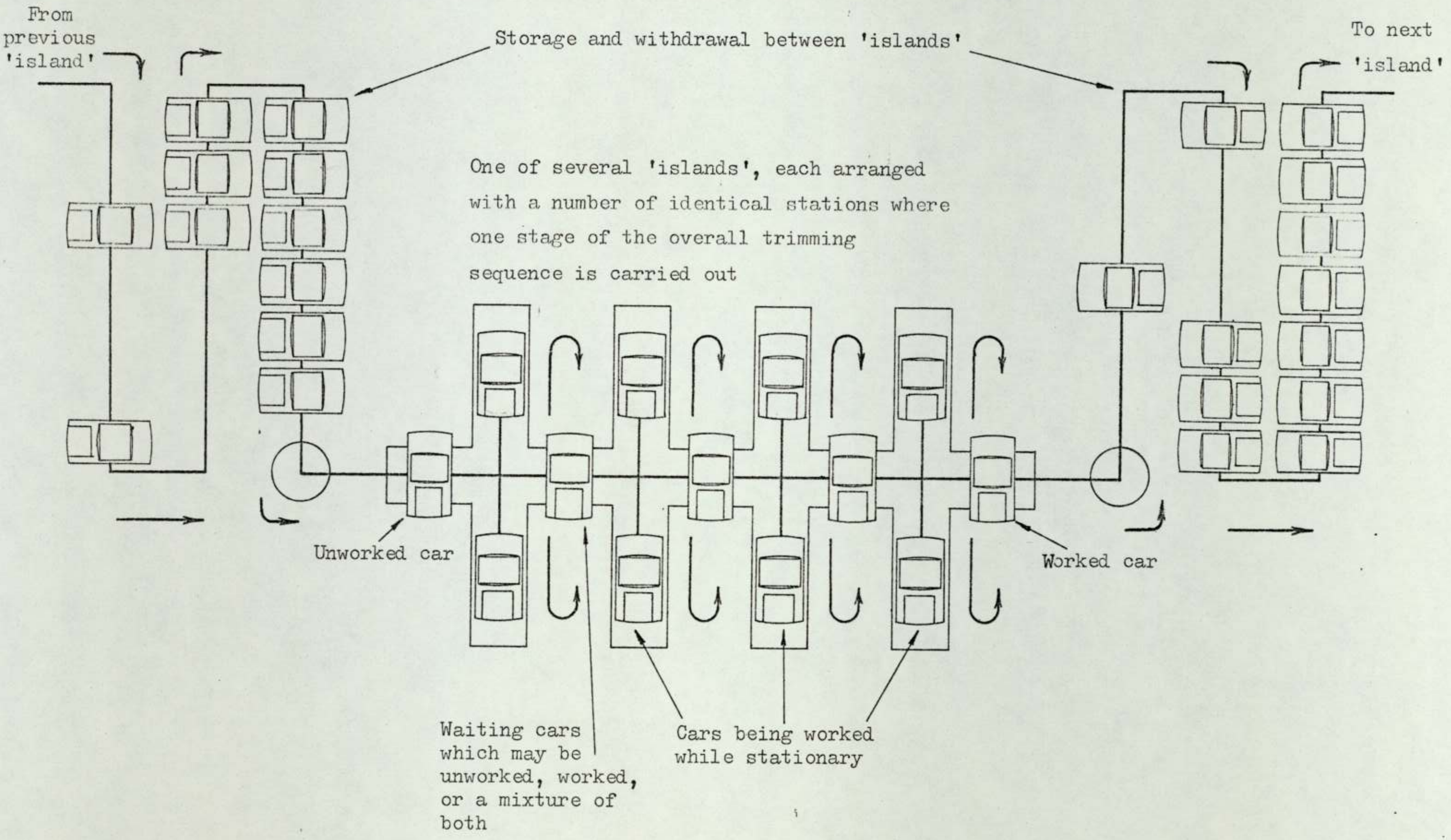


FIGURE 3. VEHICLE ASSEMBLY ON THE 'ISLAND PRINCIPLE'



At the Mirafiori plant, Fiat have chosen to automate the 132 body line, all the main spotwelding operations being achieved with a series of Unimate programmable manipulators or 'robot' units. Unimates were chosen in preference to fully integrated welding machines or multiwelders because they tend to be less expensive, more reliable and better suited to the relatively low production volume of the 132 model.

Fiat opted for automation on body build because they felt that the arduous manual welding operations were not conducive with an improved working environment and therefore not suitable for the implementation of a group assembly system. The 132 line was chosen for the exercise because of the low volume of build and because the seams to be welded were such that Unimates could be used.

Outside the motor industry, the Philips Company in Holland, faced with efficiency problems caused by model change delays, material shortages, labour turnover and absenteeism, embarked on a series of work structuring experiments (11). The first of these, in 1960, involved splitting a 100 station flow line manned by female workers engaged in electronics assembly into 5 more or less equal groups. These groups were separated by buffer stores containing approximately one hour's work. Each work group, including its own inspector and supervisor, was allocated a defined set of tasks and was arranged in such a way as to improve interpersonal contact. No adjustment was made to the cycle time, this experiment relying upon an improved social inter-reaction between the operators to induce a more pleasant working environment.

Since this period, Philips have implemented a large number of work structuring experiments including situations aimed at providing job enlargement, job rotation and job enrichment.

So far Philips have been able to conclude from the experiments that job enlargement generally improves quality, productivity, flexibility and the attitude of the workers towards their work. Job rotation, although having disadvantages such as loss of routine and longer training times, provides greater job knowledge and variety of work. Job enrichment was found to yield increased productivity.

All these experiments have, in one form or another, involved splitting up the assembly line into smaller units and reorganising the operators into work groups. This has led to many writers hailing the end of the assembly line. Wilde (12) disagrees with this, the thesis of his paper being that group working is not an alternative production system but rather a different dimension of work organisation, the use of which is compatible with the employment of the various existing types of production systems, including the flow line. The veracity of this statement depends upon the definition of group working. Clearly any type of production system involves groups of workers. For example, a vehicle assembly line consists of a group of workers. It may be argued that assembly line workers do not function as a group, the clearly defined boundaries of each work station cutting them off from one another. At some stations however, several operators can be found working together and yet this is still not hailed as group working.

The distinguishing feature of the Volvo-type work group and one which defines group working, is the freedom given to the work group members to organise the way in which they work. It is this autonomous working environment that is thought to promote a closer social contact between the group members yielding the behavioural advantages sought after.

On this basis, there is no reason why group working concepts cannot be extended to all production systems including the flow line, although organising the operators to facilitate this social contact can impose severe restrictions on assembly line layout. The Volvo truck plant at Gothenberg and the experiments at Philips in fact back up this thesis, the flow line assembly systems being split up to accommodate a group working environment but in essence the flow line principle remains.

Imberman (13) disagrees with the whole concept of group working including autonomy and job enlargement and maintains that assembly line workers are not repelled by repetitive work because it is straightforward and carries very little responsibility. Imberman substantiates this statement with a study of 3,800 hourly paid workers from five American plants. He concludes from the study that most employees prefer jobs with less high-quality demands, with less direct responsibility, with less troublesome variety and with more money.

The relevance of these conclusions is, however, doubtful, the sample of five American plants being much too small. The social conditions in America are vastly different from those in Scandinavia or Europe, besides which the workers involved in the survey had never experienced group working and probably knew very little about it, certainly not enough to substantiate preferences. Human beings in general tend to be extremely wary of change and possibly this is all the survey reflects.

Britain's involvement in group working is at present one of observation only, but with growing industrial unrest the question must be asked as to whether it would work in this country (14). The needs in this country, however, appear to be quite different from Sweden's. We are short not of labour but of harmony between the factory floor and the boardroom and of the high productivity that goes with it.

In Sweden, there is no differential between the wages paid by the motor industry and those paid outside, thus necessitating other incentives to attract labour. In this country, a differential in favour of the motor industry still exists and appears to be of sufficient magnitude to eliminate labour recruitment problems.

Over the last decade, the Swedish motor industry has experienced very few industrial disputes, the harmony that existed between union and management providing the ideal climate for negotiations. In fact, much of the impetus towards a group working system came from the unions. In this country, the industrial climate is vastly different, especially in the motor industry where poor labour relations are one of Britain's most serious problems. One consensus of opinion often held by persons not employed on the shop floor is that the blue-collar unions are at present too powerful and that autonomy on the shop floor would play right into their hands.

The working conditions in Britain are, however, poor by Sweden's standards and could be a major contributing factor in much of the industrial unrest that exists today. It is interesting to note, however, that in comparison to other industries in this country the working conditions in the motor industry are good and yet industrial relations poor.

In summary, it does not seem as if industry in this country is ready to introduce such radical changes as those tried by Volvo or to absorb the additional cost associated with group working systems. It is interesting to note that Volvo, Saab and Fiat all felt it necessary to either build new factories or to extensively expand old ones to accommodate the additional space this new technique requires. The cost of implementing a group working system was claimed by Fiat to be 20% more than for a conventional system although Saab quote only 10%.

In view of the uncertainty surrounding the long term benefits of group working plus the many other factors that can influence operator behaviour such as pacing and payment incentives, the pursuit of more predictable areas of research may prove more fruitful.

One such area, for example, is the design of assembly lines to minimise the effects of production stoppages and operator work rate variability. Past research in this area is extremely fragmented and although the implementation of good assembly line design will optimise the efficiency of a system, interest has appeared to have waned as a result of the more intriguing but perhaps less rewarding behavioural experiments.

CHAPTER THREE

PAYMENT SYSTEMS

Although there are a great many variations, all payment systems can be categorised under the following headings.

(a)	Time Rate	(TR)
(b)	Measured Daywork	(MDW)
(c)	Payment by Results	(PBR)

The post war period up to the early 1960's was characterised by the widespread and largely unchallenged popularity of PBR or piecework. At that time, PBR was regarded as the appropriate method of motivating employees engaged on work of a repetitive nature.

Since this period, a mixture of economic, industrial relations and technological factors have caused payment systems to come under review. For example, much of the work discussed in Chapter 2 such as group working, where radical changes have been made to the working environment, raises questions as to the appropriate payment system. PBR harmonises with short-cycle work when the emphasis is on productivity. As soon as quality requirements assume major importance, quality and quantity can become the subject of a conflict for the worker if wages are awarded soley on a basis of quantity. Group working aims at giving the fullest possible responsibility for a job including quality and, therefore, the form of renumeration must be consistent with this.

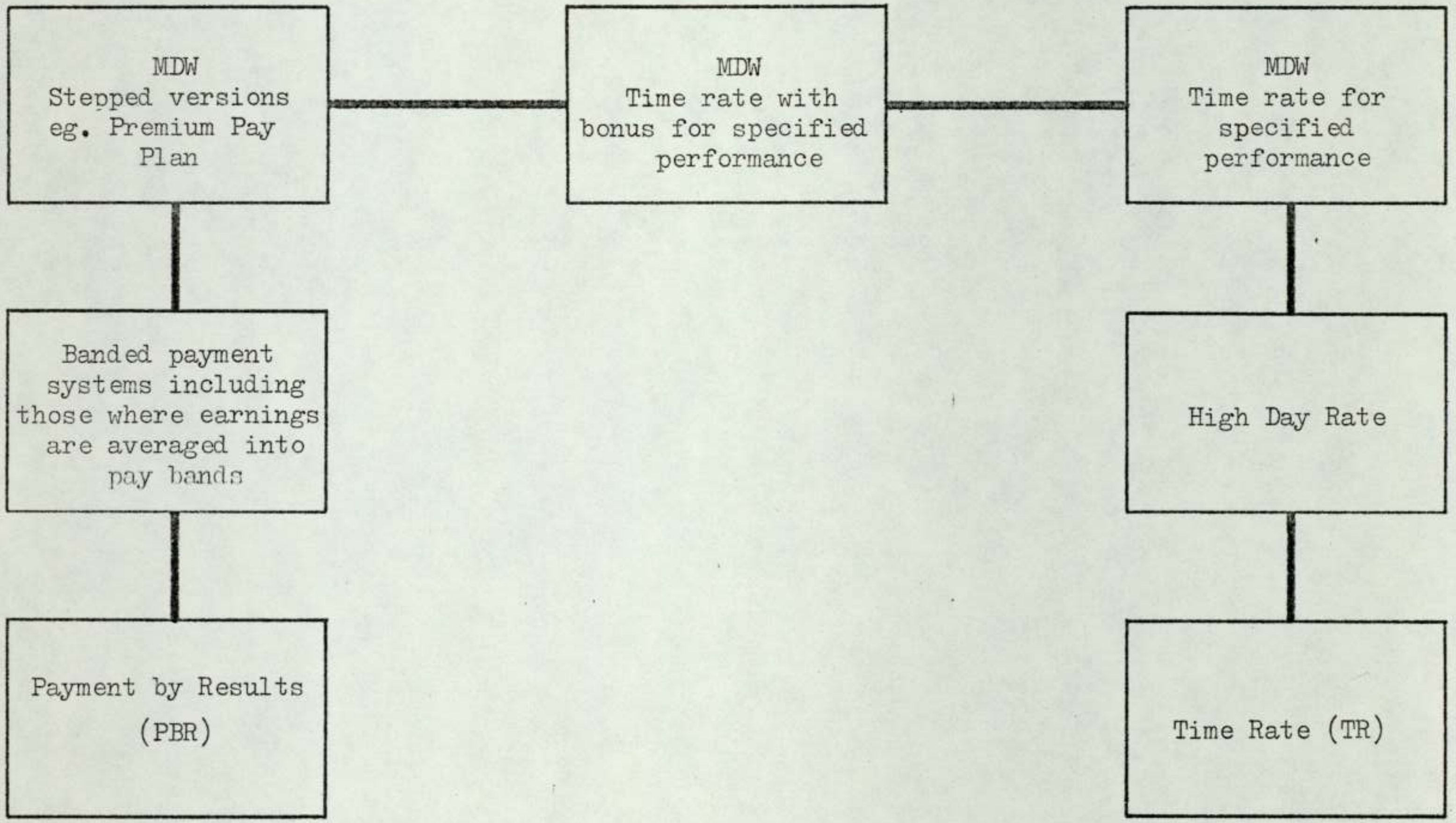
In general, a payment system is seen as a means of inducing effort and as an item of cost, the latter being of particular concern when market or financial pressures are acute. Neither TR or PBR completely fulfill these objectives. TR, being a straightforward payment for time at work, does not induce effort, performance and payment being unrelated. PBR, whilst inducing effort, is often the cause of unstable wage bills and bad industrial relations caused by frequent haggling over prices and times. These inadequacies have subsequently led to a growing sector of industry to opt for MDW (15).

Difficulties in terminology abound in discussion of payment systems and not least of MDW. The definition given by the Office of Manpower Economics in its report (16) on MDW adequately defines its essential features and is as follows:

' In MDW the pay of the employee is fixed on the understanding that he will maintain a specified level of performance but the pay does not fluctuate in the short term with his actual performance. This arrangement relies on some form of work measurement or assessment, as a means of both defining the required level of performance and of monitoring the actual level.'

Within this definition, three main types of MDW can be identified as follows, their relationship to PBR and TR being designated in figure 4.

FIGURE 4. PAYMENT SYSTEMS



(a) Payment on a time basis with a requirement that employees maintain standard performance based on work measurement, i.e. time rate for a specified performance.

(b) Payment on a time basis with a fixed bonus for maintaining standard performance based on work measurement, i.e. time rate with a bonus for specified performance.

(c) As in (a) or (b) above, but each individual can opt to maintain one of a series of performance levels to which differing rates of pay are attached, e.g. stepped measured daywork, premium pay plan, i.e. stepped versions of (a) or (b) above.

The Office of Manpower Economics' report (16) resulted from a study of MDW undertaken at the request of the Secretary of State for Employment following a growing popularity in payment systems of this kind. The data for the study was compiled from a statistical survey of 3,000 establishments and an attitude survey questionnaire from nearly 850 individual employees.

The report concluded that in general the introduction of MDW improved industrial relations and stabilised production and labour costs. The overall effectiveness of MDW, however, was found to vary enormously under differing circumstances with no clear indication of its suitability to a particular situation. One such factor of considerable influence was the conditions prevailing at the implementation stage, MDW more often being seen as an escape from an unsatisfactory situation than as a move to some clearly desired alternative. It was, however, apparent that MDW could be particularly helpful where PBR had previously been applied, by improving industrial relations, and that where it succeeded TR it could make a significant contribution to the improvement of effort.

Both Mercer (17) and Bernstein (18) highlight the serious repercussions that can result from implementing MDW purely because other systems have failed. Bernstein believes that a payment scheme should have the result of increasing output and lowering unit costs. In addition, it should promote job satisfaction and an equitable grade structure which reflects the variation in job demands and should be flexible enough to cope with technological and economical change. In particular, a payment system should allow participation with management as a continuing activity in determining agreed rules to control, administer and evaluate the output/pay relationship.

A changeover to MDW also enforces changes in the role of the shop floor supervisor, an additional responsibility for maintaining employee performance requiring supervision of an extremely high calibre. A special effort is also required from management in consultation, negotiation and maintenance of the scheme, without which MDW is as vulnerable to decay as any other form of payment system.

A survey carried out in Swedish industry examines 73 plants that have in recent years changed from one system of payment to another (19). The conclusions clearly show that when plants changed from PBR to TR substantial reductions in production efficiency resulted, in the region of 15% to 25%. Those who changed from PBR or TR to a premium system experienced increases in production efficiency, TR to a premium system yielding dramatic improvements in the order of 25% to 35%.

The premium system adopted is generally described as a fixed wage plus a performance related bonus. This description fits that of a MDW scheme but further examination of the report reveals that the bonus is in fact calculated on actual production figures. This suggests that the bonus can vary weekly, a feature that is not an aspect of MDW.

The results displayed in the form of production efficiencies are most decisive with the outcome that the premium system is strongly recommended. Production efficiency, however, is based on production figures alone and takes no account of cost. Bearing in mind that a payment system is both a form of operator incentive and a cost item, performance figures alone are not sufficient upon which to base a comparison of payment systems. For example, if the new payment scheme consisted of a bonus based on production figures added onto a fixed wage calculated from the average earnings of the old system, i.e. PBR or TR, then it seems reasonable to expect that an increase in production would result. The opportunity for the operator to increase his earnings would in this instance be the motivating force. On production figures alone the new scheme would be justified but the cost of such an exercise could turn profits into losses.

In summary, of the three payment systems discussed, MDW appears to be the most suited to today's industrial environment. It is stressed, however, that the implementation and maintenance of it requires strong management, good industrial relations and an extremely high standard of shop floor supervision. Without these assets, MDW, especially when implemented without a bonus scheme, can rapidly deteriorate in the form of poor operator performance.

CHAPTER FOUR

OPERATOR WORK RATE VARIABILITY

The work rate of an operator engaged on a repetitive task will tend to vary from cycle to cycle. The resulting cycle time variation may be described by means of a probability distribution, the shape of which has been studied under various operating conditions by several researchers. These include Dudley (20,21,22), Conrad (23), Sury (24), Murrell (25) and Seymour (26).

As a result of a number of factory based production studies of repetitive manual operations (20,22) backed up with a series of laboratory based experiments (21), Dudley concludes that the shape of the probability distribution is influenced by certain operating conditions and varies between a normal and positively skewed distribution. He found that unpaced manual tasks yielded positively skewed distributions whilst process controlled or paced rendered a more normal distribution.

Experiments with trainee operators revealed that, irrespective of operating conditions, their work times described a more symmetrical or normal distribution as also did the experienced operator when told to work at a reduced pace.

These results support other investigators such as Conrad (23) who, in addition to demonstrating the skew effect in unpaced work time distributions, states that it would cause approximately 66% of total work times to be less than the mean time. Sury (24), reporting on a series of industrial based experiments including a study of the effect of both feed rate and tolerance time on the output of a conveyorised assembly system, found that the degree of positive skewness varied with feed rate, lower feed rates yielding near normal distributions.

Seymour (26) plotted the time distributions of the motion elements within a task including the therbligs, 'grasp', 'move', 'position' and'reach'. The total number of observations was too few to make any definite conclusions, however, the elements 'grasp' and 'position' showed some positive skewness.

All the above researchers, when determining the shape of the operators' work time distribution, have studied short cycle time operations, in the main less than 30 seconds, presumably to save time. Many assembly line operations, however, have a cycle time much longer than 30 seconds, a cycle time of less than a minute being difficult to find in the motor industry. Further research is, therefore, necessary to determine whether or not an operator engaged on a long cycle time operation describes a work time distribution of the same shape as that determined by the above researchers.

Operator variability is usually measured in terms of standard deviation or coefficient of variation (standard deviation/mean cycle time) of his work time distribution. From a brief survey of frequency distributions for unpaced manual operations, Slack (27) found that the coefficient of variation of work time distributions could vary from 0.008 to 0.5 but were most likely to be about 0.27.

Although many researchers have either investigated or discussed the shape of work time distributions none, with the exception of Slack's (27) brief survey, have attempted to quantify or relate coefficient of variation with types of work. Within certain bands of variation pertaining to individual operators, intuitively it seems likely that, for certain types of work, the coefficient of variation should remain constant. The shape of the distribution alone is of little use to the design engineer, the absence of 'coefficient of variation' data prohibiting its application in such exercises as computer simulation.

The effect of operator work rate variability on a series of work stations is a detrimental one, the output from a system without interstation storage being dictated by the speed of the slowest operator. Although the work time distribution for each individual operator can be described as a normal or positively skewed distribution, a distribution of interdeparture times from the end of the line would show a bias of times greater than the operator's individual mean cycle time. Intuitively, the distribution would tend to be negatively skewed. It therefore follows that the efficiency of a series of work stations without interstation storage will decrease with the addition of operators due to a proportional increase in the incidence of poor cycle times.

The introduction of interstation storage, by reducing the dependability of one station on another, not only reduces the transmittal of poor cycle times but enables benefits to be gained from the occurrance of cycle times shorter than the mean.

Many of the earlier researchers attempted to determine the effect of operator work rate variability on the efficiency of a series of work stations, with and without interstation storage, using an analytical approach. The most popular method used was queuing theory. This method assumes poisson arrivals and exponential service times, the former excluding systems of fixed or small variable arrival rates and the latter greatly exaggerating the effect of operator variability. Queuing theory also increases in complexity with the increase in number of stations, hence analyses by this method are restricted to less than five stations. In practice, an assembly line of less than five stations is rarely employed, thus limiting the application of this work.

Analytical studies using this approach have been made by Hatcher (28), Hillier and Boling (29), Hunt (30), Knott (31) Koenigsberg (32) and Goode and Saltzman (33). Alternative mathematical models have been derived by Buzacott (34), Koenigsberg (32), Goode and Saltzman (33) and Muth (35), the latter researcher developing a model that is not confined to the use of negative exponentially distributed work times. From this model Muth (35) has derived a series of curves which can be used to evaluate the influence of the number of stations and the variability of the elemental times upon the line production rate.

Although the analytical approach does provide a precise mathematical solution, severe restrictions associated with the size of system that can be analysed and the distributions that can be used, limit the usefulness of the solutions.

An alternative form of investigation involves computer simulation; Anderson and Moodie (36), Barten (37), Knott (31) and Slack (38) all adopting this method. This form of analysis greatly improves the flexibility and accuracy of modelling by facilitating the investigation of larger systems and the use of more realistic distributions. It does, however, require specialised facilities and expertise in computer programming as well as being time consuming and expensive. To overcome some of these problems, Anderson and Moodie (36) and Knott (31) have used computer simulation to derive empirical formulae. These formulae can then be used instead of simulation to determine the effect of changes in certain variables. This enables the engineer to quickly calculate efficiency values without having specialised knowledge of computer simulation.

In general, all researchers agree that the efficiency of a series of work stations is a function of interstation storage capacity and that small increases in storage capacity can yield significant efficiency improvements.

CHAPTER FIVE

PACING

Murrell (39) states that a system is paced when an operator is induced, either mechanically or by adjacent operatives, to work at a rate other than that of his or her own choosing.

This definition covers an extremely wide variety of working conditions, all systems with exception of those with large buffer stores between operators fitting this classification. Although adjacent operators will, under certain conditions depending upon sociological and system design factors, induce a degree of pacing upon one another, if their work rate is not governed by the cycle time of a machine or motion of a conveyor, then they as individuals or as a team are free to vary their pace and are usually classified as unpaced. A more common definition is, therefore, that an operator is only paced if his work rate is influenced by the cycle time of a machine or the motion of a conveyor.

The effect of pacing on operators performance has been studied by a number of researchers, some of the results having been discussed in Chapter 4 when detailing the effect of pacing on operator work time distributions.

Conrad (23,40,41), following a series of studies of paced and unpaced operations, concluded that in general self-paced machine work yielded the highest level of operator performance. Conrad (23) reached this conclusion from the discovery that an operator working at a machine whose cycle time is the same as the mean cycle time of the operator will, for one-third of the time, require more time than the system permits. On the remaining occasions, the operator, having completed the cycle, will wait idly for the next unit to arrive. When a task is unpaced the operator, without prejudicing the quality of his performance, can stop working at any instance in time for an indefinite period. The work can then be taken up where it was left off and the operator is free to decide when he will initiate a movement.

To facilitate these conditions Conrad (41) recommends the use of buffer storage between each manned station. The operator's mean rate of working would then be the correct rate at which to feed the store and it would also be the output rate of the system. Operators working on a rigidly paced conveyorised system must inevitably be under utilised to ensure that the probability of a part passing by unprocessed is quite small.

Buffa (42) conducted a series of experiments in an attempt to gain some insight into the effect of feed rate and time available on the performance of operators engaged on conveyor paced work plus a comparison of paced and unpaced working. From this, Buffa concluded that performance times are not a function of time available but a function of feed rate only, a discovery that both Conrad (23) and Hunt (30) agree with.

Sury (24), however, disagrees with Buffa's findings, his studies revealing that operator performance is influenced by both feed rate and time available on conveyor paced work. Whilst Sury's experiments were executed in industry and involved experienced operators, Buffa based his conclusions on laboratory studies. Without further experimentation, the correct conclusions cannot be determined but intuitively the reactions of the experienced operator will be different from those of the experimental subject.

To simulate an unpaced working condition, Buffa told his subjects to work at a pace that they felt they could maintain all day. Each subject was exposed to about three hours of experiments from which only a few minutes of unpaced working was recorded. The accuracy of the unpaced working results is, therefore, dependant upon the ability of the experimental subject to adopt a normal unpaced performance level. In view of his lack of experience and the different motivating factors that exist with laboratory based studies, it seems unlikely that this estimate will be a good one.

The cycle times of the operations studied by Buffa and Sury were extremely short, in the region of five seconds. It is, therefore, questioned as to whether the reactions of an operator engaged on longer cycle times, whether paced or unpaced, are the same as those engaged on short cycle time operations.

Although pacing is an area of research that has been studied by many researchers, some of whom are mentioned above, there still appears to be areas, such as the study of long cycle time operations, that require investigation and areas where uncertainty still exists. The latter area is a problem common to this type of study, operator reaction to various work conditions varying from operator to operator.

In general, all researchers agree that unpaced working is to be preferred, under the correct conditions an unpaced system being potentially more efficient than an equivalent paced one.

CHAPTER SIX

SYSTEM RELIABILITY

Sandler (43) states in his book on system reliability engineering that there are two ways of achieving reliability. The first is to develop highly reliable parts for use in equipment and systems; the second is to design reliable systems from less reliable parts.

Most plant and equipment at present in use in such industries as the motor industry, when analysed in isolation, is of reasonable reliability. When used in large numbers or in conjunction with other equipment on an assembly line, dramatic reductions in system reliability can result. This effect can be demonstrated with the following example from the motor industry.

> The probability of a spot welding set, as used in the motor industry for vehicle body build, breaking down is of the order of 0.00032. This figure was calculated from stoppage records of an actual vehicle body build track on a basis of stoppages being related to bodies built. On a track building a body every minute, in the region of 150 such sets may be required. If the assembly line is of a tied nature, hence the bodies in their various stages of assembly cannot move independently of one another, then a breakdown on any one welding set will force

the entire line to stop. If P is the probability of an assembly line stoppage due to welding set failure, p the individual welding set breakdown probability and n the number of sets, then:

$$P = 1 - (1 - p)^{150}$$

$$P = 1 - (1 - 0.00032)^{150}$$

$$P = 0.0469$$

If the cycle time of the assembly line is one minute and the mean stoppage duration is 2.32 minutes per set (taken from shop floor recordings), then with the probability of a system stoppage being 0.0469 the system reliability becomes 89.13%. This compares with an individual welding set reliability of 99.93%. Hence, although the individual welding set reliability is high, combining large amounts of equipment on a tied system can considerably reduce the level of reliability.

The development of highly reliable parts can prove extremely costly, a serious disadvantage when selling in a competitive market to a cost orientated industry. In many cases much of the plant and equipment used in industries such as the motor industry is designed for a specific function and as such is unproven until in operation. It would seem , therefore, that unless industry insists upon equipment of higher reliability and is willing to pay for it, then manufacturers will continue to supply equipment at the present level of reliability.

The alternative, as suggested by Sandler (43), and one that is possibly more economical, is to design assembly systems such that the effects of breakdowns are minimised. This involves the use of interstation storage, each station being to a certain degree, isolated from the events on the adjacent stations. The degree of isolation is dependent upon such factors as cycle time, stoppage time and capacity of interstation storage.

This area of research is closely related to that discussed in Chapter 4, both operator variability and the occurrance of breakdowns reducing the efficiency of a series of work stations by increasing the mean processing time of the system. Unlike operator variability research, however, the study of the effect of breakdowns and the use of various design factors to minimise their impact on a series of work stations, has rarely been pursued. Presumably this is because of the difficulty in generalising the problem, the frequency and duration of breakdowns varying substantially from one industry to another, and the problems associated with representing the occurrance of breakdowns with conventional mathematics.

To overcome this latter problem Freeman (44) resorted to computer simulation, the occurrance and duration of breakdowns being randomly simulated. Using a three station automated production line model, Freeman attempted to investigate the operational and economic aspects of the number and sequence of work stations and the amount and allocation of storage capacity amongst them. In view of these objectives, a three station production line is far too short for analysis, the vague nature and inaccuracy of the conclusions supporting this fact.

Whilst condemning extreme allocation of buffer capacity such that there is no buffer capacity between some pairs of stations and all between others, Freeman advocates the allocation of more buffer capacity to bad stations. Freeman also concludes that the end of the line is more critical than the front and should, therefore, be allocated more buffer capacity.

The employment of additional buffer capacity to bad stations is in itself a doubtful one and the conclusion that the end of the line is more critical than the front is incorrect. Assuming normal working conditions apply, a breakdown at any station on the line will result in a loss of production capacity that cannot be made up. The degree with which the breakdown inhibits production at other stations is unrelated to position and will depend upon various design factors such as the size of buffer capacity. A breakdown at the front of a line can restrict production by starving succeeding stations of partially processed units in the same way that a breakdown at the end of the line will restrict production by blocking the output from preceeding stations.

Freeman, however, is not the first to make this conclusion, some of the work reviewed by Koenigsberg (32) also maintains that breakdowns at the end of a line have a greater effect on the rest of the system than those occurring at the front. This line of thought would appear to stem from an approximation made to simplify analysis, losses due to breakdowns being considered in one direction only, i.e. those caused by blocking.

The allocation of additional buffer capacity to counteract a bad station is totally ineffective in the long term, a much better approach being to rearrange the stations such that the problem facilities are equally divided amongst them. If this is not possible, the work load of the bad station should be rearranged such that its production capacity is increased by an amount to offset the additional breakdowns. Buffer capacity is then provided to cater for the fluctuations in output from adjacent stations.

The existance of a bad station effectively unbalances the line, its mean processing time including breakdowns, being greater than the other stations. It is inevitable, therefore, that buffer capacity before a problem station will tend to fill, a condition that severely limits its function as a buffer. Likewise, the succeeding buffer capacity will tend to run empty. Ideally, the prevailing state of a buffer store between work stations should be half full, this condition being achieved by the stations either side of it having the same effective production capacity. In this state, a buffer store satisfies its intended function of merely buffering fluctuations in output from adjacent stations. No matter how much buffer storage capacity is provided, the production capacity of the system cannot exceed that of the worst station.

Buzacott (34,45,46) conducted a series of detailed investigations into the effects of breakdowns on systems with and without interstation storage and concluded that buffer stores are only useful when variations in processing times occur and when the mean supply and demand from them are equal. Buzacott (46) also investigated the use of various ways in which the stations of a production system can be connected, as an alternative solution to the problem station. Three variations are considered, standby, parallel and splitting, the latter involving the use of duplicate stations operating at half rate, being recommended as the most efficient.

For most of his investigations, Buzacott has derived formula to enable efficiency estimations to be made for various station-buffer store configurations. Because of the complexity of the mathematics, analyses using the derived formulae are restricted to systems having less than five stations, fixed inter-breakdown times and constant breakdown duration. The lack of flexibility and unrealistic assumptions that are made considerably restrict the use of these equations.

CHAPTER SEVEN

PRODUCTION LINE CLASSIFICATION

Basically there are two main categories of production line, tied and untied systems.

A tied system is defined as one where the assemblies in their various stages of completion cannot be moved independently of one another. Included in this category are all continuously moving or intermittent conveyorised systems without interstation storage. On both systems the product or part being assembled has a positive connection with the transfer mechanism and is moved from station to station in a continuous or intermittent manner. In the latter case the conveyor may either be set into motion at pre-determined intervals or initiated by one of the operators.

Tied systems are extensively used in the motor industry, the size and weight of a car body necessitating the use of some form of mechanical handling device, the continuous and intermittent conveyors being the most convenient. The major disadvantage with this type of system is a proneness to poor system efficiency, a stoppage at any station forcing the entire line to stop for the duration of the stoppage. In addition to this the output from an operator actuated intermittent line is dictated by the speed of the slowest operator, whilst the automatically actuated intermittent and continuous conveyor systems must be planned such that all operators on all occasions can complete their allocated tasks within the cycle time.

Contrary to the features of the tied system, an untied system will allow, to a certain degree, assemblies to be moved independently of one another, the degree of independence relying upon the interstation storage capacity available. The inclusion of interstation storage can greatly improve the efficiency of the production line by cushioning the effect of individual station cycle time fluctuations from the rest of the system.

Interstation storage capacity can, however, be an expensive commodity in terms of floor area used, especially when large assemblies are involved. This fact coupled with the lack of information on the benefits that can be realised from using interstation storage has inhibited the use of untied systems, especially in industries such as the motor industry.

Included in this category are manual push pull systems, power and free systems and systems where the operator removes the part or product from a moving conveyor to an adjacent work station, completes his operation, and returns the part to the conveyor. Manual push pull systems are usually associated with the production of small parts, the part or product being passed to the next station or into a buffer store upon completion. It is not impossible, however, to process large assemblies such as car bodies on push pull systems, mechanical handling equipment such as roller track being used to facilitate movement. On the power and free system, the unit of production is usually mounted on a movable pallet or platform which can be stopped or set into motion according to the wishes of the operator. The pallets derive their power from either a single moving device through an electrically actuated clutch or, in some cases, each pallet is fitted with its own prime mover, usually an electric motor. When an operator is working on a unit, he can hold the pallet at his station for the desired length of time then, on completion, he can send it into the downstream buffer and obtain another one from the upstream buffer.

CHAPTER EIGHT

VEHICLE BODY BUILD SYSTEMS

8.1 The Gateline Conveyor

This system of vehicle body construction can be classified as tied and unpaced, the body being built up from its major sub-assemblies on jig trucks powered by a continually moving carousel-type floor chain conveyor. The system derives its name from the vertical jigs or 'gates' that are used to accurately locate the sidepanels to the other major sub-assemblies during tackwelding. The gates, which are arranged in pairs, right and lefthand, are usually mated to the jig trucks and travel with them until the body is strong enough to maintain its critical dimensions.

There are several variations of the gateline conveyor system, the most common differences being the ratio of gate pairs to jig trucks and the method of supporting and powering the gates.

8.1.1 The Maxi Gateline

This gateline was the first to be installed at Cowley and consists of 54 jig trucks and 54 pairs of gates, both at a pitch of 18 ft. and is capable of producing in the region of 4,000 bodies per 80 hour week.

The gates are hung from two overhead conveyors, right and lefthand, by means of adjustable spring hangers. The sidepanel is built up on the gates in an area adjacent to the jig truck carousel, as shown in plate I, the righthand gate conveyor looping over the jig trucks to gain access to the centre of the carousel. Both the floor and overhead conveyors are continually moving and synchronised, the sidepanels upon completion being conveyed to the carousel and mated with the appropriate jig truck. A view showing the gates mating with the jig trucks is given in plate II. The gates remain clamped to the jig truck during the loading and tackwelding of all major sub-assemblies, after which they are unclamped and returned to the sidepanel build area in readiness for further sidepanel build.

The bodies remain on the gateline until the body shell is complete after which it is automatically off-loaded and conveyed to a finishing track where doors, bonnet and trucklid are fitted and all finishing operations executed. All spotwelding is completed on the gateline.

The major items of plant, apart from those normally associated with body build, include a semi-automatic monorail system to load the underframe and an automatic roof loader and body lift-off hoist. Automatic gate loaders were initially installed but later taken out of commission due to poor reliability.

The layout of the Maxi gateline is shown in figure 5.

PLATE I SIDEPANEL BUILD – MAXI GATELINE

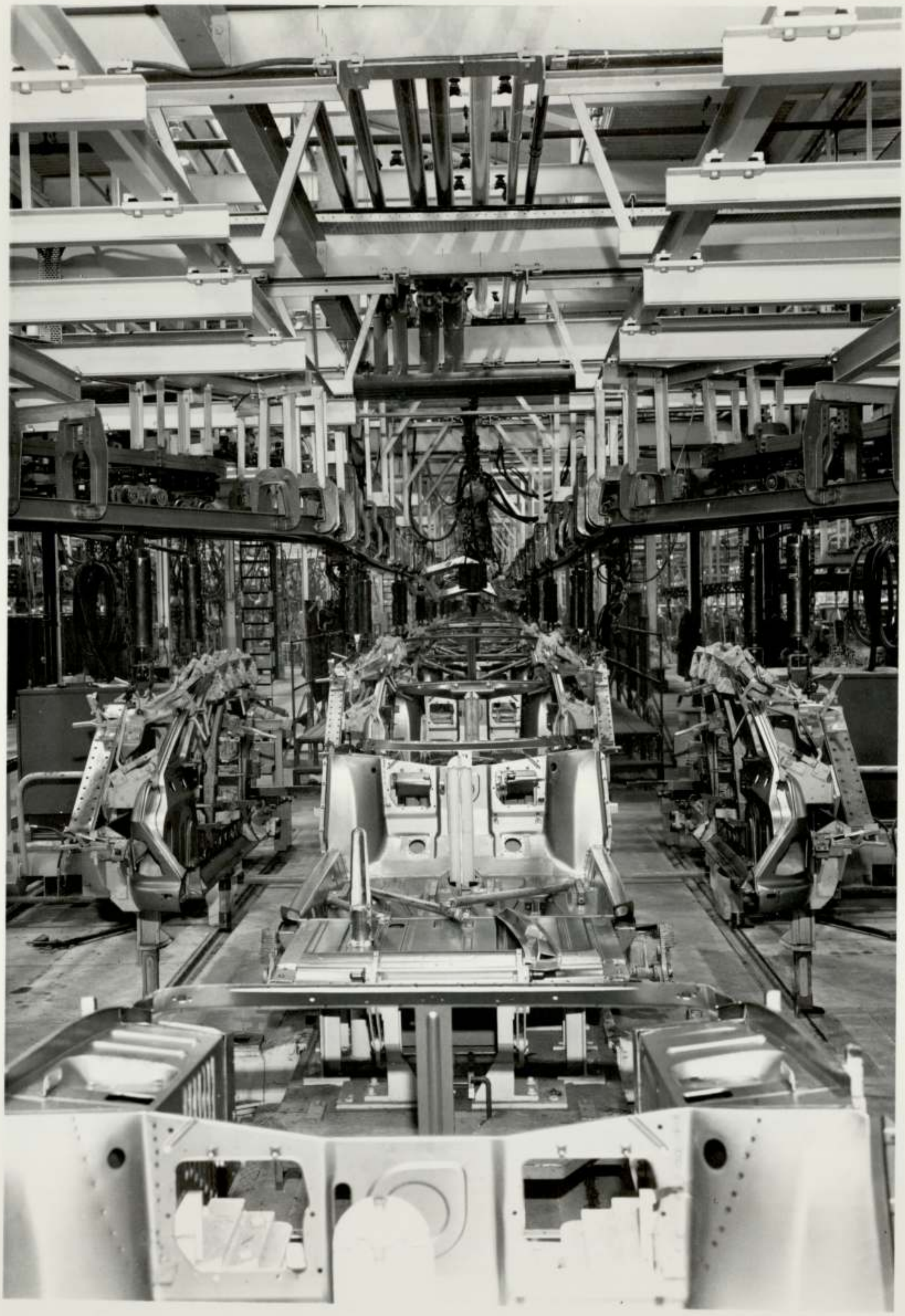


PLATE II GATE LOAD STATION - MAXI GATELINE

8.1.2 The Marina Gatelines

To meet the production requirements, two gatelines were installed at Cowley to build the Marina, both having a production capacity of about 4,000 bodies per 80 hour week. Two and four door saloons are built on one track and vans, estates and four door saloons on the other. Both gatelines are similar in layout and consist of 44 jig trucks at a pitch of 18 ft. and an equal number of gate pairs supported on overhead conveyors as on the Maxi gateline.

The only major difference between these systems and the Maxi gateline is that the sidepanel build areas are located on a mezzanine floor above the Marina jig truck carousels. This modification was made possible by the additional headroom in this area and apart from providing a saving in floor area, facilitated a direct feed of gates to both sides of the jig trucks without having to loop over them. This enabled shorter gate conveyors to be used with a subsequent reduction in number of gates and jig trucks.

As with the Maxi gateline, both Marina lines have a high degree of mechanisation, including semi-automatic underframe loaders and automatic roof loaders, gate unloaders and body lift-off hoists.

A layout drawing of one of the Marina gatelines is given in figure 6 and views showing the jig truck carousel with and without the gates in position can be found in plates III and IV.

PLATE III JIG TRUCK CAROUSEL WITH GATES IN POSITION - MARINA GATELINE

PLATE IV JIG TRUCK CAROUSEL AFTER GATE UNLOADING STATION - MARINA GATELINE

FIGURE 5. THE MAXI GATELINE

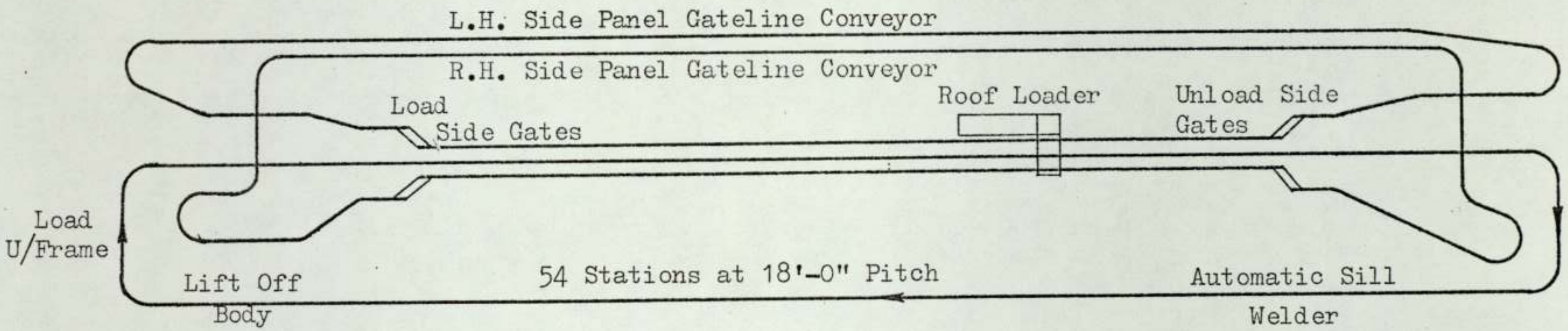
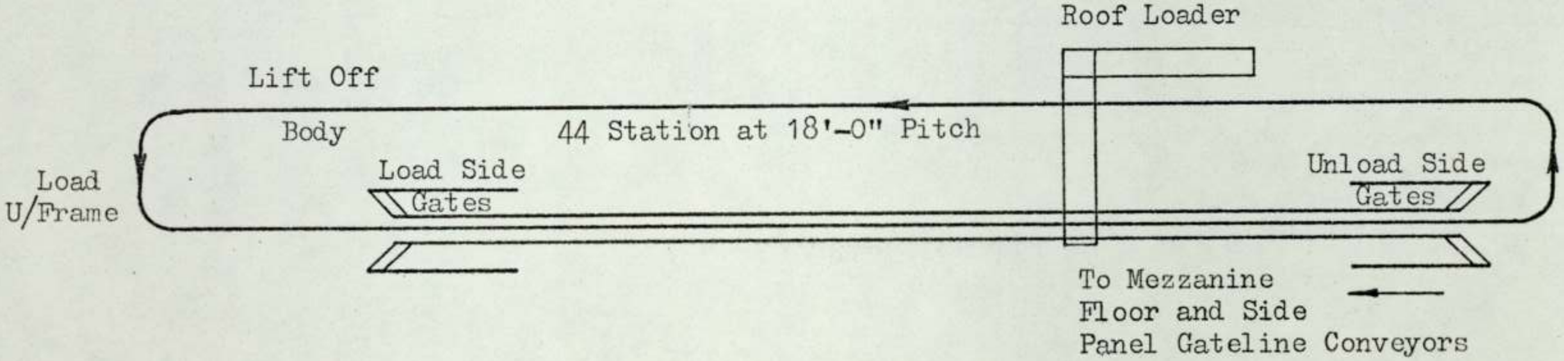


FIGURE 6. THE MARINA GATELINE

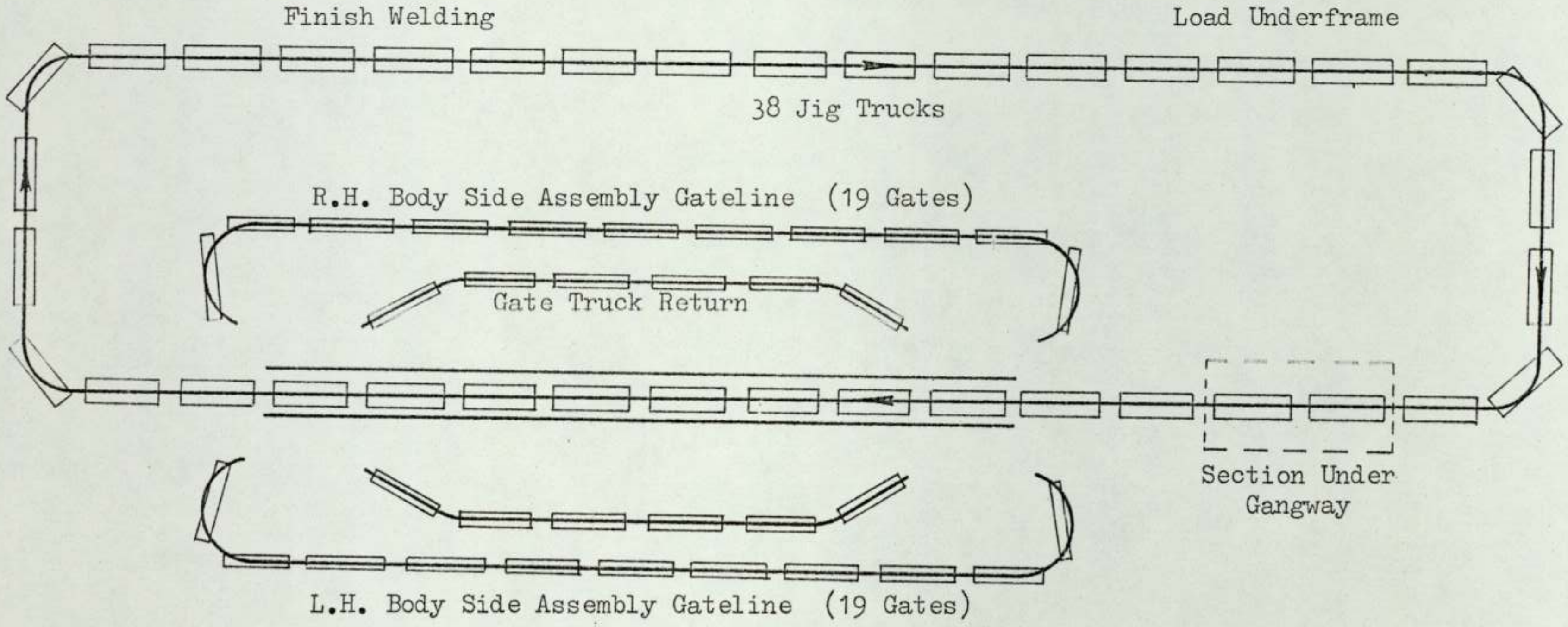


8.1.3 The Avenger (Chrysler) Gateline

This system differs from the Cowley gatelines in that the gates are floor mounted on conveyorised trucks and the ratio of jig trucks to gate pairs is 2 to 1. There are 38 jig trucks and 19 pairs of gates, both at a pitch of 18 ft., the system having a production capacity of about 3,500 bodies per 80 hour week. The advantage of having less gates than jigs trucks is that the righthand sidepanel build area and gate conveyor can run inside of the jig truck carousel. This does, however, decrease the flexibility when sequencing mixed models or variants on the gateline. The problem of getting the necessary components to the inner sidepanel build area is overcome on the Avenger gateline by a section of the jig truck carousel passing underneath a gangway.

The sidepanel is built up in the same way as before on the gates, along a straight section of each sidepanel gateline. On completion, the left and righthand sidepanels are brought in adjacent to a jig truck by means of the gates and gate trucks. At this stage, the gate trucks leave the section of powered floor conveyor and are manually pushed to the appropriate jig truck. The gates, plus their completed sidepanel assembly, are manually clamped onto the cone locations on the jig truck and the gate truck released. The gate truck is then pushed onto another section of powered floor conveyor which takes it to the gate unloading station. At the gate unloading station, the reverse of the loading procedure takes place, the gate and gate truck being

FIGURE 7. THE CHRYSLER (AVENGER) GATELINE



finally pushed back onto the powered floor conveyor of the sidepanel assembly line in readiness for further sidepanel build.

A layout drawing of the Avenger gateline is shown in figure 7.

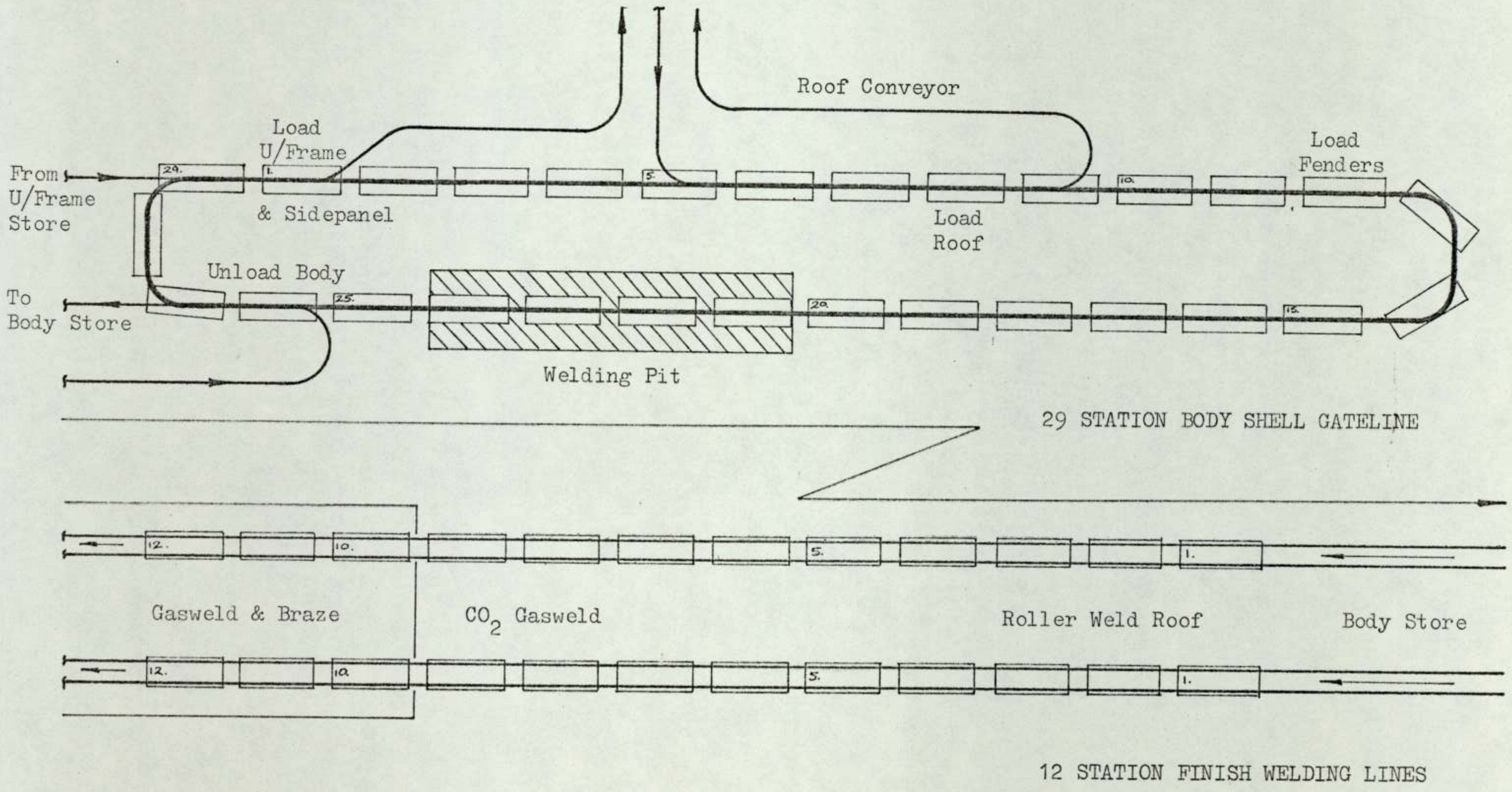
8.1.4 The Allegro (Butterfly) Gateline

This gateline, installed at Longbridge to build the Allegro, differs considerably from the Cowley system in that the sidepanels are assembled on overhead tracks completely divorced from the body build carousel. The sidepanels are delivered to the build line in a completed state, along with the underframe, on an overhead conveyor.

The gateline again consists of a series of jig trucks, 29 in all, driven by a continually moving carousel floor chain conveyor; however, on this system the gates are permenently attached to the jig trucks and are hinged at the lower ends to permit a 15 degree movement. This allows freedom of access for loading the sidepanels, underframe and other major sub-assemblies and unloading the completed body shell. Because the presence of the gates restrict welding gun access, only tackwelding can take place on the butterfly gateline, an additional track being provided for finish welding. The gateline is capable of building about 4,000 tackwelded body shells per 80 hour week.

A butterfly gateline was chosen for Allegro build at Longbridge because height and width restrictions in the area designated for

FIGURE 8. THE ALLEGRO (BUTTERFLY) GATELINE



this model eliminated a Cowley-type system.

A layout drawing showing the butterfly gateline, finish welding track and body storage between the two, is shown in figure 8.

8.1.5 The Vauxhall Viva (Butterfly) Gateline

This system is similar in concept to the Allegro butterfly gateline although the reasons for adopting it were different. The Viva sidepanel is so designed as to facilitate automatic assembly using multi-welders and therefore there is no need for an integrated sidepanel build line as with the Cowley gatelines.

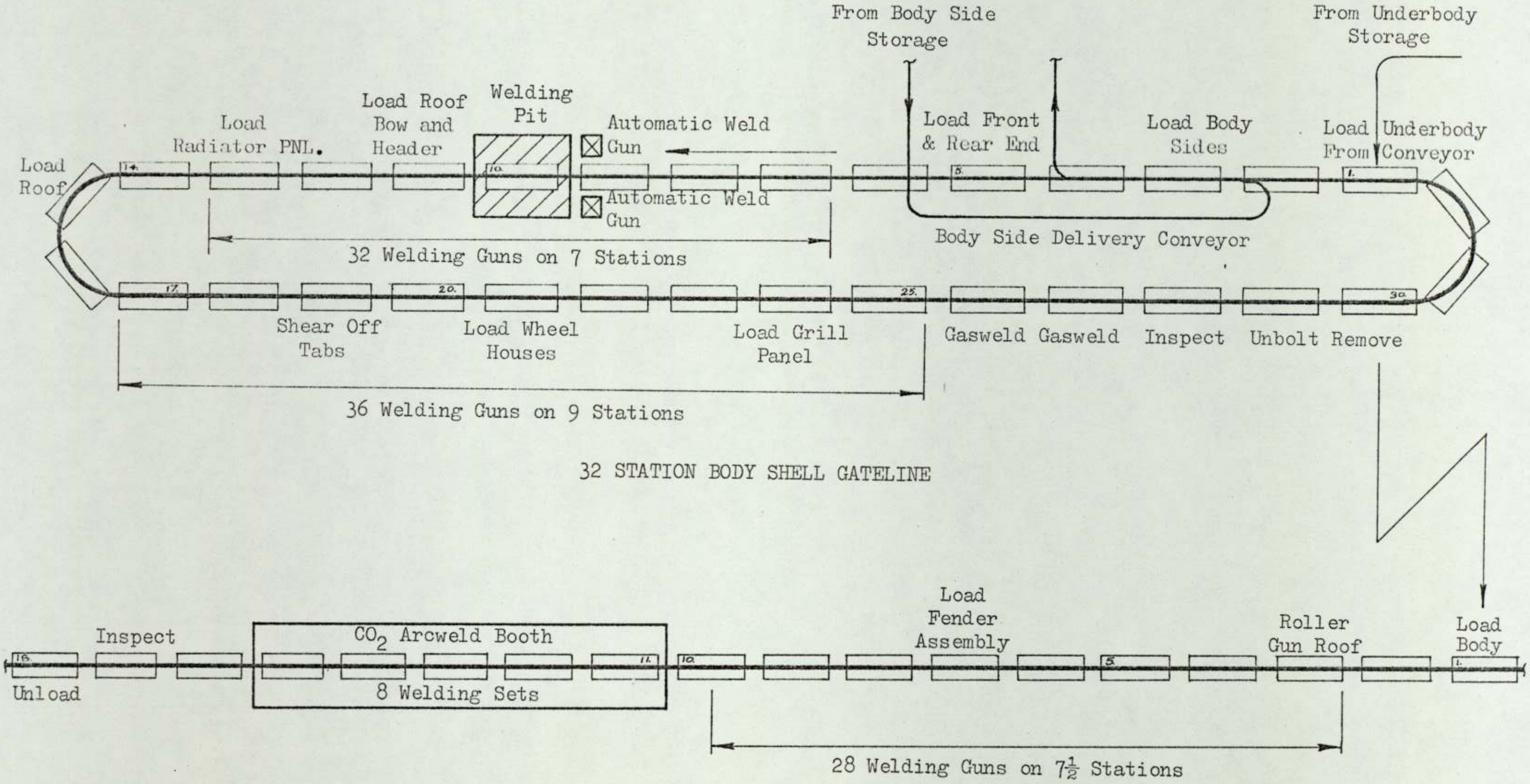
The Viva gateline has 32 jig trucks at a pitch of 17 ft., the layout for which, together with the finish welding track, is shown in figure 9.

8.2 The Intermittent Conveyor

This build system can be classified as tied and unpaced, the bodies, as the name implies, being moved along the line with intermittent motion. On this system, the bodies are stationary when worked on and mechanically conveyed to the next station when the work at all stations has been completed.

On the gateline, each body has its own jigging in the form of gates and jig truck, however, the intermittent line has only one set of

FIGURE 9. THE VAUXHALL (VIVA-BUTTERFLY) GATELINE



32 STATION BODY SHELL GATELINE

18 STATION WELDING CONVEYOR

main jigs, all bodies passing through them. The function of the main jigs, which are applied when the bodies are stationary, is to accurately align the major sub-assemblies during tackwelding operations. The sidepanel is assembled on a track divorced from the body build line and is located and tackwelded to the other major sub-assemblies at one of the main jigs.

The intermittent conveyor is a body build system that has been used extensively within British Leyland, two distinct variations being developed, one at Cowley and the other at Longbridge.

8.2.1 The Cowley Intermittent Conveyor

The bodies on the Cowley intermittent system are conveyed through a series of box jigs and welding stations on jig trucks. The box jigs, an example of which is shown in plate V, consist of a static frame with a number of pneumatically operated locations and clamps which are used to hold the major sub-assemblies in position during tack-welding operations. The sub-assemblies are usually manually loaded at the stations prior to the jigging stations, the static nature of the box jigs restricting access.

Because jig trucks are used, a conveyor system that returns the trucks from the last station has to be employed. The preferred method of achieving this is the carousel floor chain conveyor although one particular installation at Cowley uses two sections of straight floor track running in opposite directions, the trucks being traversed from one to the other at each end. The number of

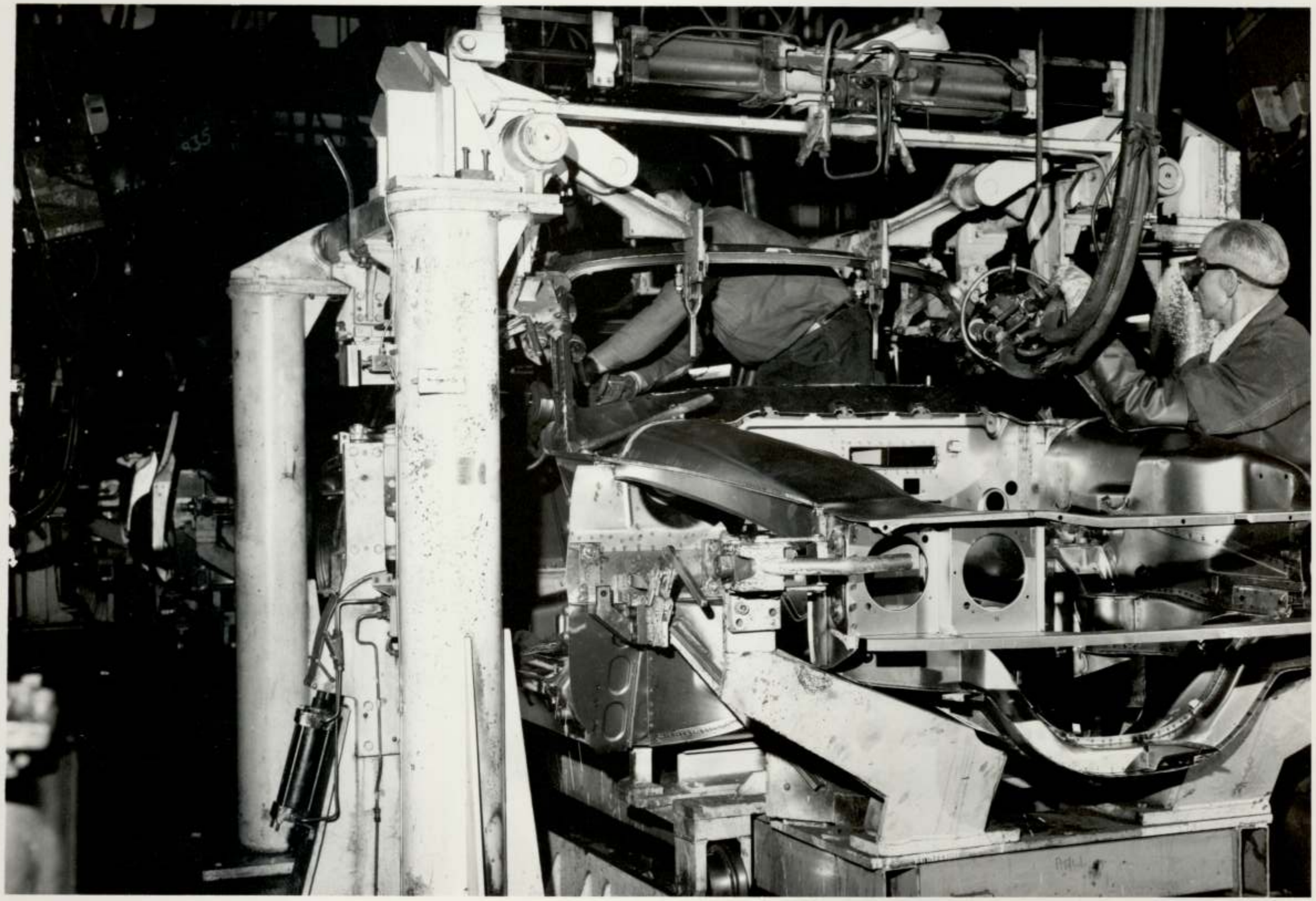


PLATE V BOX JIG - COWLEY INTERMITTENT CONVEYOR

PLATE VI WELDING STATION - COWLEY INTERMITTENT CONVEYOR

PLATE VII TRUNNION FIXTURE - COWLEY INTERMITTENT CONVEYOR stations on the Cowley intermittent system can vary considerably and is determined by the total work content and the planned production capacity.

A layout drawing of a Cowley intermittent system is given in figure 10 and views showing the body on a jig truck at a welding station and a body in an inverted position in a trunnion fixture is given in plates VI and VII respectively. The latter facility is used to provide the operator with a suitable working height when welding along the underframe. This type of facility is only possible on a system where the body is worked on in a stationary condition. This problem is overcome on the gateline by providing pits for the operator to stand in.

8.2.2 The Longbridge Intermittent Conveyor

This system, a diagram of which can be seen in figure 11, differs from the Cowley intermittent conveyor in that the bodies are assembled on slat conveyors as opposed to jig trucks. The slat conveyor has a number of identical sets of jigs bolted to it at regular intervals and it is these which locate and hold the underframe. A view of a track jig can be seen in plate VIII.

The track usually has between seven and ten stations depending upon the total work content of the specific body being built and is usually planned for a production capacity of about 800 bodies per 80 hour week. Some of these stations, known as jigging stations, have vertical jigs or gates at each side of the track,

FIGURE 10. THE COWLEY INTERMITTENT CONVEYOR

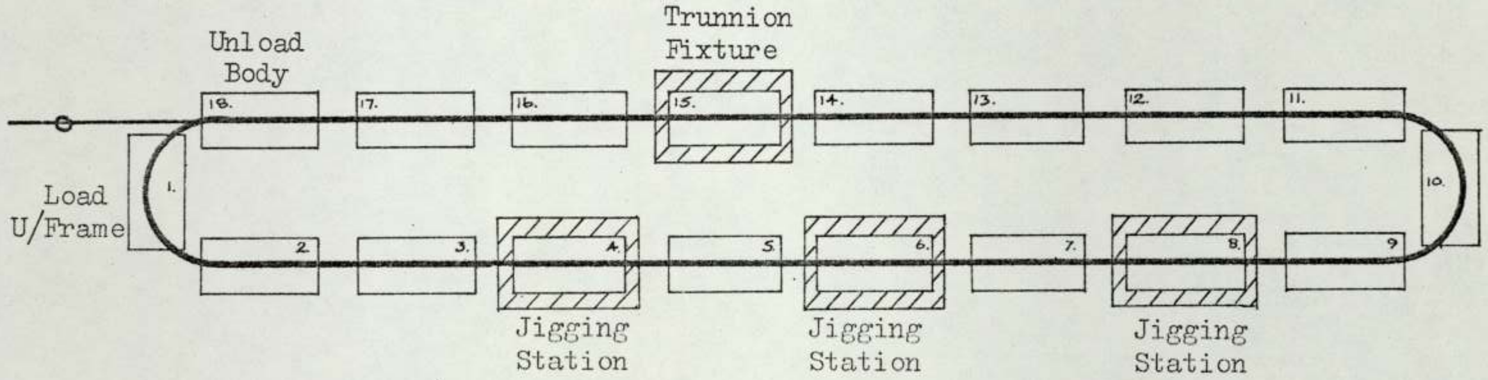
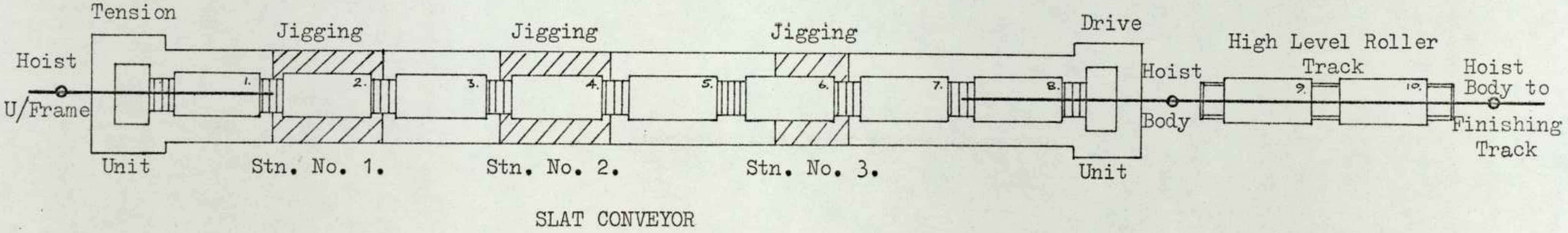


FIGURE 11. THE LONGBRIDGE INTERMITTENT CONVEYOR



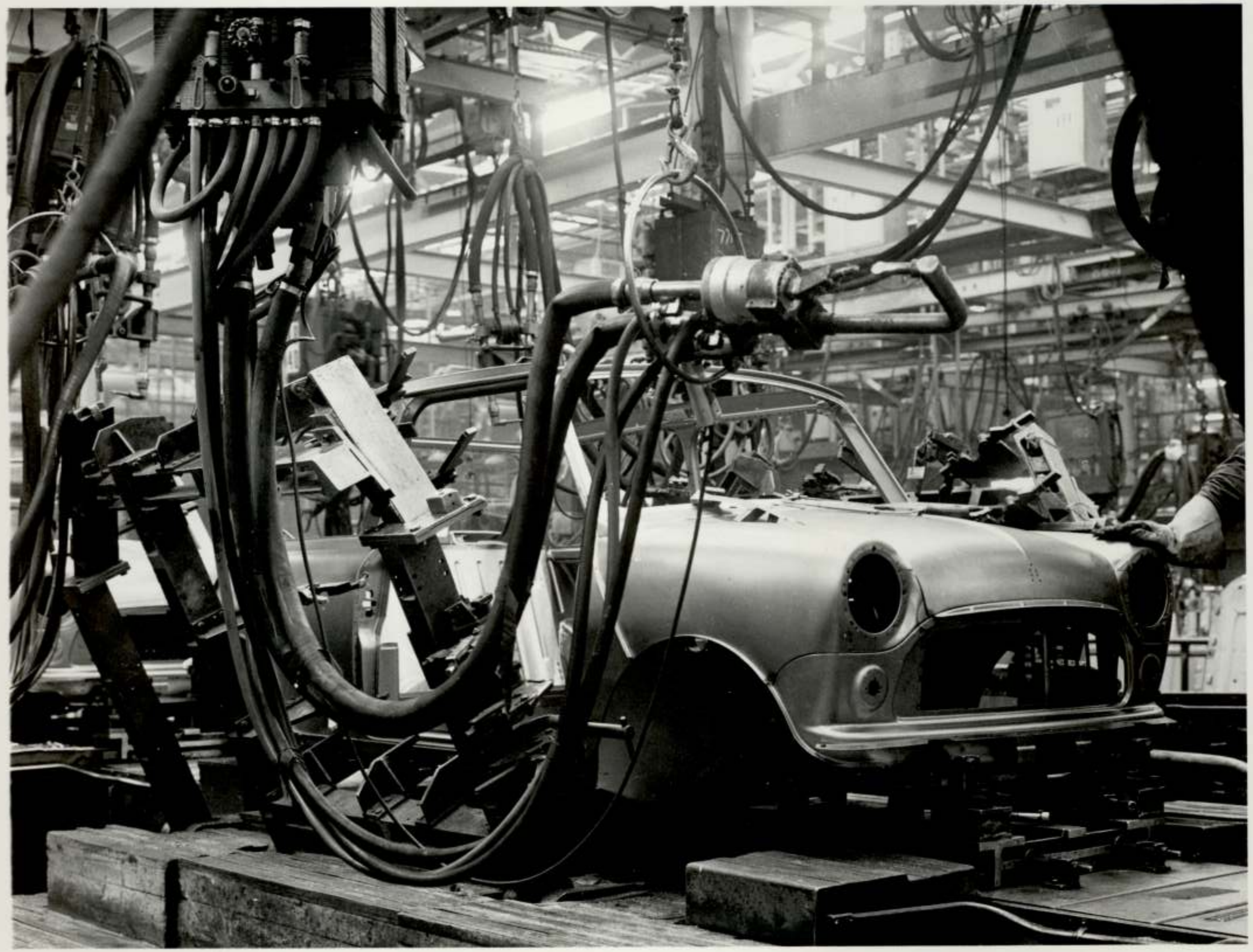


PLATE VIII SLAT CONVEYOR AND TRACK JIGS - LONGBRIDGE INTERMITTENT CONVEYOR

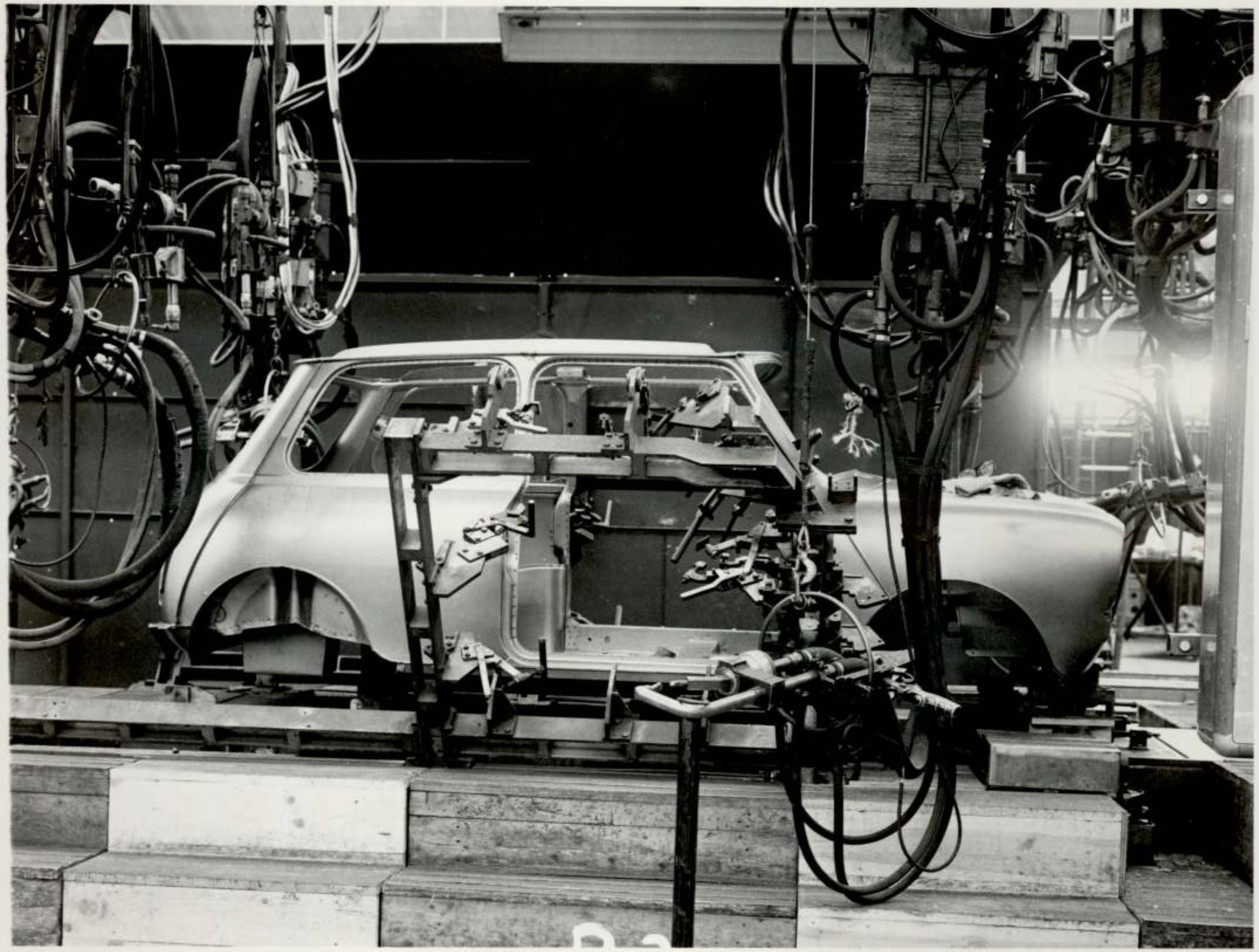


PLATE IX JIGGING STATION - LONGBRIDGE INTERMITTENT CONVEYOR as can be seen in plate IX. These jigs, like those on the butterfly gateline, have the ability to swing away from the vertical through about 25 degrees and it is while they are in this position that the major sub-assemblies such as the sidepanels are loaded. They are returned to the upright position to hold the assembled parts into correct alignment during tackwelding operations.

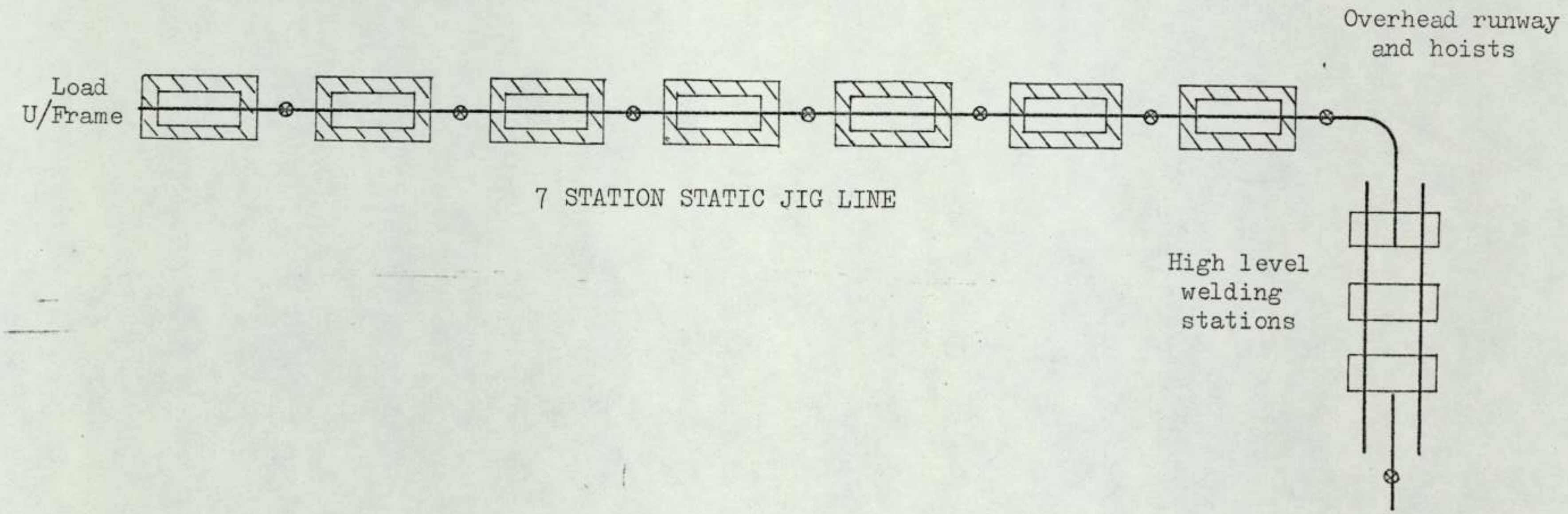
8.3 The Yo-Yo System

In effect, this system is the predecessor of the intermittent conveyor but is still used in British Leyland for low volume build. The line consists of a series of static welding and jigging stations, the body being hoisted from one to the other. The system takes its name from the up and down motion experienced by the body as it is hoisted in and out of the stations.

Unlike both the gateline and the intermittent conveyor, which are tied-paced and tied-unpaced respectively, the yo-yo system is classified as untied and hence unpaced, the absence of a mechanised conveyor facilitating, to a certain degree, independent body conveyance.

A layout drawing of a Yo-Yo system is shown in figure 12.

FIGURE 12. THE YO-YO SYSTEM



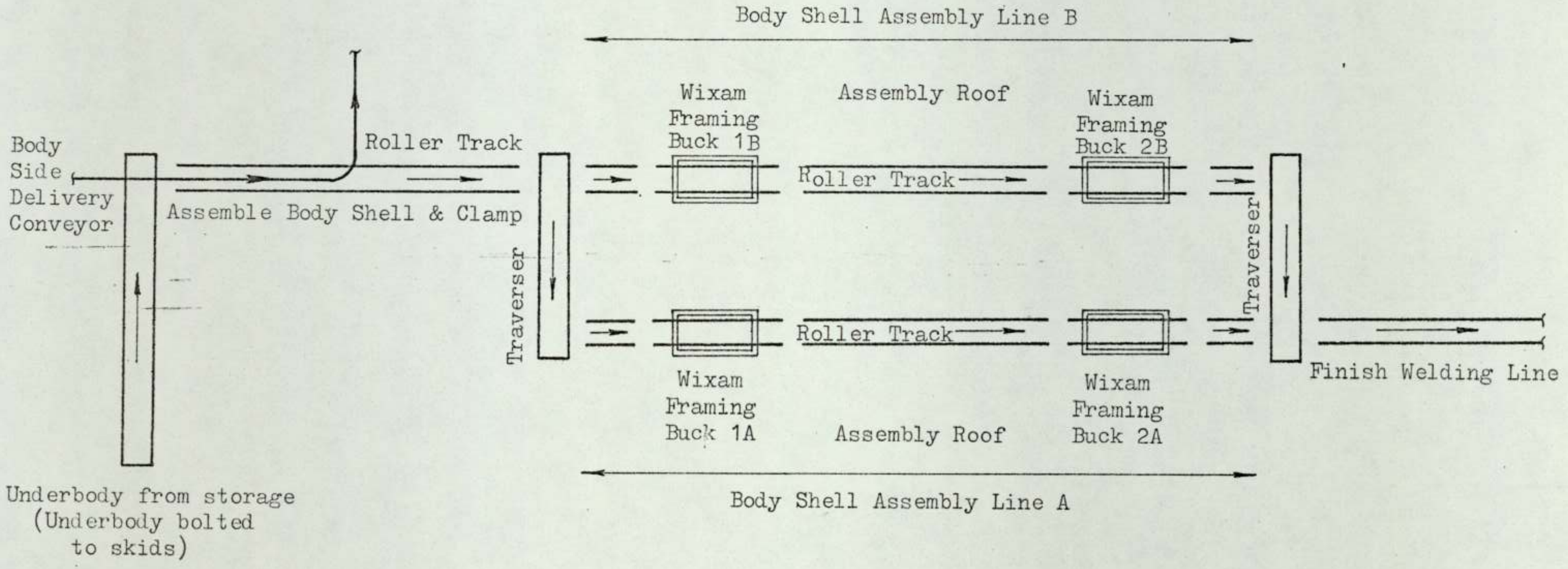
8.4 The Ford Framing Buck Assembly

Like the yo-yo system, the Ford framing buck assembly (a diagram of which is given in figure 13) is untied and unpaced. The use of roller track, however, to convey the bodies between stations and highly automated framing bucks that align and spotweld, makes this system more conducive to high volume production, each line being capable of about 1,600 bodies per 80 hour week.

The first stage in the assembly is to bolt the underframe to a skid. The skid is a type of frame with two skid rails underneath, the underframe bolting onto a number of locations on the frame. It is the skid rails that run on the roller track and facilitate easy manual movement of bodies. This system dispenses with the more conventional types of conveyor such as the jig truck and floor conveyor or slat conveyor as used in the gateline and intermittent systems. The major sub-assemblies are assembled and hand clamped together at a station prior to the first framing buck. The skid is then manually pushed along the track and located in the framing buck.

The framing bucks are a Ford development and are tailor made for each model. In effect, they wrap around the hand assembled parts, pushing them accurately into alignment then firmly clamping them into position while various manual and automatic spotwelding operations are carried out.

FIGURE 13. THE FORD FRAMING BUCK ASSEMBLY



A complete build track consists of two framing bucks and two sections of roller track, one in front of each framing buck, the section between the two bucks being used for ancillary spot-welding and roof assembly. A short section of track follows the second framing buck where finish welding takes place.

This system of build incorporates more automation and mechanisation than the other systems, the body being stationary during all operations facilitating the use of extensive low level multi-welding.

8.5 The Balloon Assembly

This method of build was used extensively at the Ford Motor Co. prior to the adoption of the framing buck system, several years ago.

The major difference between this and other systems is the order with which the principal sub-assemblies are put together. In all the other build systems described in this text, the body is assembled around the underframe but in ballooning the reverse happens, the underframe being the last major item to be assembled.

All major skin assemblies, except the underframe, are thus brought in on overhead conveyors and located into large static framing jigs where sufficient tackwelding is carried out to retain the essential body dimensions. The body minus the underframe is known as the balloon assembly. The tacked balloon assembly is subsequently lifted onto an overhead conveyor and dropped onto the underframe assembly. The two assemblies are peg clamped together and hoisted onto a jig truck where tackwelding takes place, finish welding being carried out on a separate track.

The advantage of adopting this type of system is that the absence of the underframe in the balloon assembly facilitates access from underneath with automatic welding equipment. Unfortunately, assembling the underframe last places design limitations on the body.

8.6 A Discussion of Relative Merits

With the exception of the Ford framing buck method of assembly and the outdated Yo-Yo system which is only used for low volume production, all car body build systems described in this chapter are of a tied nature. In addition to this, many of these employ a large number of stations and short cycle times, the combination of which renders a tied system vulnerable to poor efficiency. It would appear from this that in the majority of cases, design engineers have either failed to recognise and understand the relationships between system design and system efficiency or that the advantages gained from adopting tied systems of this type outweigh that of increased efficiency.

Many of the factors that influence the design of an assembly system are inter-related with a subsequent restrictive influence on the permutations available. The popularity of the gateline, for example, can be attributed to its ability to build different models and derivatives on the same line because each body effectively has its own jigging in the form of gates and jig truck and the facility to change models by simply changing the jig truck and gate locations. In addition, the gateline is potentially the most accurate system of build because the jigging travels with the body, firmly supporting it for the duration of all body shell assembly and tackwelding operations. On all other systems, the jigging remains stationary, the bodies in their various stages of assembly being conveyed between jigging stations in a relatively unsupported state. The use of jig trucks and gates can, therefore, be cited as the main reason for these advantages.

On the detrimental side, however, the combined weight of the jig truck and gates is such that manual conveyance is not feasible, necessitating the employment of a mechanised conveyor. This immediately imposes a restriction, the conventional motorised chain conveyor tying the system.

The use of trucks also places a restriction on the shape of the line, the trucks having to be returned to the first station upon completion of body build. The usual configuration adopted is the carousel although on one particular installation at Cowley a system of parallel lines with transfer mechanisms at both ends was used.

The disadvantage with the carousel is that the area in the centre of the track is both a waste of space and inaccessible to palletised sub-assemblies. The latter of these necessitates the use of delivery conveyors and sufficient headroom for the assemblies to pass over the top of the track. In addition, the material flow to and from the carousel is far from ideal, finished bodies leaving at the same end as the major sub-assemblies are loaded. In terms of floor area, materials handling and material flow, the straight line Longbridge intermittent and Ford framing buck systems of build are to be preferred.

The capital cost of a gateline installation, which includes a large amount of jigging and a high degree of mechanisation, is high and can only be justified for high volume production. To achieve a high output without duplication of lines involves using a short cycle time which in turn necessitates the use of a large number of stations and operators. This type of layout, as well as being prone to poor system efficiency, is inflexible to variations in production volumes. Flexibility of this nature can be important if a model fails to sell at the volume predicted by market research. In such a situation, a gateline is forced to build at a rate below its capacity with the consequence of under utilised plant, equipment and floor area. Where systems such as the Longbridge intermittent conveyor and the Ford framing buck assembly are used for high volume production, a number of identical lines are required. Under utilisation problems can, therefore, be lessened by progressively adding lines to meet the production schedule which can be reviewed after the model has been launched.

The lower production capacity of each line on the Ford and Longbridge systems eliminates the need to build different models and derivatives on the same line, although allocating a track to each derivative, does restrict the ratio of derivative build and can result in under utilisation when only a small number of each derivative are required.

Intermittent motion is less efficient than continual motion due to the production time lost conveying the body between stations. Continual motion, such as on the gateline, theoretically enables the body to be continually worked on, although it does have the disadvantage of severely restricting the use of automated plant such as multiwelders. The Longbridge and Ford systems, where the bodies are stationary during the execution of all operations, are ideal for automation but if flexibility and efficiency are to be maintained by keeping the systems small in size, the use of expensive equipment becomes less feasible.

In total, there are many inter-related factors associated with assembly line design, each of which leads to a number of advantages and disadvantages. The decision as to which system to adopt is, therefore, a complex one and one that in the past appears to have been influenced more by intuition than scientific fact. Of all the factors discussed, none would appear to be of more importance than good system efficiency. From this it must be concluded that the tendency to adopt tied, lengthy, low cycle time assembly lines is due to a lack of understanding of those factors which constitute good system efficiency. This fact clearly indicates that research concerned with the factors that influence system efficiency is inconclusive and inadequately presented to provide industry with the information it needs.

CHAPTER NINE

THE SPONSORING COMPANY

9.1 Cowley Body Plant History

Vehicle body building began at Cowley in 1926, the Pressed Steel Company as it was then, pioneering the all steel car body in this country. The company was originally established to produce car bodies for William Morris (later Lord Nuffield), but in 1930 this interest was withdrawn and subsequently work was undertaken for other vehicle manufacturers. The success of the all steel body led to a rapid expansion of the Pressed Steel Company and in 1955 a second plant was built on a site at Swindon.

In 1965, a merger took place between Pressed Steel and the British Motor Corporation, the Corporation's metalworking factories, Fisher and Ludlow Ltd. being integrated with the Pressed Steel Company to form Pressed Steel Fisher Ltd. This effectively concentrated all of B.M.C.'s body building facilities into one group with factories at Cowley, Swindon, Birmingham (Castle Bromwich and Common Lane) and Llanelli.

This organisation remained until 1968 when a merger between B.M.C. and Leyland took place, the new organisation being called British Leyland. Following internal reorganisation, a divisional structure was established and the name Pressed Steel Fisher finally relinquished. Subsequently, the Cowley plant became part of

British Leyland's Body and Assembly Division and took the name of Cowley Body Plant. This organisation has remained to date.

9.2 Body Building at Cowley

Since 1926, various body build systems have been developed at Cowley. Originally the systems were extremely simple, the bodies in their various stages of assembly being hoisted in and out of a series of box jigs. However, to facilitate easier movement and additional support for the assemblies, the hoisting operations were replaced by a series of trucks. From this system developed the 'intermittent conveyor', the trucks being used to rigidly support the body, and a mechanised conveyor used to move them from station to station, the truck and body being held stationary during the execution of all assembly operations.

The 'intermittent conveyor' was the major system of build used at Cowley until 1967 when, as a result of a feasibility study comparing different systems, a decision was made to adopt the gateline for future vehicle body build.

As a result of this decision, four gatelines have been installed within the Body and Assembly Division, three at Cowley and one at Longbridge, with a fifth at present being installed at Castle Bromwich. At General Motors and Chryslers, however, this system of build has been in operation for a number of years, their designs very much influencing the evolution of British Leyland's first gateline.

CHAPTER TEN

THE PROBLEM

The feasibility study conducted in 1966 at Cowley Body Plant compared three systems of build, these being:

a) Balloon Assembly
b) Gateline Conveyor
c) Intermittent Conveyor

To facilitate a comparison, each system was planned and evaluated around a common body and appraised in terms of capital, tooling and operating costs, the latter being calculated from direct and indirect labour content. The body chosen for this exercise was one being built at Cowley on an intermittent system and hence all data related to the gateline and ballooning systems was ficticious. This fact became the major criticism of this evaluation which hardened when the costs associated with the implementation of the first gateline system at Cowley were well in excess of those estimated for the evaluation.

It was as a result of this criticism that in 1969 the author undertook for a B.Sc. project an evaluation of vehicle body build systems (47). This evaluation was again in the form of a cost comparison plus a discussion of those considerations that could not be expressed in monetary terms. Unlike the initial report, only existing systems were evaluated, therefore using real data. An evaluation on this basis was now possible, with two gatelines in operation at Cowley. The merger between Pressed Steel and the British Motor Corporation also made access to other plants within the Corporation much easier and a survey of these plants revealed an intermittent system of build at both Longbridge and Castle Bromwich that was quite different from the Cowley system. This system, which originated at Longbridge, was subsequently called the Longbridge Intermittent System and included in the analysis.

The conclusions of this report endorsed the decision to adopt the gateline but only for production volumes above 2,400 bodies per 80 hour week. Below this, the Longbridge intermittent system was to be preferred. Prior to this second report, the Ford Motor Co. had abandoned the ballooning assembly in favour of a framing buck system and although a cost evaluation was not possible a study of its attributes was carried out. This showed that this system of build was unique in that it was designed for a high output and yet was untied. It was the most automated of those evaluated and potentially the most efficient. The absence of detailed information, however, prevented a direct comparison with the other systems.

This second report, like the first one, was capital cost orientated with little emphasis on system efficiency. Since the introduction of the gateline at Cowley and the replacement of piecework with a measured daywork payment system, poor efficiency has been a major problem.

The decision to adopt measured daywork was made because of an escalation in operating costs and the incidence of petty disputes attributed to the frequent bargaining of piecework rates. Implementation was in stages, commencing with the Maxi body-in-white production facilities. These facilities were initially designed for and had already operated under piecework and although Marina production later commenced under measured daywork, the experience with this payment system at Cowley was still too short to base the planning on anything other than the conditions that prevailed under piecework.

After both the Maxi and Marina gatelines had been in operation for a short while, it soon became apparent that their efficiency was lower than normally experienced on body build facilities. This was initially attributed to the newness of the facilities and inexperience of the operators. With the level of efficiency, however, running between sixty and seventy percent and not improving significantly with time, it became apparent that a combination of gateline and measured daywork was having an adverse effect on system efficiency.

The type of measured daywork implemented at Cowley was a time rate for a specified performance. At first the operators were reluctant to move away from piecework as earnings at Cowley under this system had been high. An agreement which included a compensatory lump sum payment was, however, finally made. Industrial relations problems continued to plague production at

Cowley, bargaining for improved piecework rates being replaced by disputes over manning. All attempts to control the new payment system were thwarted by the operators with the result that it degenerated into a straightforward time rate payment. All incentives to keep the lines running had effectively been removed with the result that operator performance declined.

The conditions under which measured dayrate was introduced into Cowley coupled with the lack of control following implementation can be blamed for part of the decrease in system efficiency. In fact, the experience with measured daywork at Cowley substantiates much of the work discussed in Chapter 3, such as the importance of the correct conditions for implementation. The solution to this problem is a difficult one, the situation may improve with time but as yet there are no signs to substantiate this. The introduction of a performance related bonus would certainly increase operator effort but to implement such a scheme in the present circumstance could be extremely costly.

The other contributing factor to poor system efficiency is the introduction of the gateline system of build, the tying together of large numbers of operators and large amounts of plant and equipment with a high degree of mechanisation increasing the incidence of stoppages. Whilst this problem cannot be solved in the short term, steps can be taken to ensure that in the future the potential efficiency of a production system is known before installation.

At present there exists no comprehensive procedures or data to facilitate simple efficiency calculations at the assembly line design stage. This is seen as a major obstacle that has to be overcome before efficiency can be confidently designed into a system. This project, therefore, sets out to investigate the effects of the major design factors on system efficiency, to quantify them and to present them in an understandable form such that efficiency calculations can be made at the assembly line design stage.

CHAPTER ELEVEN

SUMMARY OF INTRODUCTION

Assembly system design is an extremely complex field of research with many inter-related design factors and working conditions influencing the ultimate level of efficiency. Past research in this area is of a fragmented nature and does little to aid the assembly line design engineer in his difficult task.

Experiments designed at inducing greater operator motivation by increasing job satisfaction have in recent years tended to overshadow the more conventional areas of research. The success of this work, aimed at solving absenteeism and labour turnover problems, is still to be established, but intuitively in the longterm the reactions to different working environments will vary from one operator to another.

More predictable areas of research include the design of systems to minimise the effects of stoppages and operator work rate variability, a good design significantly increasing efficiency. Of the researchers who have worked in this area, most have studied operator work rate variability in isolation, a condition that rarely exists in practice. Most have adopted mathematics, the complexity of which restricts the conditions that can be represented, thus rendering the results of little use to industry.

Although the conclusions on many aspects of assembly line research are vague, one factor that emerges is that the use of tied systems with a large number of stations and operating with short cycle times is prone to poor efficiency. Despite this, in recent years, industry in an attempt to maximise production with minimal capital outlay has extensively employed systems of this nature. A lack of understanding relating to the factors that effect system efficiency plus an absence of a methodology to facilitate system efficiency estimations at the design stage are the most probable reasons. This must reflect the inadequacy of the research that has been executed to date.

Excessive operating costs can be incurred when a system experiences a continual low level of efficiency, additional labour and facilities being necessary to maintain schedule. The policy of appraising systems purely on a capital and direct labour cost basis is, therefore, an unsound one, but an inevitable course of action when an absence of efficiency information exists.

In the motor industry designing production lines tends to be a spasmodic occupation, systems being designed as and when required to meet a specific need. This situation usually arises when a new model is to be built, which within British Leyland, occurs about once a year. Even this requirement has, to a certain extent, been eliminated from the body build area with the installation of the gateline, model changeovers being implemented by changing only the jigging and associated equipment. As a result of this, too little time has been spent analysing the feasibility of the existing systems in a continually changing working environment. All too often the resistance to change is the dominating force.

Since the introduction of the gateline at Cowley, although the working environment has changed dramatically with the implementation of measured daywork, the practicability of this system of build has rarely been questioned. Even an efficiency as low as 60% - 70% has failed to cause sufficient concern to instigate a re-appraisal of vehicle body build systems.

Most of the blame for the poor level of efficiency on the gatelines has been directed at the introduction of measured daywork which is, at present, for industrial relations and economic reasons, irreversible. The seriousness of the situation has, to a certain extent, been obscurred by the ability to still achieve schedule by overspeeding and hence overmanning the tracks to compensate for lost production time due to stoppages. The increased operating costs associated with adopting such a policy have become so common over the past few years that they are now accepted as normal and no longer cause concern.

The capital and direct labour cost basis of the 1966 evaluation which led to the policy decision to adopt the gateline, was at that time a logical one. Most of the pressures on the motor industry were economic, system efficiency not featuring as a major problem. Production schedules in a piecework environment were achieved irrespective of breakdowns, the operators working faster to make up lost time. In addition, low production schedules meant that the production lines were shorter and less complex with the result that the incidence of breakdowns was lower. The monetary incentive for the operator to keep the lines running also resulted in an absence of many of the operator error stoppages experienced today.

In Chapter 10, it was established that although the conditions surrounding the introduction of measured daywork to Cowley and the absence of strong managerial control after implementation had contributed to a drop in build system efficiency, the gateline design was also a major factor. A general lack of understanding pertaining to this latter factor was one of the main reasons why, in light of the poor system efficiency, no re-appraisal of build systems was undertaken. Without the understanding of the effects of certain design factors on the efficiency of a production line or the means to predict system efficiency at the design stage, there is little hope of remedial action.

To rectify this situation, there is a need for further industrial based research to establish operator work rate distributions for different operating conditions and to quantify the effect of operator work rate variability and production stoppages on the efficiency of a series of work stations. To help the engineer to design efficient production lines, techniques to predict system efficiency at the design stage are also required.

PART II

DEVELOPMENT OF EFFICIENCY PREDICTING TECHNIQUES

CHAPTER TWELVE

PROBLEM ANALYSIS

12.1 The Stoppage Logs

The first task in a study of this nature is to analyse the cause of the problem, in this instance, the reason for poor system efficiency on the gatelines.

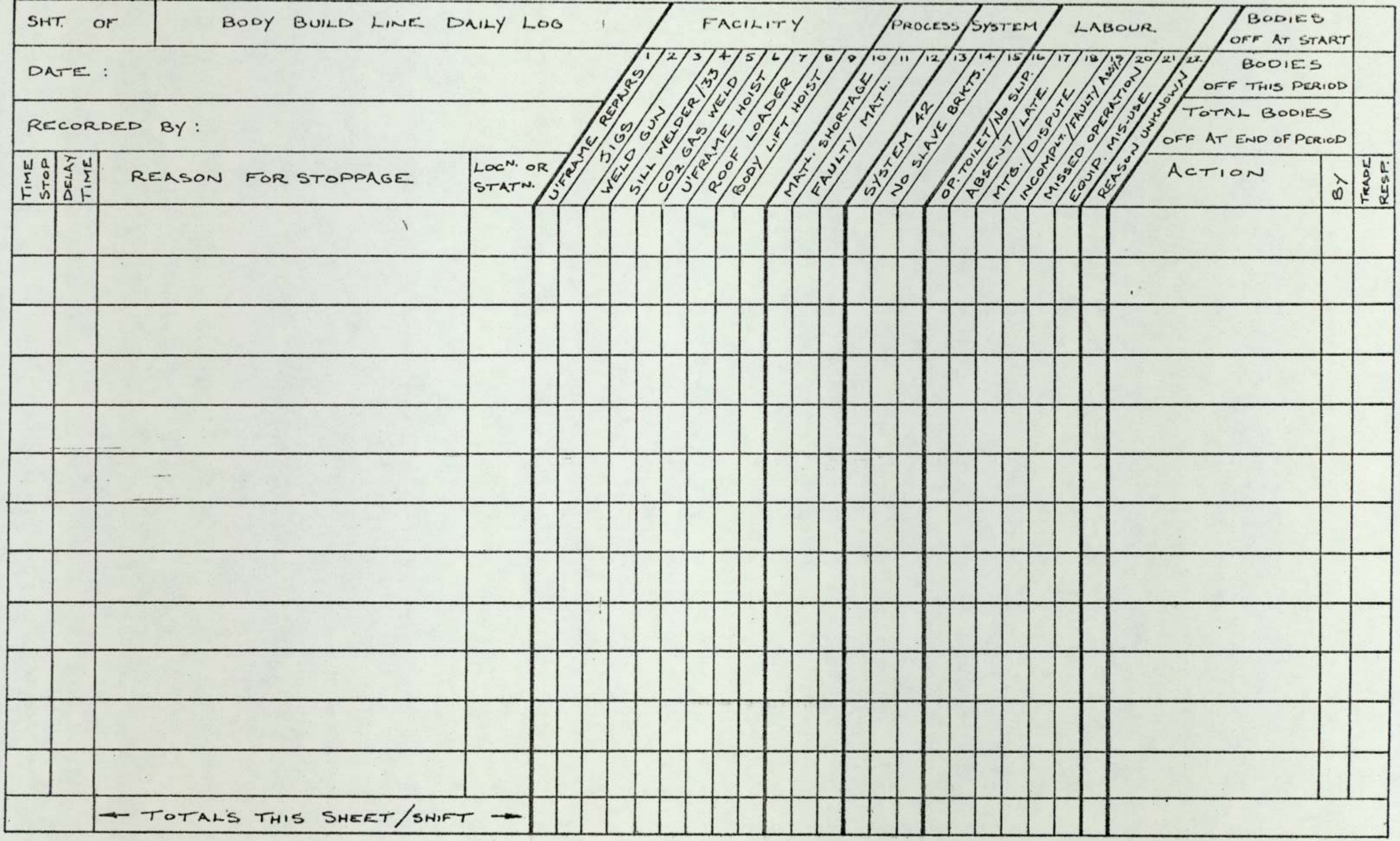
Following the implementation of measured daywork, a system of logging stoppages was introduced on the Maxi gateline and subsequently on both Marina gatelines. A copy of the stoppage log format is shown in figure 14. This system of recording stoppages is unique at British Leyland in that it is impartially executed, past systems being either maintenance or production supervision orientated and thus susceptible to bias. Impartiality is achieved by allocating a man to each gateline solely for the purpose of recording stoppages.

All stoppages are investigated as they occur, the cause and duration being recorded. The logs are kept on a shift basis and have been recorded on the Maxi gateline for about four years and on the Marina gateline for three and a half years. Thus a good sample is available for analysis.

12.2 Stoppage Analysis

Of the three gatelines in use at Cowley, the first of the Marina

FIGURE 14. EXAMPLE OF STOPPAGE LOG FORMAT



SHT. OF

BODY BUILD LINE DAILY LOG

DATE :

RECORDED BY :

TIME STOP

DELAY TIME

REASON FOR STOPPAGE

LOCN. OR STATN.

FACILITY

PROCESS

SYSTEM

LABOUR.

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22

U'FRAME REPAIRS

JIGS

WELD GUN

SILL WELDER/33

CO2 GAS WELD

U'FRAME HOIST

ROOF LOADER

BODY LIFT HOIST

MATL. SHORTAGE

FAULTY MATL.

SYSTEM 42

NO SLAVE BRKTS.

OP. TOILET/NO SLIP.

ABSENT/LATE.

MTG./DISPUTE

INCOMPLT./FAULTY ASS'Y

MISSED OPERATION

EQUIP. MIS-USE

REASON UNKNOWN

BODIES OFF AT START

BODIES OFF THIS PERIOD

TOTAL BODIES OFF AT END OF PERIOD

ACTION

BY

TRADE RESP.

← TOTAL'S THIS SHEET/SHIFT →

lines, building 2 and 4 door saloon bodies, was on the highest schedule and experiencing the lowest efficiency. This line was generally considered as the major problem area and was, therefore, the first to be analysed.

To facilitate analysis, the stoppages were classified under five headings, these being:

a) Facility
b) Process
c) System
d) Labour
e) Reasons Unknown

Facility stoppages are all those caused by plant and equipment breakdown, whilst process covers those due to material shortage or faulty material. System stoppages occur when areas beyond the gateline are stopped resulting in congestion of bodies and subsequent stoppages on the gateline. Labour stoppages include all those resulting from:

a) Operator absenteeism or lateness
b) Missed operations
c) Faulty assemblies
d) Incorrect equipment use
e) No slip man available

Although all stoppages are undesirable, facility, process and labour stoppages are of prime importance to the analysis as it is the effect of these that may be lessened by varying body build system design. System stoppages can be reduced with the inclusion of buffer storage between major process areas; however, many of these stoppages are as a result of disputes or major facility breakdowns downstream and are of such a magnitude as to render most buffer stores inadequate. The provision of larger buffer stores is usually uneconomical.

The sample chosen for analysis consisted of the stoppage logs from 20 weeks normal production, a normal week being classified as one devoid of disputes or major holdups before or after the gateline. The total number of times each type of stoppage occurred varied considerably over the sample period but a duration of 20 weeks was found to provide sufficient data to attain an acceptable level of accuracy.

A measure of the required sample size was attained by periodically calculating equipment reliabilities for ascending sample sizes and comparing the difference. Comparing reliability values for sample sizes of 19 and 20 weeks production, the difference in most instances was in the order of 0.1% the worst case being 0.5%. Bearing in mind the time involved in analysing the stoppage logs, this degree of accuracy was considered adequate and hence a sample size of 20 weeks was chosen.

Inspection of the sample revealed that only 0.27% of production time lost was recorded under the category of 'reason unknown'. However, a comparison of bodies built, 24,044 in total, and actual production time, (Potential production time - Total stoppage time), revealed a total of 2.96% of production time unaccounted for. Again, this was considered a reasonable accuracy for the purpose of analysis.

An inspection of the reliability figures, a full list of which is given in Appendix A, showed that most of the facilities were above 99% reliable, the lowest performance of 98.31% coming from the automatic roof loader. This piece of equipment was specifically designed for the gateline and was thus unproven at the time of installation. Items of equipment common to body-in-white production were generally of higher reliability, an example being the spotwelding set with a performance level of 99.93%.

The analysis of those stoppages attributed to operator faults, efficiency values for which are given in Appendix A, showed the individual operator efficiency to be in the region of 99.95%, again an acceptable level. Poor system efficiency on the gateline cannot, therefore, be directly attributed to poor reliability of the individual items of plant and equipment or poor individual operator efficiency. It is caused more by the cumulative effect of all stoppages resulting from the tied nature of the gateline, the incidence of stoppages on the gateline being high simply because of the large quantity of plant and equipment and numbers of operators involved.

CHAPTER THIRTEEN

THE EFFICIENCY DATA

13.1 Defining the Data Required

To study the effects of production line design on system efficiency, it was deemed necessary to adopt a modelling technique. Earlier researchers, as detailed in Chapter 4, looked to mathematics for this solution, queuing theory being the popular method. More recently, however, the advent of computer simulation has given the researcher greater flexibility to simulate more complex systems using realistic data and becomes the obvious choice.

When designing a model to study the effect of production line design on system efficiency, the first task is to establish procedures for simulating stoppages and operator work rate variability.

13.1.1 The Stoppage Data

Stoppages can be conveniently split into two parts:

a) The probability of a stoppage

b) The stoppage duration

Both parts can be represented by probability distributions and sampled by the 'Monte Carlo' technique.

Stoppage probabilities form rectangular distributions as the probability remains constant for each piece of equipment or stoppage cause. Intuitively, the incidence of breakdown is relative to equipment usage and hence the stoppage probabilities are calculated on the number of bodies processed between stoppages. Thus for each type of stoppage:

$$\text{Probability of a stoppage} = \frac{\text{Total number of stoppages during sample period}}{\text{Number of bodies processed during sample period}}$$

The probabilities for each type of stoppage were calculated from data taken from the 20 week sample of stoppage logs. The downtime distributions were also taken from these logs and found to approximate to a negative exponential, only the mean varying for each type of stoppage.

A complete list of relevant stoppage probabilities and mean stoppage durations, plus the development of the downtime distributions, are shown in Appendix A.

13.1.2 The Operator Work Rate Distribution

Operator work rate variability can also be represented by a probability distribution and sampled as before. The shape of this distribution will obviously vary from operator to operator and be influenced by the operating conditions. To establish the shape of the distribution, therefore, with any confidence, would require many shop floor studies and constitute a major research project in itself.

It was the intention, however, to carry out a limited number of shop floor studies to use in the simulation exercises. Unfortunately, industrial relations problems prevented this. Fortunately, this did not constitute a serious setback as these studies were intended more as a validation of past work than as an essential part of the project.

The discussion of past work in Chapter 4 indicates that operators engaged on unpaced manual tasks describe work rate distributions that are positively skewed whilst more normal distributions result from processed controlled or paced operations. In addition, the work times of an operator, irrespective of operating conditions, when working well within his performance capabilities will describe a normal distribution.

The pace of an operator working on an assembly line will either be influenced by the speed of the track such as on the gateline, or the work rate of adjacent operators on systems such as the intermittent conveyor and framing buck assembly. In all cases, the assembly line operator is not free to work at his own pace and will usually adjust his work rate to suit the work rate of the gang, this effectively being the speed of the slowest operator. Likewise, the speed of the gateline must be such that all operators can, on all occasions, complete their tasks within the allocated cycle time. From this it seems reasonable to assume that most assembly line operators are working well within themselves. The likelihood of this condition prevailing at Cowley seems even more probable, the system of payment providing no incentive for the operators to raise their pace. In view of the uncertainty surrounding the shape of the work rate distribution for operators engaged on longer cycle times and the conditions that prevail in assembly line work, it seems reasonable, for the purpose of the simulation exercises, to adopt the normal distribution to represent operator work rate variability.

All details of the normal distribution used are presented in Appendix A.

13.2 Computer Simulation

To validate the established stoppage probabilities, associated downtime distributions and operator work rate distributions, plus the procedures for simulating their occurrence, computer simulation models were written for the Maxi, Marina and Allegro gatelines, the Cowley and Longbridge intermittent systems and the Yo-Yo system. A comparison was then made between the system efficiencies established from the simulation models and those extracted from actual production figures.

The simulation package chosen, to a large extent dictated by the computing facilities available at British Leyland, Cowley, was G.P.S.S./360 (General Purpose Simulation System) language (48,49). This is a special purpose symbolic simulation language written by I.B.M. for physical system modelling and, like nearly all of the

American simulation languages, it is material based with the 'transaction' forming the base. For the purpose of this study, the transaction will represent the body shell, in its various stages of completion, passing through the system.

When simulating the gateline, which can be classified as both tied and paced, there is no need to simulate operator work rate variability. The cycle time of the gateline should be adequate in length to cover all normal variations in the operator's work rate. On occasions when an operator exceeds the fixed cycle time, the line is forced to stop, the stoppage being recorded and investigated in the usual way. Stoppage data drawn from the stoppage logs should, therefore, cover all such situations.

Unlike the gateline, the intermittent conveyor which is classified as tied and unpaced, has a non-constant cycle time and hence the occurrence of exceptionally long cycle times are not apparent as stoppages and cannot be simulated as such. In this case, operator work rate variability is represented with a normal distribution and sampled using the 'Monte Carlo' technique.

Systems such as the Ford framing buck assembly and the Yo-Yo system, which are untied and unpaced, can be simulated in the same way as the intermittent conveyor.

All systems were simulated on a station to station basis, the equipment, labour and material supply being listed, and the stoppage probability and associated mean downtime for each station calculated from the following formulae:

$$\text{Station Stoppage Probability} = 1 - (1 - p_1)^{n1} (1 - p_2)^{n2} (1 - p_3)^{n3} \ldots\ldots$$

$$\text{Station Mean Stoppage Duration} = \frac{(P_1 \times m_1) + (P_2 \times m_2) + (P_3 \times m_3) \quad \ldots\ldots\ldots}{P_1 \quad + \quad P_2 \quad + \quad P_3 \quad \ldots\ldots\ldots}$$

where $P_1 = 1 - (1 - p_1)^{n1}$ $\qquad P_2 = 1 - (1 - p_2)^{n2}$

$$P_3 = 1 - (1 - p_3)^{n3}$$

p_1 , p_2 , p_3 .... are individual item probabilities

m_1 , m_2 , m_3 .... are individual item mean downtimes

n_1 , n_2 , n_3 .... are number off each item

Before simulation can commence, in addition to writing the programs, full details of which are given in Appendix B, the simulated production period, the duration of warm-up and the clock-unit has to be determined.

13.2.1 Production Period

Choosing the production period is analogous to determining the sample size in statistical sampling, available computing capacity and associated costs imposing restrictions on the period that can be simulated. However, it is important that the period chosen is long enough to yield results that are representative of the real situation. For example, the incidence and duration of stoppages on a production line are irregular and simulated as such therefore too short a sample period may lead to unrealistic efficiency values by covering periods devoid of, or loaded with, stoppages.

For this study, each system was simulated for a total production time of 120 hours. This was achieved in three runs of 40 hours, the sequence of random numbers used to sample the distributions being changed for each run. Simulating in 40 hour runs facilitated an assessment of the sample period. Large differences in the results of each run would have indicated that 40 hours was too short a run length. However, this was not the case and the strategy of simulating three 40 hour production runs was considered adequate.

13.2.2 Warm-up Duration

In practice, very few production systems are ever in the empty state. For example, a body build system will always be full of bodies in various stages of completion, the only contradication being at the rundown of an old model or the commencement of a new one. Therefore, unless this latter condition is to be studied, the model must be 'warmed' so as to reach a steady state.

Although seven body build lines were to be simulated in this particular study, it was not deemed necessary to establish warm-up periods for each model. From a quick appraisal of the systems, in terms of number of stations and cycle time, the model requiring the longest warm-up period was quickly established. This was found to be the Maxi gateline.

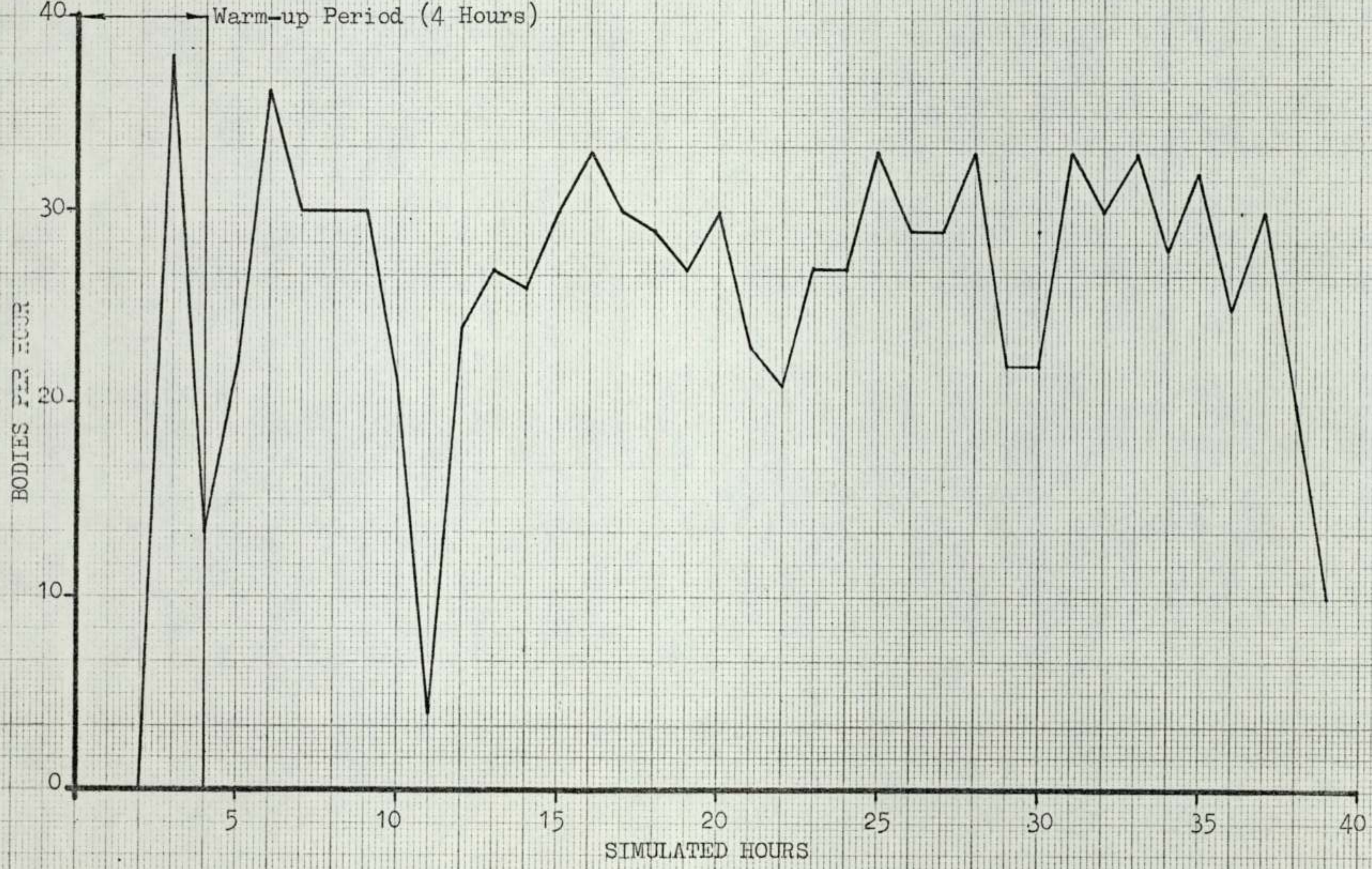
The principle of the warm-up criterion used in this particular study was the overall stability of the modelled production system. This meant an examination of the number of bodies leaving the system every hour. The decision as to when the warm-up is sufficient is not critical providing that the period chosen is longer than the transient period. However, in terms of computer time, an excessive warm-up is undesirable.

In terms of the Maxi gateline model, the transient conditions existed for approximately three to four hours, as can be seen in figure 15 and thus the warm-up period was chosen as four hours and subsequently used for all these simulation studies.

13.2.3 Clock Unit

The clock unit can be any unit of time such as hours, minutes, tenths of a minute and so on. The choice of clock unit depends

FIGURE 15. WARM-UP MONITORING (MAXI GATELINE MODEL)



on the system being simulated and the degree of sensitivity required. For this project, it was necessary to simulate cycle time and mean downtime to an accuracy of one decimal place. As the program can only operate in interger clock units, one tenth of a minute was chosen. This meant that a cycle time of 1.2 minutes was simulated as 12 one tenths of a minute.

13.3 Efficiency Data Validation

A computer simulation model is often only a good approximation to the real system but nevertheless it can be a powerful tool when used to compare strategies. When comparing simulation results with 'real world' results, a degree of tolerance is, therefore, acceptable. For the comparison of simulated and actual system efficiency values, a tolerance of ±5% was felt to be suitable and as can be seen from the table below, all results are within this limit. This is a good indication that the operator work rate distributions, stoppage probabilities and associated downtime distributions, plus the procedures for simulating their occurrence, were accurate.

BUILD SYSTEMS	% SYSTEM EFFICIENCIES		
	SIMULATED	ACTUAL	DIFFERENCE
Maxi gateline	72.7	75.8	+ 3.1
No.1 Marina gateline	63.8	65.4	+ 1.6
No.2 Marina gateline	70.5	70.0	- 0.5
Allegro gateline	77.7	78.2	+ 0.5
Cowley intermittent	76.5	80.0	+ 3.5
Longbridge intermittent	81.2	85.3	+ 4.1
Swindon Yo-Yo	75.0	79.7	+ 4.7

13.4 The Use of the Efficiency Data

Most of the equipment in use on vehicle body build lines is common and therefore once the breakdown patterns have been established, they can be used, in conjunction with the data relating to operator performance which can also be assumed to be constant for all operators, to predict the efficiency of future installations. This has been shown to be true with the above simulations, accurate system efficiency values being determined for seven build systems, all the efficiency data coming from the Marina gateline stoppage logs. Thus, with the aid of computer simulation and the efficiency data presented in Appendix A, the efficiency of future build systems can be determined at the design stage.

Unfortunately, the facilities or expertise to use computer simulation is not always available, the latter often being the case in the design office where the systems are initiated. Even when these facilities are available, computer simulation can be very time consuming, especially if striving for good efficiency, on a trial and error basis. Therefore, there is a need of a greater understanding of those areas that influence system efficiency such that a more logical approach can be applied to production line design.

The next stage in the project sets out to satisfy this need and establish tabulated data to facilitate quick and simple efficiency estimations without resorting to computer simulation.

CHAPTER FOURTEEN

THE DESIGN FACTOR EXPERIMENTS

14.1 The Design Factors.

Production line inefficiency is caused by operator work rate variability and stoppages due to operator error, plant and equipment breakdown and material shortage. However, the degree with which these inefficiencies are transmitted to the rest of the line and hence their influence on the total system efficiency is related to the following design factors:

a) Classification (Tied or Untied)
b) Interstation storage capacity
c) Number of stations
d) Number of operators per station
e) Mean cycle time

To optimise system efficiency for any specific production situation, involves the correct manipulation of the above design factors. Before this can be achieved, relationships between system efficiency and the design factors must be established and to do this involves studying each of them in isolation. This is achieved with the aid of computer simulation and carried out by systematically varying each of the design factors in turn whilst holding those remaining constant. To facilitate an analysis of the experimental results, it was necessary to keep the value of each constant the same, for all relevant experiments.

14.2 Designing the Experiments

To simplify analysis and provide results that yield the greatest possible flexibility from a user's point of view, it is convenient to split the experiments into two distinct areas, these being:

a) Area A - Inefficiency caused by stoppages due to equipment breakdown, material shortage and operator error.

b) Area B - Inefficiency caused by operator work rate variability.

As detailed in Section 13.2, it is convenient to simulate paced systems by including only Area A inefficiencies, excessive work rate variations featuring as stoppages and being simulated as such. Unpaced systems, however, such as the intermittent conveyor include both Areas A and B, the total system inefficiency being the summation of the two.

i.e. If Es = Percentage system efficiency due to stoppages

Ds = Percentage system delay due to stoppages

Ev = Percentage system efficiency due to operator work rate variability

Dv = Percentage system delay due to operator work rate variability

Then

$$E_S = 100 - D_S \quad \text{and} \quad E_V = 100 - D_V$$

If E_T = Total Percentage System Efficiency

Then $E_T = 100 - (D_S + D_V)$

or $E_T = E_S + E_V - 100$

To facilitate the execution of the experiments, six simulation models were written in G.P.S.S./360, the flow charts and programs for which are shown in Appendix B. The six models, which cover each of the situations listed below, were written in such a way that various design features could be easily changed between runs.

14.2.1 The Simulation Models

a) Area A - Tied without interstation storage capacity
b) " - Untied without interstation storage capacity
c) " - Untied with interstation storage capacity
d) Area B - Tied without interstation storage capacity
e) " - Untied without interstation storage capacity
f) " - Untied with interstation storage capacity

Each production line arrangement was simulated on a station by station basis, all stoppage probabilities and downtime distributions being equally applied to all stations. Likewise the normal distribution, which was used to describe operator work rate variability, was assumed to be the same for all operators with an equal number of operators at each station. The strategy of adopting identical stations was necessary to facilitate an analysis and to enable relationships to be derived between the design factors and system efficiency. In practice, this situation rarely exists but a study of a series of dissimilar stations would impose such a large number of variations that analysis would be impossible.

Stations that continually experience dissimilar stoppage and operator work rate patterns effectively have different mean productions rate capabilities with the result that the output from the line is dictated by the production rate through the worst station. The provision of interstation storage, whilst increasing the overall efficiency of the line by isolating minor production rate fluctuations to the stations at which they occur, does nothing to improve an out of balance condition between two stations. The use of identical stations is, therefore, the ideal arrangement and one that should be strived for at the design stage if maximum utilisation of plant, equipment and manpower is to be achieved on all stations.

It is, therefore, questionable as to whether or not the analysis of dissimilar stations would provide any more useful information than the study of identical stations. The study of the latter for the benefits of simulation and analysis would appear to be justified.

Any limitations resulting from this strategy will be identified in Section 16.3 when actual performance figures and simulation results of dissimilar station assembly lines will be compared with those established from relationships developed from these experiments.

14.2.2 The Variables

The following is a list of all variables arranged under the areas of study to which they are applicable. They consist of the inefficiency causes, i.e. stoppages and work rate variability, plus the design factors that influence the effect of these causes on the overall system efficiency.

Area A - Variables

a) Stoppage Probability
b) Mean Downtime (mins)
c) Number of Stations
d) Cycle Time (mins)
e) Interstation Storage Capacity
f) Classification (i.e. Tied or Untied)

Area B - Variables

a) Coefficient of Variation $\frac{\text{Standard Deviation}}{\text{Mean Cycle Time}}$

b) Number of Stations

c) Number of Operators per Station

d) Interstation Storage Capacity

e) Classification (i.e. Tied or Untied)

Although the range covered by each variable is usually small for a specific type of production line such as a vehicle body build track, to facilitate a more accurate and comprehensive analysis, a wide range of values for each variable was applied.

CHAPTER FIFTEEN

ANALYSIS OF DESIGN FACTOR EXPERIMENTS

15.1 Format of Results

From the three system efficiency values found for each strategy resulting from simulating three 40 hour production runs, the mean system efficiency was calculated for all strategies as follows:

$$\% \text{ System Efficiency} = \frac{\text{Actual bodies build}}{\text{Potential build}} \times 100\%$$

$$\text{where} \quad \text{Potential Build} = \frac{\text{Length of production run (mins)}}{\text{Cycle time} \qquad \text{(mins)}}$$

The results were tabulated and graphs plotted of percentage delay (100% - percentage efficiency) against each of the variables, curves for tied and untied systems with different values of interstation storage capacity being plotted for each case.

Percentage delay, as opposed to percentage efficiency, was used for convenience, the graphs in this form being more suitable for further analysis. For example, percentage efficiency plotted against station stoppage probability would yield a relationship of decreasing system efficiency with increasing probability, a zero probability corresponding to 100% efficiency. To facilitate further analysis, it was more convenient if this relationship passed through the origin of the graph and thus, by subtracting each of the efficiency values from 100%, this was achieved.

The tabulation of results and graphs for each of the experiments are shown in Appendix C.

15.2 Discussion of Results

15.2.1 Area A - Increasing Station Stoppage Probability (Graph C.1)

An increase in the probability of a station stoppage can be seen to result in a decrease in system efficiency and hence an increase in percentage delay. However, the rate of increase reduces with increasing stoppage probability, the reason for which can be explained with the aid of the following probability equation.

If P is the probability of a production line stoppage on a tied system, p the individual stoppage probability for each station and n the number of stations, then

$$P = 1 - (1 - p)^n$$

P is directly proportional to percentage delay and hence the response of the latter to an increase in station stoppage probability can be likened to the response of P in the above equation. The relationship between P, and subsequently percentage delay, and p, will therefore be non-linear for n greater than one.

If n is given an arbitrary value greater than one and held constant as p is increased, then P will also increase in value, but the rate of increase will drop with increasing p. This is the same relationship as that shown in Graph C.1, thus substantiating the trend in the results.

The curves for each of the untied systems follow the same pattern as that of the tied production line. However, a direct association with the above probability equation is complicated by untying the stations and introducing interstation storage capacity.

The tied system is the least efficient one, although for the conditions simulated, the difference between tied and untied without interstation storage was marginal. The reason for the difference is that delays on the untied systems will only stop the flow of bodies on those stations upstream from the cause of the delay. The bodies downstream will continue to be processed in the normal way with the result that the stations immediately after the delay will be progressively emptied. The resulting gap in the flow of bodies will subsequently be either transmitted down the line when normal production resumes, or utilised in the event of a delay downstream. This flexibility that the untied system possesses, therefore, reduces the total lost production time at each station, thus increasing system efficiency.

The introduction of interstation storage capacity into the untied system further increases system efficiency by reducing the interdependence of consecutive stations. For the particular system simulated for this experiment, the addition of an interstation storage capacity of one yielded a considerable improvement in system efficiency, especially in the instance of high stoppage probability. The introduction of further storage capacity between stations showed only a small improvement.

15.2.2 Area A - Increasing Mean Stoppage Duration (Graph C.3)

This graph can be seen to be of the same form as Graph C.1, the percentage delay increasing as the mean downtime per stoppage is increased. The similarity can be explained by also associating the relationship between percentage delay and mean downtime with the probability equation presented in Section 15.2.1.

Although the stoppage probability per station on a bodies processed basis was constant for the duration of this experiment, the probability of each station being in an inoperative state, calculated on a time basis, increased proportionally with increasing mean stoppage duration. The subsequent increase in percentage delay was, however, not directly proportional but related to the power n where n is the number of stations.

The probability of the station being inoperative can be calculated as follows:

$$p_T = \frac{p \times q}{t}$$

where p_T = probability of a station being inoperative, calculated on a time basis.

p = probability of a station stoppage, calculated on a bodies processed basis.

$\bar{q}$ = the mean stoppage duration per station.

t = cycle time.

15.2.3 Area A - Increasing the Number of Stations (Graph C.5)

For the conditions simulated, the tied system experienced considerable losses in system efficiency with increasing number of stations. The rate of decrease lessened as the number of stations was increased, but between the range of 1 and 50 stations it was small. This indicates that in this instance, further efficiency losses would be experienced if the number of stations was increased beyond fifty. However, the shape of the curve also indicates that at some stage the decrease in efficiency would be minimal for increasing number of stations although this would appear to occur well short of the 100% delay point. If the value of p in the probability equation is greater than zero, then as n increases, P increases. If n is very large then P approaches the value one, thus representing a system stoppage per body processed. However, the percentage delay is a function of stoppage probability, mean stoppage duration per station and cycle time, the percentage delay steady state condition being achieved at a value less than 100% if the mean stoppage duration is less than the cycle time. This substantiates the results of this experiment, in this instance the mean stoppage duration being only a fifth of the cycle time. The curve for the tied system would, therefore, be expected to level out at the 20% delay point.

Untying the system again has the effect of reducing the percentage delay, considerable reductions taking place where systems with large numbers of stations are involved. This again can be attributed to the fact that stations on an untied system are not forced down immediately a stoppage occurs on another station.

15.2.4 Area A - Increasing the Cycle Time (Graph C.7)

An assumption made for the purpose of simulation and one that is intuitively valid, is that the frequency of stoppages is directly proportional to the number of assemblies processed. The frequency of stoppages is, therefore, inversely proportional to the mean cycle time. The duration of a stoppage, however, is not related to cycle time but has a constant mean for each stoppage cause. The total downtime, therefore, increases with decrease in cycle time with a resulting reduction in system efficiency.

The curves presented in Graph C.7 substantiate this reasoning, system efficiency improving with increasing cycle time.

15.2.5 Area B - Increasing the Coefficient of Variation (Graph C.9)

The effect of increasing the coefficient of variation of the operators work rate distribution can be likened to increasing stoppage probability and mean stoppage duration, all three increasing the incidence of production delays. Thus it was anticipated that the family of curves plotted from the results of experiment 5 would be similar to those shown in Graphs C.1 and C.3, i.e. the slope of the curves decreasing with increasing x-axis values. For the tied and untied system without interstation storage, this hypothesis was upheld although the decrease in the slope of the curves was small for the range of coefficients of variation simulated. However, the addition of interstation storage capacity changed this, the rate of increase in percentage delay becoming larger for increasing coefficient of variation. This phenomena could not be logically explained and thus steps were taken to substantiate the results of this experiment.

The relationship between percentage delay and the coefficient of variation for a system with interstation storage is an area previously studied by Slack (38), his results comparing favourably with those from this experiment. It is, therefore, highly significant that the results from experiment 5 for an untied system with interstation storage are valid. Any doubts are, therefore, transferred to the results from the simulation of tied and untied systems without interstation storage. Unfortunately, no previous work was found that contained results of a comparable form and thus the simulation models were examined.

The examination took the form of a reappraisal of allocated warm-up time, clock unit chosen and production period simulated, and a review of the program for possible logic errors. To ensure that the production period simulated was adequate, further simulations were executed with double the original production period and the results compared.

The examination revealed no errors, the results of the simulation reruns comparing favourably with those depicted in Graph C.9. With renewed confidence, the results for the tied and untied systems without interstation storage were taken as correct. Although this phenomena of different types of relationship for systems with and without interstation storage could not be logically explained, it was accepted as correct, and thus provides an area where further research is necessary.

15.2.6 Area B - Increasing the Number of Stations (Graph C.11)

The curves resulting from plotting percentage delay against number of stations for a system devoid of stoppages but experiencing variations in each operator's work rate are similar in form to those for a system with a fixed cycle time but experiencing stoppages, as depicted in Graph C.5. This is to be expected, an increase in the number of stations, and subsequently an increase in the number of operators, increasing the incidence of poor cycle times.

15.2.7 Area B - Increasing the Number of Operators per Station (Graph C.13)

For a tied system, the effect of increasing the number of operators per station is the same as increasing the number of single operator stations. Thus the relationship for the tied system in Graph C.13 is the same as the tied system in Graph C.11 between the limits of 4 and 20 stations.

The introduction of interstation storage, as in all the experiments, increases system efficiency, the introduction of a capacity of one being adequate for most situations simulated.

15.3 Equating the Relationships

The discussion of results in Section 15.2, the graphs for which are presented in Appendix C, provides a good insight into the nature of production line inefficiency and the influence of the design factors. However, to enable quantative system efficiency estimations to be made, these relationships must be equated. In most cases, more than one equation can be made to fit a particular curve, the most convenient form being chosen. In this instance, it is convenient for all the relationships to be presented in a linear form, firstly to facilitate further analysis, as will be seen in the next chapter, and secondly to simplify equating them. To do this involves manipulating the axes of each graph on a trial and error basis until good approximations to straight lines are achieved. There are many tests that can be applied, one of the most common being to log both axes, any curve approximating to the form $y = bx^m$ becoming a straight line when logged.

e.g.
$$\log_{10}y = m\log_{10}x + \log_{10}b$$
$$(Y = mX + C)$$

Applying this technique to all of the results, therefore plotting the logarithm of percentage delay against the logarithm of each input variable, visual inspection revealed that all of the relationships, with one exception, approximated to straight lines. Therefore, the general equation for these relationships was taken as

$$y = bx^{m}$$

where y represents percentage delay, x the input variable and b and m constants. The exception, percentage delay plotted against the number of operators per station, after being subjected to further tests, was found to approximate to a linear form when logging the x-axis only. Therefore, the equation to this linear relationship was of the form

$$y = m\log_{10}x + \log_{10}b$$

Hence the general equation for the curves shown in Graph C.13 is

$$y = \log_{10}(bx^{m})$$

Each of the curves discussed in section 15.2 can be equated by establishing values for b and m from the linear relationships shown in Appendix C. However, visual determination of the best straight line for each relationship is prevented by the scatter of points, a common occurrence with experimental results of this nature. Therefore, the mathematical method of least squares was used to establish the best straight lines with the results available and sebsequently values for b and m determined for each relationship. As there were a large number of equations to establish, a computer program to execute the method of least squares was written in Fortran IV Language (50).

The use of the equations in this form are limited, each equation relating to only one specific variable as well as being invalid for conditions deviating from those for which it was derived. For example, the equation

$$D = 68.68p^{1.071}$$

was established for an untied system with no interstation storage capacity, four stations, mean stoppage time of 1 minute and a fixed cycle time of 5 minutes. The equations enables system percentage delay (D) to be calculated for different values of station stoppage probabilities (p) as long as the above conditions prevail. If the production line design under analysis has ten stations, then this equation cannot be used. The equation

$$D = 2.87n^{0.439}$$

however, relates percentage delay and number of stations (n) for the same conditions as above with the exception that the number of stations now becomes the variable and the station stoppage probability held constant at 0.1. A ten station production line can now be analysed. If the percentage delay is required for a ten station line with a station stoppage prbability of 0.05, then neither of these equations can be used directly, although as an approximation, interpolation is a possibility if the other conditions comply. Further deviations from these simulated conditions render the equations of little use.

A set of more comprehensive multivariable efficiency equations are, therefore, required and can be achieved by combining the linear relationships presented in Appendix C. The derivation of these multivariable equations is shown in the next chapter.

CHAPTER SIXTEEN

THE EFFICIENCY EQUATIONS

16.1 Derivation of Efficiency Equations

The total system percentage delay can be calculated by summing the percentage delays due to production stoppages and operator work rate variability. Therefore, as with the execution of the experiments, it was more convenient to analyse these areas independently of one another.

i.e.
$$D_T = D_S + D_V$$

$$E_T = 100 - D_T$$

where

D_T = Total System Percentage Delay

D_S = Percentage Delay resulting from Stoppages

D_V = Percentage Delay resulting from Operator Work Rate Variability

E_T = Total System Percentage Efficiency

To derive multivariable efficiency equations for each study area involves combining the linear relationships established in the previous chapter. Unfortunately, these relationships, whilst demonstrating the effect of each of the variables on system efficiency and, in the equated form, facilitating the execution of efficiency calculations for a few specific conditions, cannot be directly combined using simple mathematics. A multi-variable equation can, however, be derived if all the individual relationships are expressed in terms of the same variable, each relationship being derived for a different combination of arbitrary values for the remaining design factor variables. All the relationships must be linear and therefore only two values for each design factor are necessary to define the relationship. To ensure that the relationships were of a linear nature, those conditions which were found to render linearity in the previous chapter were applied to the appropriate variables.

16.1.1 Study Area A – Inefficiency resulting from stoppages due to equipment breakdown, material shortage and operator error.

Notation

$p = \log_{10}$ (probability of a stoppage per station)

$q = \log_{10}$ (mean stoppage time in minutes)

$t = \log_{10}$ (cycle time in minutes)

$n = \log_{10}$ (number of stations)

$Y = \log_{10}$ (percentage delay)

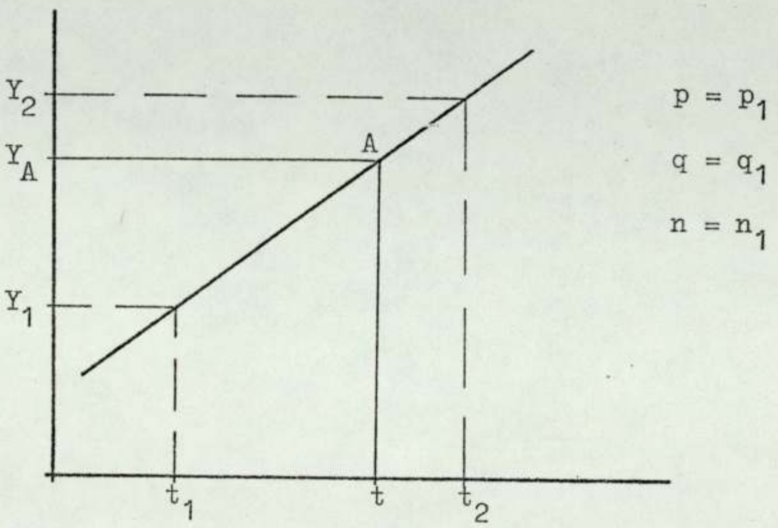
D = percentage delay

$$Y = \log_{10} D$$

It was established in the previous chapter that all of the relationships contained within this study area were of linear form when both percentage delay and the input variable were logged. Therefore, using the above notation, the generalised multi-variable efficiency equation was derived for study area A as follows:

<u>One Variable</u> (t)

Graph 1.



The equation to the straight line is

$$Y_A = \frac{t_2 - t.Y_1}{t_2 - t_1} + \frac{t - t_1.Y_2}{t_2 - t_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots 1.$$

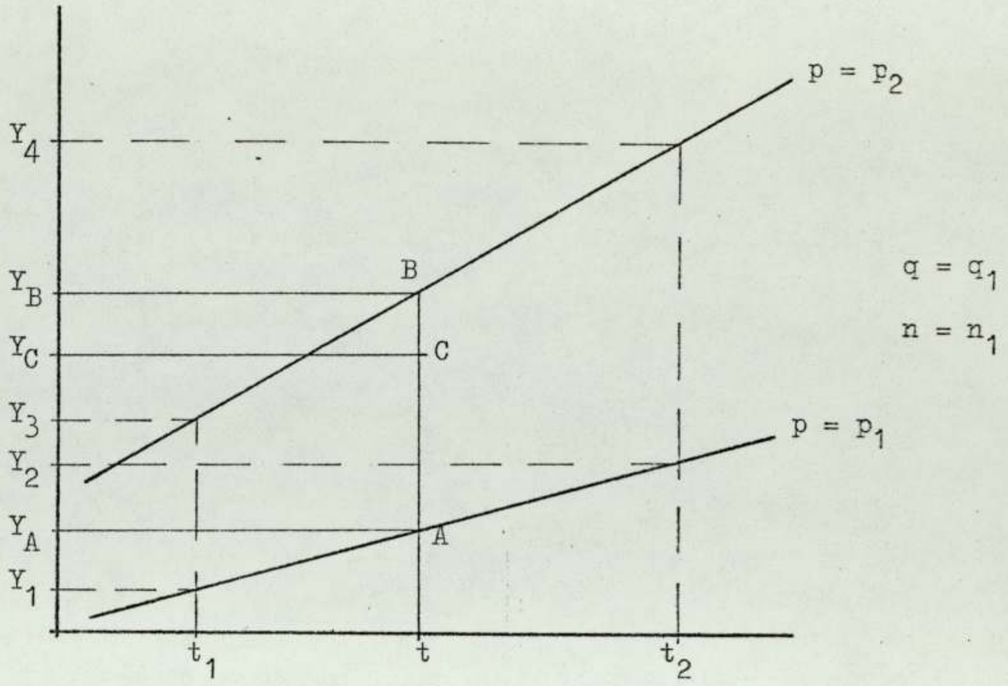
Let $$a = \frac{t_2 - t}{t_2 - t_1} \quad \text{then } (1 - a) = \frac{t - t_1}{t_2 - t_1}$$

Equation 1. becomes

$$Y_A = a.Y_1 + (1 - a)Y_2$$

Two Variables (t,p)

Graph 2.



From Graph 2

$$Y_A = aY_1 + (1 - a)Y_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.$$

$$Y_B = aY_3 + (1 - a)Y_4 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.$$

Combining equations 1 and 2 to find Y_c

$$Y_C = \frac{p_2 - p.Y_A}{p_2 - p_1} + \frac{p - p_1.Y_B}{p_2 - p_1} \quad \ldots\ldots\ldots\ldots 3.$$

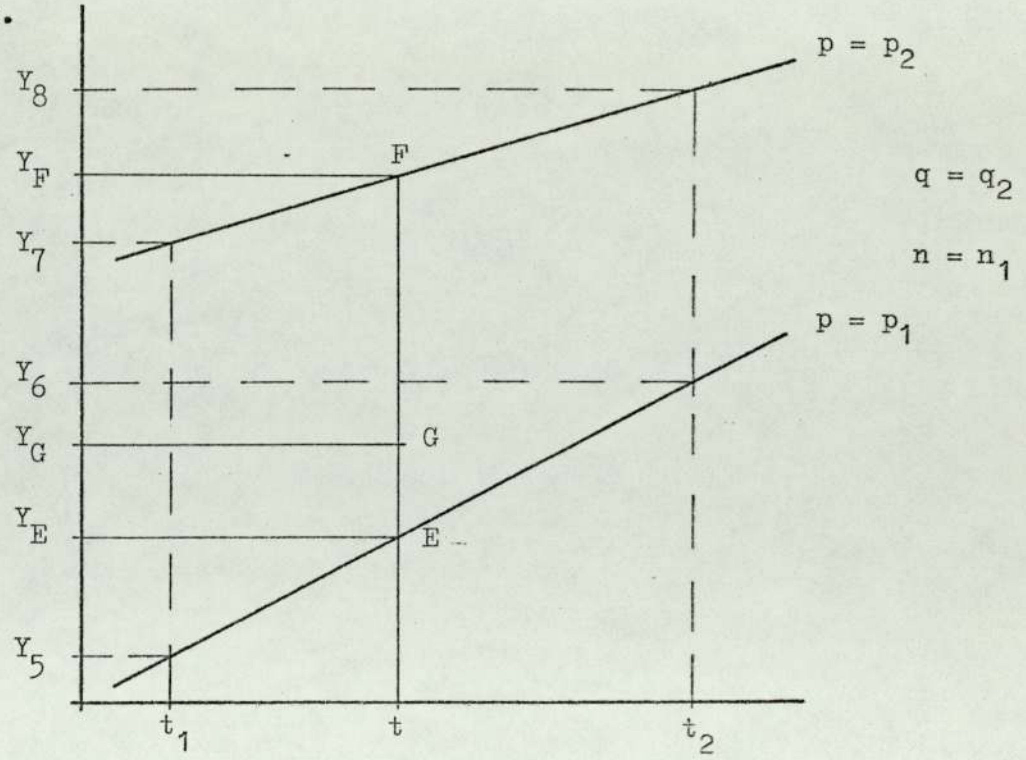
Let $b = \frac{p_2 - p}{p_2 - p_1}$ then $(1 - b) = \frac{p - p_1}{p_2 - p_1}$

Equation 3. becomes

$$Y_C = bY_A + (1 - b)Y_B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.$$

Three Variables (t, p, q)

Graph 3.



From Graph 3

$$Y_E = aY_5 + (1 - a)Y_6 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 4.$$

$$Y_F = aY_7 + (1 - a)Y_8 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 5.$$

Combining equations 4 and 5 to find Y_G

$$Y_G = bY_E + (1 - b)Y_F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 6.$$

To find the logarithm of percentage delay Y_H for a point H somewhere between the planes bounded by the curves in graphs 2 and 3, equations 3 and 6 are combined as follows:

$$Y_H = \frac{q_2 - q . Y_C}{q_2 - q_1} + \frac{q - q_1 . Y_G}{q_2 - q_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 7.$$

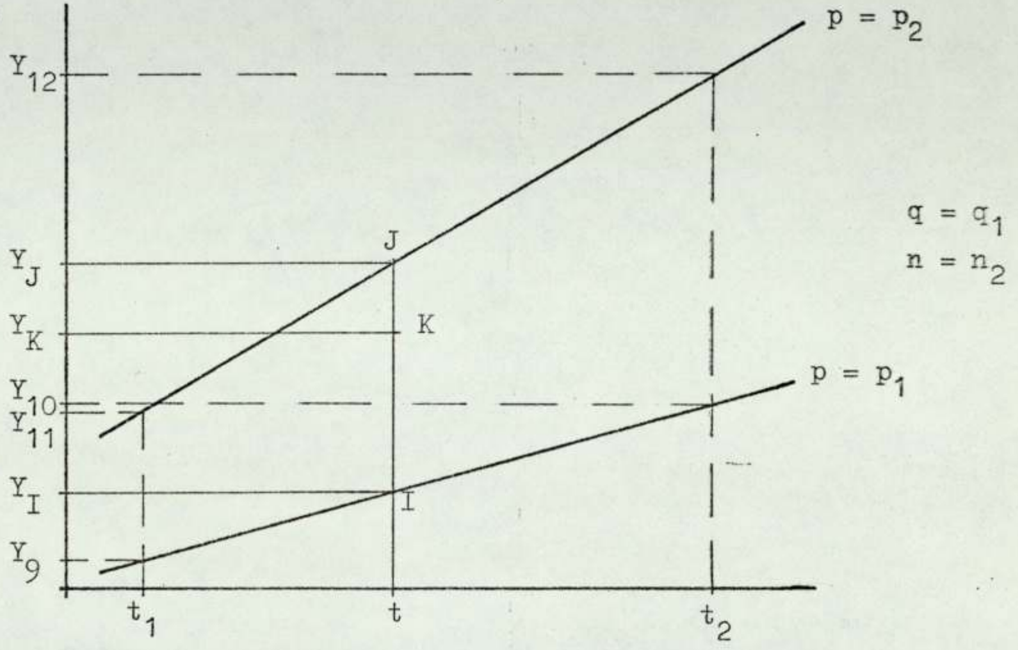
Let $c = \dfrac{q_2 - q}{q_2 - q_1}$ then $(1 - c) = \dfrac{q - q_1}{q_2 - q_1}$

Equation 7. becomes

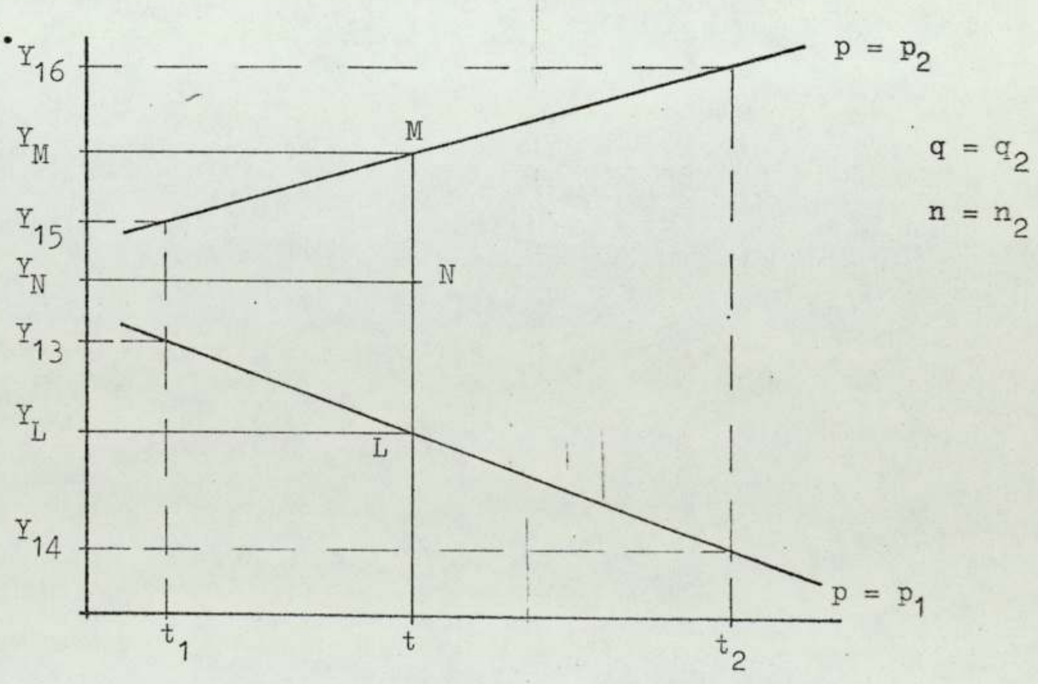
$$Y_H = cY_C + (1 - c)Y_G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 7.$$

<u>Four Variables</u> (t, p, q, n)

Graph 4.



Graph 5.



From Graph 4.

$$Y_X = aY_9 + (1 - a)Y_{10} \qquad \ldots\ldots\ldots\ldots \qquad 8.$$

$$Y_J = aY_{11} + (1 - a)Y_{12} \qquad \ldots\ldots\ldots\ldots \qquad 9.$$

Combining equations 8 and 9 to find Y_K

$$Y_K = bY_X + (1 - b)Y_J \qquad \ldots\ldots\ldots\ldots \qquad 10.$$

From Graph 5.

$$Y_L = aY_{13} + (1 - a)Y_{14} \qquad \ldots\ldots\ldots\ldots \qquad 11.$$

$$Y_M = aY_{15} + (1 - a)Y_{16} \qquad \ldots\ldots\ldots\ldots \qquad 12.$$

Combining equations 11 and 12 to find Y_N

$$Y_N = bY_L + (1 - b)Y_M \qquad \ldots\ldots\ldots\ldots \qquad 13.$$

To find the logarithm of percentage delay for a point P, somewhere between the planes bounded by the curves in graphs 4 and 5, equations 10 and 13 are combined as follows:

$$Y_P = cY_K + (1 - c)Y_N \qquad \ldots\ldots\ldots\ldots \qquad 14.$$

Subsequently, the logarithm of percentage delay Y_Q for four variables, is a combination of equations 7 and 14 and can be a point Q situated anywhere between the planes bounded by the curves in equations 2, 3, 4 and 5.

$$Y_Q = \frac{n_2 - n . Y_H}{n_2 - n_1} + \frac{n - n_1 . Y_P}{n_2 - n_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 15.$$

Let $d = \frac{n_2 - n}{n_2 - n_1}$ then $(1 - d) = \frac{n - n_1}{n_2 - n_1}$

Equation 15. becomes

$$Y_Q = dY_H + (1 - d)Y_P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 15.$$

Substituting in equation 15, relationships for Y_H and Y_P, from equations 7 and 14.

$$Y_Q = d\left[cY_C + (1-c)Y_G\right] + (1-d)\left[cY_K + (1-c)Y_N\right] \quad \ldots\ldots \; 16.$$

Substituting in equation 16, relationships for Y_C, Y_G, Y_K and Y_N, from equations 3, 6, 10 and 13.

$$\begin{aligned} Y_Q = {} & d\Big(c\big[bY_A + (1-b)Y_B\big] + (1-c)\big[bY_E + (1-b)Y_F\big]\Big) \\ & (1-d)\Big(c\big[bY_I + (1-b)Y_J\big] + (1-c)\big[bY_L + (1-b)Y_M\big]\Big) \ldots\ldots \; 17. \end{aligned}$$

Substituting in equation 17. relationships for Y_A, Y_B, Y_E, Y_F, Y_I, Y_J, Y_L and Y_M, from equations 1, 2, 4, 5, 8, 9, 11 and 12.

$$\begin{aligned} Y_Q = {} & d\Big[c\Big(b\big[aY_1 + (1-a)Y_2\big] + (1-b)\big[aY_3 + (1-a)Y_4\big]\Big) + \\ & (1-c)\Big(b\big[aY_5 + (1-a)Y_6\big] + (1-b)\big[aY_7 + (1-a)Y_8\big]\Big)\Big] + \\ & (1-d)\Big[c\Big(b\big[aY_9 + (1-a)Y_{10}\big] + (1-b)\big[aY_{11} + (1-a)Y_{12}\big]\Big) + \\ & (1-c)\Big(b\big[aY_{13} + (1-a)Y_{14}\big] + (1-b)\big[aY_{15} + (1-a)Y_{16}\big]\Big)\Big] \ldots \; 18. \end{aligned}$$

Multiplying out equation 18 and collecting like terms, the general equation becomes:

$$
\begin{aligned}
Y_Q = {} & abcd(Y_1 - Y_2 - Y_3 + Y_4 - Y_5 + Y_6 + Y_7 - Y_8 - Y_9 + \\
& \quad Y_{10} + Y_{11} - Y_{12} + Y_{13} - Y_{14} - Y_{15} + Y_{16}) + \\
& bcd(Y_2 - Y_4 - Y_6 + Y_8 - Y_{10} + Y_{12} + Y_{14} - Y_{16}) + \\
& acd(Y_3 - Y_4 - Y_7 + Y_8 - Y_{11} + Y_{12} + Y_{15} - Y_{16}) + \\
& abd(Y_5 - Y_6 - Y_7 + Y_8 - Y_{13} + Y_{14} + Y_{15} - Y_{16}) + \\
& abc(Y_9 - Y_{10} - Y_{11} + Y_{12} - Y_{13} + Y_{14} + Y_{15} - Y_{16}) + \\
& cd(Y_4 - Y_8 - Y_{12} + Y_{16}) + \\
& bd(Y_6 - Y_8 - Y_{14} + Y_{16}) + \\
& ad(Y_7 - Y_8 - Y_{15} + Y_{16}) + \\
& bc(Y_{10} - Y_{12} - Y_{14} + Y_{16}) + \\
& ac(Y_{11} - Y_{12} - Y_{15} + Y_{16}) + \\
& ab(Y_{13} - Y_{14} - Y_{15} + Y_{16}) + \\
& d(Y_8 - Y_{16}) + \\
& c(Y_{12} - Y_{16}) + \\
& b(Y_{14} - Y_{16}) + \\
& a(Y_{15} - Y_{16}) + \\
& Y_{16}
\end{aligned}
$$

where $a = \dfrac{t_2 - t}{t_2 - t_1}$ $\qquad b = \dfrac{p_2 - p}{p_2 - p_1}$

$c = \dfrac{q_2 - q}{q_2 - q_1}$ $\qquad d = \dfrac{n_2 - n}{n_2 - n_1}$

Y_1 to Y_{16} represent logarithms of percentage delay for the sixteen combinations that result from combining the four design factor variables t, p, q and n when two values are assigned to each variable, e.g. t_1 and t_2, p_1 and p_2, q_1 and q_2 and n_1 and n_2. The combinations as depicted in graphs 1 to 5 are as follows:

Y_1	from	t_1	p_1	q_1	n_1
Y_2	"	t_2	p_1	q_1	n_1
Y_3	"	t_1	p_2	q_1	n_1
Y_4	"	t_2	p_2	q_1	n_1
Y_5	"	t_1	p_1	q_2	n_1
Y_6	"	t_2	p_1	q_2	n_1
Y_7	"	t_1	p_2	q_2	n_1
Y_8	"	t_2	p_2	q_2	n_1
Y_9	"	t_1	p_1	q_1	n_2
Y_{10}	"	t_2	p_1	q_1	n_2
Y_{11}	"	t_1	p_2	q_1	n_2
Y_{12}	"	t_2	p_2	q_1	n_2
Y_{13}	"	t_1	p_1	q_2	n_2
Y_{14}	"	t_2	p_1	q_2	n_2
Y_{15}	"	t_1	p_2	q_2	n_2
Y_{16}	"	t_2	p_2	q_2	n_2

To test that the general equation was algebraically sound, values for t, p, q and n corresponding to each combination, were systematically substituted into the equations for a, b, c and d and subsequently the results from these substituted into the general equation. Algebraic soundness was established if the result from the general equation was equal to the Y value corresponding to the combination equated.

e.g. Let $t = t_2$, $p = p_2$, $q = q_2$ and $n = n_2$

Then $a = 0$, $b = 0$, $c = 0$ and $d = 0$

Substituting these values for a, b, c and d into the general equation, Y_Q was found to equal Y_{16}. From the above list of combinations it can be seen that the combination t_2, p_2, q_2, n_2 also corresponds to the value Y_{16}. This test was applied for each of the input combinations and the equation found to yield the correct solutions in each case. Therefore, the equation was proven to be algebraically sound.

To establish numerical values for Y_1 to Y_{16}, suitable values were chosen for t_1 , t_2 , p_1 , p_2 , q_1 , q_2 , n_1 and n_2, and each of the sixteen combinations shown on the previous page simulated using G.P.S.S./360 computer simulation language. By simulating these combinations for both tied and untied production lines and for interstation storage capacities from 0 to 8, a number of values for Y_1 to Y_{16} were established.

In previous simulation studies, such as those designed to study the effect of the design factors on system efficiency, the results were presented in a graphical form. Inaccuracies in these results, due to the restricted length of simulated production period, were minimised by mathematically fitting the best curve with the points available. However, in this study each graph is known to be of a linear form and defined by the minimum necessary two points. There are eight straight line graphs in all defined by a total of sixteen points, these being the values Y_1 to Y_{16}. Therefore the validity of the final equations is very much dependant upon the accuracy of these values.

To achieve greater accuracy the simulated production period was increased to cover a potential throughput of 960 bodies. This represented a production period of 16 hours with a cycle time of 1 minute (t_1) and 80 hours with a cycle time of 5 minutes (t_2). Additionally for the untied systems, graphs were plotted of the logarithm of percentage delay values Y_1 to Y_{16} against interstation storage capacity. As expected smooth curves resulted, therefore enabling discrepancies in individual results to be corrected by visually fitting the best curve to the available points.

Values for Y_1 to Y_{16} were substituted into the general equation resulting in the formation of a series of multi-variable efficiency equations corresponding to tied and untied systems without interstation storage and untied systems with interstation storage of 1 to 8 inclusive. From these equations, details of which are given in Appendix D, efficiency calculations can be made for different station-storage configurations for a wide range of values of t , p , q and n.

Full details of the simulation studies are given in Appendix B.

16.1.2 Study Area B - Inefficiency due to operator work rate variability.

It was established from the analysis of the experiments in the previous chapter that for this study area the logarithm of percentage delay plotted against the logarithms of each of the three variables rendered linear relationships in only two of the three graphs. The relationship between percentage delay and the number of operators per station possessed different characteristics and was subsequently found to approximate to a straight line by logging the x-axis only.

To derive a generalised multi-variable efficiency equation as in the previous study area, it is important that all three relationships are presented in a linear form. This means that only two of the three relationships involve percentage delay in a logged condition, therefore complicating a combination. This problem can, however, be overcome by establishing a series of linear relationships in terms of percentage delay and the logarithm of the variable displaying the different characteristics for different values of the other variables. The derivation of the generalised multi-variable efficiency equation for study area B can then be carried out as follows:

Notation:

$m = \log_{10}$(number of operators per station)

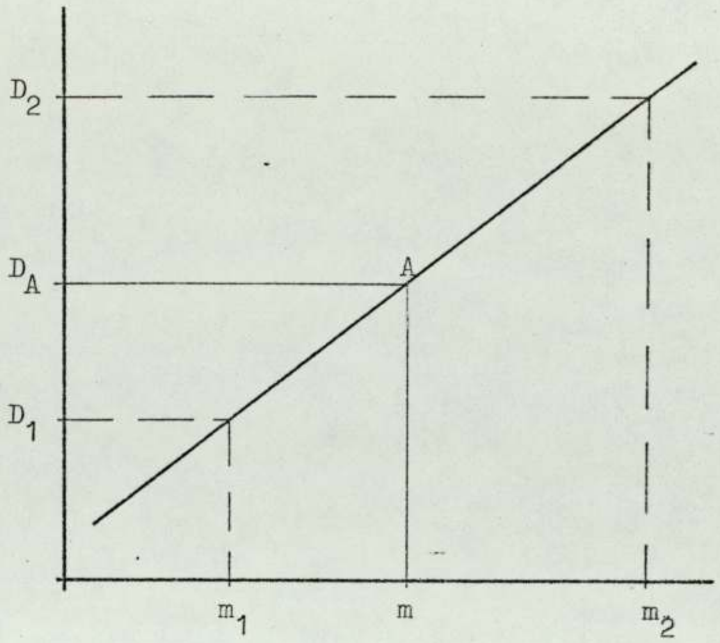
$n = \log_{10}$(number of stations)

$V = \log_{10}$(coefficient of variation)

D = percentage delay

One Variable (m)

Graph 1.



$n = n_1$

$V = V_1$

The equation to the straight line is

$$D_A = \frac{m_2 - m.D_1}{m_2 - m_1} + \frac{m - m_1.D_2}{m_2 - m_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; 1.$$

$$\text{Let} \quad e = \frac{m_2 - m}{m_2 - m_1} \quad \text{then} \quad (1 - e) = \frac{m - m_1}{m_2 - m_1}$$

Equation 1. becomes

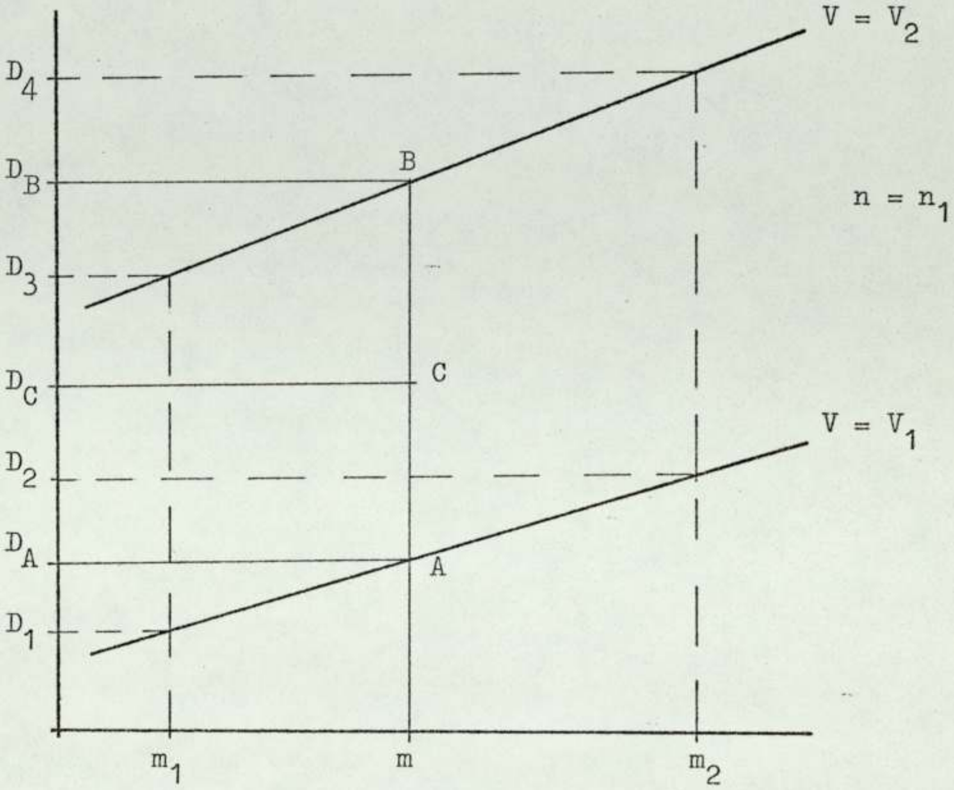
$$D_A = eD_1 + (1 - e)D_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 1.$$

The remaining two straight line relationships involve the logarithm of percentage delay plotted against the logarithm of number of stations and the logarithm of coefficient of variation. Therefore to enable these relationships to be combined with the one shown previously, equation 1. must be logged.

i.e. $\log_{10}D_A = \log_{10}\left[eD_1 + (1 - e)D_2\right]$ .... 2.

<u>Two Variables</u> (m, V)

Graph 2.



From graph 2

$\log_{10}D_A = \log_{10}\left[eD_1 + (1 - e)D_2\right]$ .... 2.

$\log_{10}D_B = \log_{10}\left[eD_3 + (1 - e)D_4\right]$ .... 3.

Combining equations 2 and 3 to find D_C

$$\log_{10}D_C = \frac{V_2 - V}{V_2 - V_1}\cdot\log_{10}D_A + \frac{V - V_1}{V_2 - V_1}\cdot\log_{10}D_B \qquad \text{............ 4.}$$

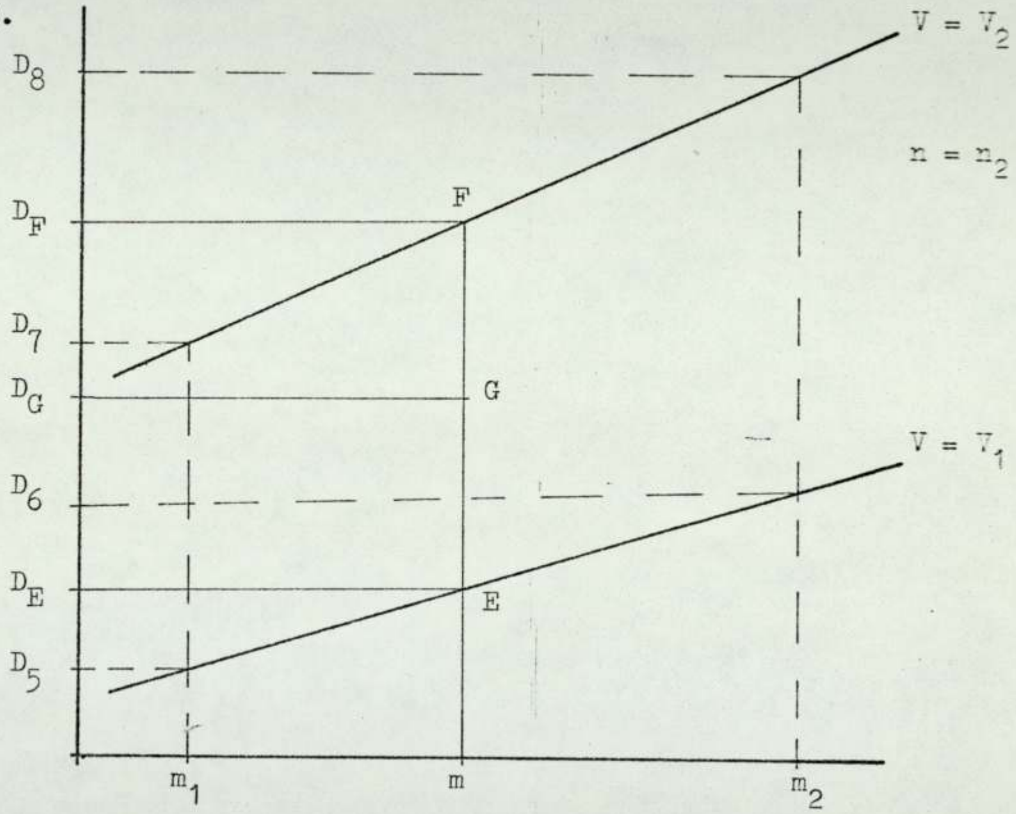
Let $f = \dfrac{V_2 - V}{V_2 - V_1}$ then $(1 - f) = \dfrac{V - V_1}{V_2 - V_1}$

Equation 4. becomes

$$\log_{10}D_C = f.\log_{10}D_A + (1 - f)\log_{10}D_B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.$$

<u>Three Variables</u> (m, V, n)

Graph 3.



From graph 3

$$\log_{10}D_E = \log_{10}\left[eD_5 + (1 - e)D_6\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.$$

$$\log_{10}D_F = \log_{10}\left[eD_7 + (1 - e)D_8\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.$$

Combining equations 5 and 6 to find D_G

$$\log_{10}D_G = f.\log_{10}D_E + (1 - f)\log_{10}D_F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.$$

To find the logarithm of percentage delay for a point H, somewhere between the planes bounded by the curves in graphs 2 and 3, equations 4 and 7 are combined as follows:

$$\log_{10}D_H = \frac{n_2 - n}{n_2 - n_1}.\log_{10}D_C + \frac{n - n_1}{n_2 - n_1}.\log_{10}D_G \quad \ldots\ldots\ldots\ldots 8.$$

Let $d = \frac{n_2 - n}{n_2 - n_1}$ then $(1 - d) = \frac{n - n_1}{n_2 - n_1}$

Equation 8. becomes

$$\log_{10}D_H = d\log_{10}D_C + (1 - d)\log_{10}D_G \quad \ldots\ldots\ldots\ldots\ldots\ldots 8.$$

Substituting in equation 8., relationships for $\log_{10}D_C$ and $\log_{10}D_G$, from equations 4 and 7.

$$\log_{10}G_H = d\left[f.\log_{10}D_A + (1 - f)\log_{10}D_B\right] + (1 - d)\left[f.\log_{10}D_E + (1 - f)\log_{10}D_F\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9.$$

Substituting in equation 9, relationships for $\log_{10}D_A$, $\log_{10}D_B$, $\log_{10}D_E$ and $\log_{10}D_F$, from equations 2, 3, 5 and 6.

$$\begin{aligned}\log_{10}D_H = {} & d\left[f\left(\log_{10}\left[eD_1 + (1-e)D_2\right]\right) + (1-f)\left(\log_{10}\left[eD_3 + (1-e)D_4\right]\right)\right] + \\ & (1-d)\left[f\left(\log_{10}\left[eD_5 + (1-e)D_6\right]\right) + (1-f)\left(\log_{10}\left[eD_7 + (1-e)D_8\right]\right)\right] \ldots 10.\end{aligned}$$

Multiplying out equation 10. and re-organising the general equation becomes

$$\begin{aligned}\log_{10}D_H = {} & df\left[\left(\log_{10}\left[eD_1 + (1-e)D_2\right]\right) - \left(\log_{10}\left[eD_3 + (1-e)D_4\right]\right)\right. \\ & \left. - \left(\log_{10}\left[eD_5 + (1-e)D_6\right]\right) + \left(\log_{10}\left[eD_7 + (1-e)D_8\right]\right)\right] \\ & + d\left[\left(\log_{10}\left[eD_3 + (1-e)D_4\right]\right) - \left(\log_{10}\left[eD_7 + (1-e)D_8\right]\right)\right] \\ & + f\left[\left(\log_{10}\left[eD_5 + (1-e)D_6\right]\right) - \left(\log_{10}\left[eD_7 + (1-e)D_8\right]\right)\right] \\ & + \left[\left(\log_{10}\left[eD_7 + (1-e)D_8\right]\right)\right]\end{aligned}$$

where $e = \dfrac{m_2 - m}{m_2 - m_1}$ $\qquad f = \dfrac{V_2 - V}{V_2 - V_1}$

$$d = \frac{n_2 - n}{n_2 - n_1}$$

D_1 to D_8 represent percentage delays for the eight combinations that result from combining the three design factor variables m, V and n when two values are assigned to each variable, e.g. m_1

and m_2, V_1 and V_2 and n_1 and n_2. The combinations, as depicted in graphs 1 to 3, are as follows:

D_1	from	m_1	V_1	n_1
D_2	"	m_2	V_1	n_1
D_3	"	m_1	V_2	n_1
D_4	"	m_2	V_2	n_1
D_5	"	m_1	V_1	n_2
D_6	"	m_2	V_1	n_2
D_7	"	m_1	V_2	n_2
D_8	"	m_2	V_2	n_2

Algebraic soundness was determined for the general equation and numerical values found for D_1 to D_8 for different types of production line, i.e. tied, untied and systems with interstation storage, in the same way as described in Section 16.1.1. Details of the simulation studies carried out to determine the numerical values are given in Appendix B and presentation of the resulting equations in Appendix D.

16.2 Compilation of Efficiency Tables

The efficiency equations supported by basic performance data such as that shown in Appendix A, enables system efficiency calculations to be made for tied and untied systems for a wide range of design factor values. However, the presentation in the form of lengthy equations does little to promote their use as an aid to production line design. The design engineer, confronted with a number of alternative production line designs, needs a simple method of determining system efficiency such that quantitative comparisons can be made. To satisfy this need, a set of efficiency tables were compiled from the multi-variable equations for a wide range of values for each design factor.

The complexity of the equations plus the large number of calculations necessary prevented manual computation and therefore a program in fortran language (51) was written to enable these calculations to be executed on the computer. Again, as throughout the development of the efficiency equations, it was convenient to compile tables for study areas A and B separately, the user adding the two where necessary.

To ensure that the tables can be used with reasonable accuracy, it is important that when compiling them the range covered by consecutive design factor values is not too large. Combining this with the number of variables involved, four in table set B and five in table set A, places a restriction on the total range that can be computed for each design factor if the tables are to be kept to a manageable size. Therefore the tables presented in Appendix E cover only those values relevant to the motor industry and the validation exercises described in Section 16.3.

16.3 Validation of Tables

16.3.1 Validation Exercises

The best method of validating the accuracy of the efficiency tables and subsequently the accuracy of the multi-variable equations is to compare the actual efficiency of existing assembly systems with values taken from the tables. To achieve this, an exercise using the body build systems that were analysed in Chapter 5 was carried out, system efficiency estimations from the tables being compared with the actual shop floor performance figures. Unfortunately, the number of systems available for comparison, seven in all, and the variation in system design and stoppage patterns, were too small to conclusively validate the tabulated values.

To provide additional validation data, a number of simulation exercises including both identical and dissimilar station assembly lines were executed, the tabulated efficiency values being compared to those obtained from the simulation. To test the adaptability of the tables to dissimilar station assembly lines, extreme conditions were simulated, adjacent stations differing in design and stoppage patterns by a greater degree than was usually experienced in practice. When using the tables to estimate the efficiency of an assembly line with dissimilar stations, mean values for design features and stoppage data were calculated for the entire system, these values being applied to the tables.

Full details of the conditions simulated and the efficiency value comparison are presented in Appendix C.

16.3.2 Discussion of Validation

The predicted efficiency values from the tables compared favourably with the actual build system performance figures, all estimates being within 9%. Of the seven build systems analysed for validation purposes, the efficiency predictions of those classified as unpaced were found to be the least accurate. Predictions for these systems necessitated the use of the two sets of tables, i.e. those based on stoppages and those on operator work rate variability. The accuracy of the efficiency values taken from the latter is dependant upon the accuracy of the coefficient of variation used, which in this case was 0.27. This value was chosen because it was the nearest tabulated figure to 0.26, a value quoted by Slack (27). It seems quite feasible, therefore, that the inaccuracies experienced when predicting the efficiency of unpaced systems, although still relatively small, could be attributed to the use of a coefficient of variation that does not accurately represent the situation being analysed. To ensure greater accuracy with these tables, shop floor studies to establish the coefficient of variation for the location in question are required.

The comparison of efficiency values established using computer simulation with those read from the tables was good, 98% of the differences being less than ± 11% with 88% less than ± 5%. Those comparisons where the difference was greater than ± 11% were of assembly lines consisting of a large number of stations encorporating stoppage probabilities and coefficients of work rate variation of a magnitude unlikely to be experienced in practice.

The final exercise to test the adaptability of the tables, and subsequently the equations, to predict the efficiency of a series of dissimilar stations by approximating to a series of identical stations, also proved to be successful. Although in some cases the diversity between stations was extreme, the efficiency values obtained from the tables were all within ± 5% of the values arrived at by computer simulation.

The validation exercises, therefore, showed that the tables, the equations and the technique of approximating dissimilar station assembly lines to a series of identical stations, were accurate enough to facilitate meaningful system efficiency predictions.

PART III

DISCUSSION, SUGGESTED FURTHER WORK AND CONCLUSIONS

CHAPTER SEVENTEEN

DISCUSSION

The study of the design factors clearly shows the influence of design on system efficiency and provides an indication of the configurations that render poor system efficiency. For example, the combination of a high number of tied stations and a short cycle time is conducive with poor system efficiency and yet many of today's high output, highly mechanised progressive assembly lines such as the gateline, encorporate these features. The reason for this appears to be a combination of management's reluctance to use untied systems, interstation storage and duplicate facilities, and a lack of understanding of the influence of these features on good system efficiency. In addition, the absence of a technique to predict system efficiency has inhibited a scientific approach to production line design.

Vehicle body building, for example, is an extremely high labour and equipment intensive stage in vehicle assembly and therefore it is reasonable to expect a high incidence of stoppages. To maintain an acceptable level of efficiency in this type of environment, interstation storage should be used to minimise the effects of individual station stoppages on the rest of the system.

Assembly lines having a high number of stations and a short cycle time, although enabling high production schedules to be met without duplication of facilities, for economic reasons restrict the application of interstation storage. For example, as the cycle time decreases, the storage capacity to cover the same stoppages, increases. Combining this with the large number of interstation storages required to buffer a system with a high number of stations, then the necessary floor area becomes excessive. In addition to this, the introduction of interstation storage effectively unties the system with the result that a method other than the continuous chain conveyor has to be found to convey the bodies in and out of the buffer stores. Manual conveyance, which is the least complex method of doing this, is not conducive with short cycle times and has in recent years been avoided, possibly because at first sight it appears to be of a retrospective nature.

To economically use interstation storage on a system involving large assemblies such as a motor car, the cycle time must be increased and the length of the line decreased. This also has the effect of reducing the production capacity of the system and if high schedules are to be met then a number of identical parallel lines must be used. The benefits in terms of increased system efficiency as indicated by the design factor study, can be dramatic with an interstation storage capacity of only one being sufficient to cover most stoppages experienced on this type of vehicle body build line.

The build system simulation exercises demonstrated that computer simulation backed up with good stoppage data was an accurate and flexible method of analysing production line performance. Applied at the design stage, it can be used in conjunction with the stoppage data to predict system efficiency and enable production lines to be designed for near optimum efficiency. In addition, the exercises served to validate the stoppage data taken from the Marina gateline stoppage logs and to show its adaptibility by facilitating other build system simulations.

The stoppage data listed in Appendix A is obviously only relevant to the environment from which it was taken, that being body building at Cowley. However, it does demonstrate that from a relatively short period of stoppage recording, a number of beneficial things can emerge, from back-up data for simulation exercises to the identification and subsequently rectification of problem facilities. The period of recording will depend upon the nature of the system being analysed and with systems such as the gateline where the cycle time is short and the incidence of stoppages high, as little as 5 weeks recording can be sufficient.

The main disadvantage with computer simulation is that to use it necessitates the availability of computing facilities and the expertise to write the programs. In addition, to design a system for optimum efficiency on a trial and error basis using simulation can be extremely time consuming and computer time is an expensive commodity.

The provision of the multi-variable efficiency equations, although less accurate and flexible than simulation, overcomes this main disadvantage by facilitating efficiency calculations without the use of a computer. Unfortunately, the equations can only handle identical station systems and therefore to accommodate efficiency calculations of systems not displaying this characteristic, as is usually the case, an approximation has to be made. This involves calculating mean values for stoppage probability, downtime and number of operators, on a station basis and feeding these values into the relevant equation. This method appears to be a reasonable one, the comparison of simulation results comparing favourably with those calculated from the equations using this approximation.

One of the more important aspects concerned with the introduction of new techniques is the method of presentation. In the past, many researchers, although making a valid contribution to this area of research, have failed to arouse the interest of industry because their presentation is indecipherable to the layman.

The multi-variable efficiency equations, for example, although not complicated, are rather long and to manually calculate efficiency values for a large number of design variants would prove to be extremely tedious to an extent that could dissuade the user from employing them.

The strategy of compiling a set of efficiency tables from the equations as well as overcoming this problem, provides the user with a quick and simple method of making system efficiency predictions. They do, however, as with so many quick techniques, sacrifice accuracy for speed and simplicity, stoppage probability, downtime and number of stations being approximated to the nearest tabulated value.

The accuracy of the tables is relative to the magnitude of the interval between consecutive input values, the smaller the interval the more accurate the tables. If the interval is reduced, either the overall range of the tables is reduced or the number of tabulated efficiency values is increased. With several variables involved, a small reduction in the interval can result in a large increase in the number of tabulated efficiency values with the outcome that a compromise between accuracy and restricting the tables to a manageable size, has to be made.

If computing facilities are available, the equations, although not particularly suitable for manual computation, can be easily computerised and stored on file such that calculations can be made as required by feeding in the relevant input data.

One of the main functions of the proposed techniques is to facilitate more meaningful assembly line design comparisons. The efficiency of an assembly line will vary from shift to shift and therefore the accuracy of the predicted value, as well as being difficult to ascertain, is not too important. It is the means to compare that is important and for this function both the equations and the tables are adequate.

The ultimate measure of an assembly line's capabilities, in addition to being able to achieve the production schedule, is the cost per unit produced. This figure encorporates both capital and operating costs and is the only real accurate method of appraising assembly systems. In the past the absence of a method to calculate system efficiency at the design stage and a general lack of efficiency data has resulted in a bias towards capital cost appraisals. The folly of such an approach is evident at Cowley, the gateline comparing favourably on a capital cost basis but the strategy of overspeeding and overmanning to compensate for lost production time due to stoppages, rendering inefficiency a major cost item. The provision of the system efficiency predicting techniques, by facilitating more meaningful appraisals, will enable such problems to be identified prior to installation.

Although much of the work described in this project is biased towards the body build function of vehicle assembly, the results, in the form of the efficiency equations, have been developed to cover a wide range of production line configurations. The efficiency data presented in Appendix A, however, is only relevant to vehicle body building and the onus is now upon management to implement recording procedures and to establish efficiency data in other production areas.

The scope of production line design research has, in recent years, been greatly extended with the advent of computer simulation. Most past research (28 to 37 and 45 to 47), however, was conducted in and around the early 1960's and consequently is inhibited by the complexity of the mathematical techniques employed. Queuing theory, which lends itself to the modelling of exponentially distributed work times, was the most commonly used at this time although, as with all mathematical analyses, the complexity of the technique restricted studies to systems having less than five stations. The study of the effect of breakdowns on a series of work stations, although an area often causing more disruption than operator work rate variability, is not easily represented mathematically and consequently has rarely been pursued. In general, past research has done little more than indicate basic relationships in an unquantified form and has been of little use to industry.

In this project, the study of the design factors alone has gone further than any previous research in identifying the influence of the major design parameters on the efficiency of a series of work stations experiencing both stoppages and operator work rate variability. Hillier and Boling (29) and Slack (38) in the course of their studies have graphically related the effect of certain design factors on a series of work stations experiencing only operator work rate variability, the curves comparing favourably with those established in this project.

The use of computer simulation for analysis facilitated the study of longer lines and the use of more realistic distributions, therefore, enabling empirical formula to be developed for a wide range of production line configurations. The results of this project have, therefore, achieved more than past research by quantifying relationships and providing industry with techniques to facilitate accurate efficiency predictions at the production line design stage.

Many of the conclusions established throughout the execution of this project have been relayed to management at British Leyland although as yet the final package detailing the efficiency predicting techniques has not been presented. The reaction to proposals such as the adoption of smaller untied production lines has been one of interest, although without the means to quantify the benefits this soon waned. The efficiency predicting techniques now enable such benefits to be quantified and it is intended in the near future to pursue more strongly these proposals.

CHAPTER EIGHTEEN

FURTHER WORK

18.1 Operator Work Rate Variability

18.1.1 Determination of Coefficient of Variation

It has been suggested by Slack (27) that the coefficient of variation of operators' work times can vary from 0.008 to 0.5 but is most likely to be about 0.27. To quantify efficiency losses due to work rate variability using simulation, empirical formulae or the tables, the coefficient of variation must be known. Apart from minor variations from one operator to another, intuitively the coefficient of variation should remain constant for certain operating conditions.

Work is required to establish whether or not the coefficient of variation is influenced by the operating conditions and if so quantify any relationships and establish values pertaining to work in the motor industry.

18.1.2 Clarification of Distribution

Although a number of researchers, the details of which are given in Chapter 4, have found the shape of the operator's work rate distribution to vary from a normal to a positively skewed distribution, all investigations have involved short cycle time work, i.e. less than one minute and often as low as five seconds. As the cycle times in the motor industry are usually greater than one minute, a study of longer cycle time work is necessary to establish whether the distributions found from previous short cycle time studies are still applicable.

18.2 The Effect of Pacing on Operator Performance

18.2.1 Clarification of Feed Rate and Time Available Relationships

A series of experiments conducted by Buffa (43) revealed that the performance times of operators engaged on paced work was not a function of time available but of feed rate alone. Sury (24) on the other hand concluded that performance times are influenced by both feed rate and time available.

Further work is required to clarify this anomaly.

18.2.2 A Study of Longer Cycle Time Work

As with the study of operator work rate variability most investigations have involved operations with extremely short cycle times. A study of longer cycle time work is required.

18.3 Extension to Range of Equations

18.3.1 Short Cycle Time Assembly Lines

The efficiency equations that have been developed in this project will cover most assembly line situations apart from those employing short cycle times, i.e. less than one minute. As the cycle time is decreased, the interstation storage requirement increases with both stoppages and work rate variability potentially disrupting production. Work is required to develop efficiency equations that will enable efficiency predictions and optimum interstation storage capacity to be established for short cycle time assembly lines.

18.3.2 Determination of Interprocess Storage Capacity

The problem often arises as to the storage capacity necessary to buffer fluctuations in the output from adjacent production areas, e.g. body build to paint and paint to final assembly. In this instance, operator work rate variability and number of stations cease to be important but with the incidence and duration of stoppages from an entire production area being well in excess of that from a single station, the storage requirement increases.

Computer simulation can be used to analyse this type of situation but with the problem re-occurring with each new installation, the development of equations to enable optimum interprocess storage capacity to be determined, would prove beneficial.

18.3.3 Determination of Trends in Equation Constants

From an analysis of the equation constants, the results of which are shown in graphical form in Appendix C, it can be seen that trends exist. With equations developed to cover the extreme cases discussed in Sections 18.3.1 and 18.3.2, the determination of trends in the equation constants could facilitate the development of further equations by interpolation.

18.4 Extension of Stoppage Data

For the purpose of this project, all stoppage analyses were restricted to vehicle body building at Cowley and hence the stoppage data is only relevant to this process and in some cases this location. Certain operating conditions, such as the method of payment, can influence the pattern of stoppages and, therefore, it would be wrong to use stoppage data based on logs recorded in a measured daywork environment for a piecework situation.

Further work is required by the Plants wishing to adopt these techniques of predicting efficiency to log stoppages and establish data relevant to their area of production.

18.5 Vehicle Body Build System Design

Primarily it is intended that the techniques outlined in this report should be used as a management aid at the production line design stage. However, with sufficient data now available to facilitate an evaluation of vehicle body build systems, it would be beneficial, firstly, for the Plant concerned to familiarise itself with the techniques involved and, secondly, to provide an insight into the arrangements that render good system efficiency, to design and analyse a number of systems based on the production of an existing model, e.g. the Marina. Furthermore, a cost appraisal would provide invaluable information relating to the economics of installing and operating production lines designed for greater efficiency.

18.6 An Analysis of Assembly Lines with Dissimilar Stations

Apart from computer simulation, the techniques developed to predict system efficiency can only handle production lines that are first approximated to a series of identical stations. Although this method has been shown to be accurate enough to facilitate system comparisons, an investigation to establish the exact effects of this approximation for various conditions would lead to greater confidence in using the developed techniques as well as identifying any relevant compensatory action that need be taken.

18.7 Industrial Based Research

Various aspects of assembly line research have in the past attracted considerable attention, many of the works being described in Part 1. Unfortunately, very few of these have been industrial based, for convenience, experimentation in the laboratory being preferred. Intuitively, the reactions of an experimental subject to various operating conditions will differ from those of the experienced line worker with many other factors such as the method of payment and industrial relations effecting his performance.

Where possible, more industrial based research is recommended, not only to delve deeper into the many facets of assembly line design but to substantiate past research.

CHAPTER NINETEEN

CONCLUSIONS

1. The major factors that can influence the efficiency of a production line are:

   a) The social environment on the shop floor
   b) The hierarchical structure on the shop floor
   c) The payment system
   d) The degree of operator work rate variability
   e) Paced or unpaced operations
   f) The reliability of associated plant and equipment
   g) The performance level of each operator
   h) Production line design

2. Experiments with autonomous work groups in the Scandinavian motor industry aimed at increasing job satisfaction and reducing absenteeism and labour turnover are encouraging but as yet inconclusive as a long term policy.

3. Problems associated with labour turnover and hence the need for a reorganised working environment are less acute in the British motor industry due to the existance of a favourable wage differential.

4. Of the three payment systems listed overleaf, measured daywork appears to be the most suited to the present day working environment.

a) Time rate

b) Measured day work

c) Payment by results

5. A payment system is both a means of inducing effort and an item of cost, the success of measured daywork in this respect depending upon the conditions surrounding its introduction and the control applied afterwards.

6. Poor system efficiency is often more a problem of production line design rather than poor reliability of associated plant and equipment or poor operator performance.

7. The decline in system efficiency experienced in the body building function at Cowley can be attributed to two major factors:

   a) The introduction of the gateline system of build, the nature of its design inhibiting good efficiency.

   b) A degeneration in the measured daywork payment system due to a combination of poor industrial relations and a lack of managerial control.

8. The main obstacles preventing a scientific approach to designing production lines for greater efficiency were

identified as:

a) A lack of understanding pertaining to the influence of certain design factors on the efficiency of a production line.

b) The absence of data and techniques to predict system efficiency at the design stage.

9. Of the build systems described in Chapter 8, the gateline, which is classified as both tied and paced, although potentially the most accurate, is the least efficient.

10. Although prone to poor efficiency, tied systems are more commonly used in the motor industry because the mechanised chain or slat conveyor, which ties a system, is the most convenient method of transporting large assemblies.

11. For the purpose of computer simulation, a production stoppage can be conveniently represented by a stoppage probability and an associated downtime distribution, the latter approximating to a negative exponential.

12. Operator work rate variability can be conveniently represented by a normal distribution with a coefficient of variation in the region of 0.26.

13. The efficiency data compiled from the Marina gateline stoppage logs can be used in conjunction with computer simulation to analyse other build systems.

14. The efficiency of an unpaced production line is potentially greater than that of an equivalent paced system.

15. A tied system is less efficient than an untied system, the duration of each cycle on the former being dictated by the speed of the slowest operator plus any stoppage time.

16. Increases in station stoppage probability and mean stoppage duration both cause the efficiency of a series of work stations to decrease, the rate of decrease diminishing for increasing values of stoppage probability and mean downtime.

17. Increases in the coefficient of variation of the operator's work rate distribution causes a decrease in the efficiency of a series of work stations, the rate of decrease for systems without interstation storage diminishing for increasing values of coefficient of variation. For systems with interstation storage, the rate of decrease increases as the coefficient of variation becomes larger.

18. Increasing the cycle time of a production line experiencing stoppages increases its system efficiency.

19. Assuming that each station experiences stoppages or work rate variability or both, then an increase in the number of work stations has a detrimental effect on system efficiency.

20. Increasing the number of operators per station reduces system efficiency by increasing the incidence of long cycle times.

21. The inclusion of interstation storage increases the efficiency of a series of work stations by reducing the interdependence of adjacent stations.

22. The three techniques presented in this project and listed below, used in conjunction with the efficiency data, can be used to accurately predict the system efficiency of a production line at the design stage:

    a) Computer Simulation
    b) The Efficiency Equations
    c) The Efficiency Tables

Of the three, computer simulation is the most flexible and accurate and the efficiency tables the most convenient and easiest to use. The equations are most suitable for computerising such that an efficiency predicting facility is always available.

PART IV

APPENDICES

APPENDIX A

EFFICIENCY DATA

A.1 Reliability Data

Facility	% Reliability per set or item
1. Gate Load/Unload/Jigs	99.236
2. Spot Welding Set	99.926
3. Gas Welding Set	99.984
4. Body Lift Hoist	98.872
5. Roof Loader	98.313
6. Other Facilities	99.924

A.2 Material Supply Efficiency Data

Category	% Efficiency per item
1. Material Shortage	97.505
2. Faulty Material	99.964

A.3 Operator Efficiency Data

Category	% Efficiency per operator
1. Absenteeism/Lateness	99.991
2. Missed Operations	99.987
3. Incomplete/Faulty Assembly	99.862
4. Incorrect Equipment Use	99.993
5. No Slip Man Available	99.993

A.4 Stoppage Probabilities

Category	Probability
1. Gate Load/Unload Jigs	.00455 per set
2. Spot Welding Set	.00032 " "
3. Gas Welding Set	.00012 " "
4. Body Lift Hoist	.00940 per hoist
5. Roof Loader	.00819 per loader
6. Other Facilities	.00049 per station
7. Material Shortage	.00420 " "
8. Faulty Material	.00035 " "
9. Absenteeism/Lateness	.00004 per operator
10. Missed Operations	.00011 " "
11. Incomplete/Faulty Assembly	.00121 per assembly
12. Incorrect Equipment Use	.00005 per operator
13. No Slip Man Available	.00001 " "
14. Reason Unknown	.00024 per station

A.4.1 Other Useful Stoppage Probabilities

Category	Number off each Item					
	1	2	3	4	5	6
1. Spot Welding Set	.00032	.00064	.00128	.00160	.00192	.00224
2. Gas Welding Set	.00012	.00024	.00036	.00048	.00060	.00072
3. *Material	.00455	.00908	.01359	.01808	.02254	.02705
4. Incomplete/Faulty Assembly	.00121	.00242	.00363	.00484	.00605	.00726
5. *Labour	.00021	.00042	.00063	.00084	.00105	.00126

*Material - combines both material shortage and faulty material.

*Labour - combines absenteeism/lateness, missed operations, incorrect equipment use and no slip man available.

A.5 Mean Stoppage Durations

Category	Mean Stoppage Duration (mins)
1. Gate Load/Unload/Jigs	1.68
2. Spot Welding Set	2.36
3. Gas Welding Set	1.30
4. Body Lift Hoist	1.20
5. Roof Loader	2.06
6. Other Facilities	1.55
7. Material Shortage	5.94
8. Faulty Material	1.04
9. Absenteeism/Lateness	2.20
10. Missed Operations	1.15
11. Incomplete/Faulty Assembly	1.14
12. Incorrect Equipment Use	1.47
13. No Slip Man Available	2.50
14. Reason Unknown	0.55

A.5.1 Other Useful Mean Stoppage Durations

Category	Mean Stoppage Duration (mins)
1. Material *	5.56
2. Labour *	1.45

* Material - combines both material shortage and faulty material.

* Labour - combines absenteeism/lateness, missed operations, incorrect equipment use and no slip man available.

A.6 Downtime Distributions

To establish the shape of the downtime distributions and to test the hypothesis that the spread of each distribution is directly proportional to its mean, a sample of four stoppage categories were selected for analysis. The downtime frequency distributions for each of the selected stoppage categories were plotted with data taken from the Marina Gateline stoppage logs. The distributions can be seen in graphs A1,A2,A3 & A4. To convert these into a usable form, cumulative relative frequencies were calculated and the mean of each time interval divided by the relevant mean stoppage duration to render four cumulative distributions having the same mean value of one. An investigation of the resulting distributions revealed that their shapes were the same, therefore validating the hypothesis and that they could be approximated to a negative exponential distribution with a mean value of one. Graphical comparisons of the cumulative distributions are shown in graph A5 and the frequency tables in sections A.6.1, A.6.2, A.6.3 and A.6.4.

This phenomenon is a convenient one, the cumulative frequency distribution with a mean value of one being sufficient to represent all stoppage durations, values taken from this distribution during computer simulation being multiplied by the mean stoppage duration relevant to that particular stoppage. The computer samples the distribution on a random basis by generating a random number between 0 and 1, using it as a point on the x-axis and reading off the corresponding value on the y-axis. Therefore it is important that the x-axis of the distribution ranges from 0 to 1. This can be achieved by reversing the axes of the cumulative frequency distribution.

By visually inspecting the points from the four cumulative frequency distributions shown in graph A5, the best curve was determined and a series of points taken from it to be used in the simulation exercises.

Tabulation of the selected downtime distribution is shown on the next page.

TABULATION OF SELECTED DOWNTIME DISTRIBUTION

x	0	0.05	0.10	0.20	0.30	0.40	0.50	0.60
y	0	0.10	0.15	0.25	0.325	0.40	0.48	0.60

x	0.70	0.75	0.80	0.84	0.88	0.90	0.92	0.94
y	0.76	0.88	1.08	1.39	1.59	1.78	2.04	2.40

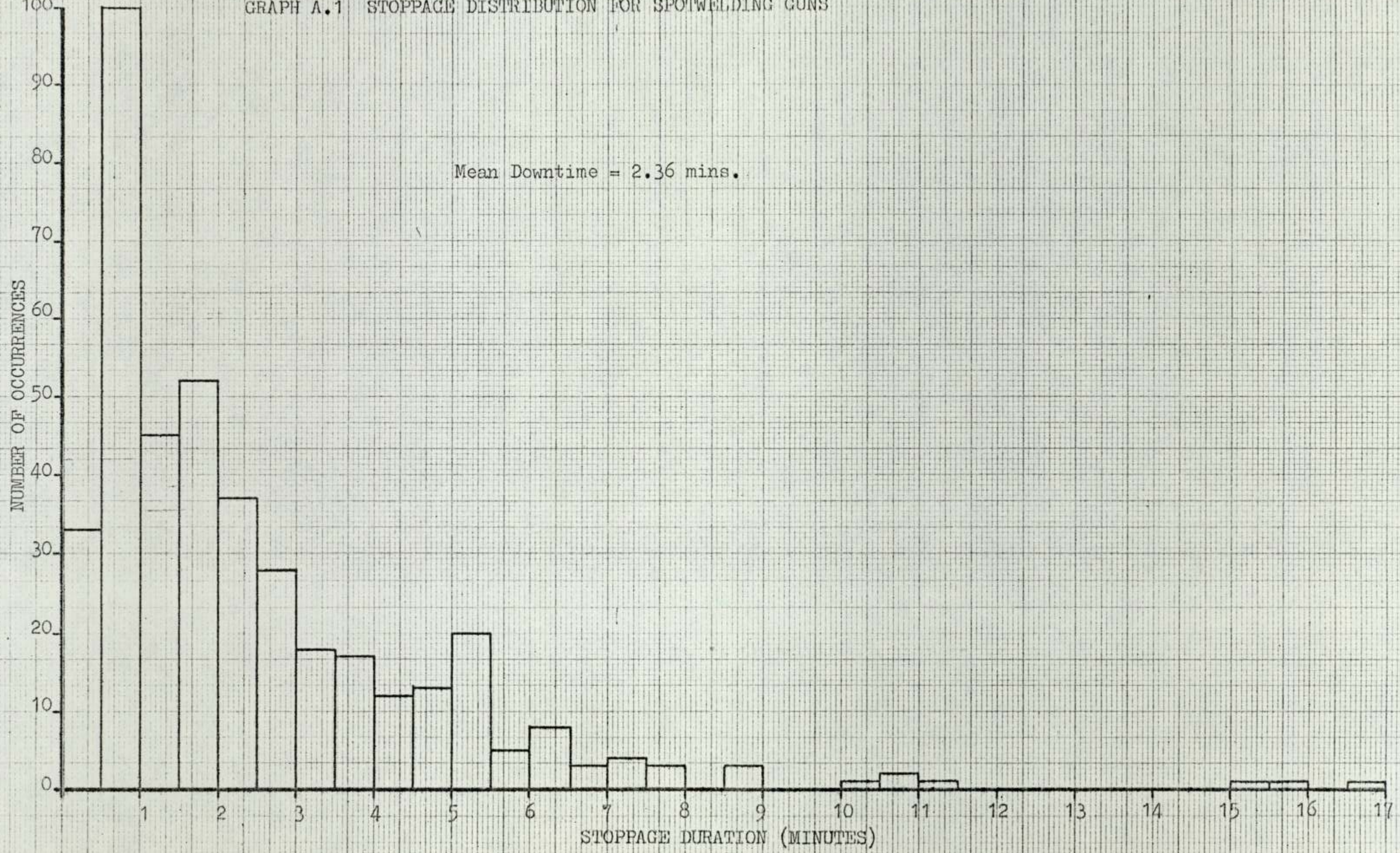
x	0.95	0.96	0.97	0.98	0.99	0.995	0.998	0.999
y	2.65	2.96	3.40	4.14	5.00	6.15	7.50	9.00

A.6.1 Analysis of Spot Welding Set Breakdowns

Mean Stoppage Duration = 2.36 minutes

Interval t (mins)	Frequency f	Relative Frequency $f/\Sigma f$	Cumulative Frequency f_c	$\frac{t_{mean}}{2.36}$
0.0 - 0.49	33	0.0809	0.0809	0.1059
0.5 - 0.99	100	0.2451	0.3260	0.3179
1.0 - 1.49	45	0.1103	0.4363	0.5297
1.5 - 1.99	52	0.1274	0.5637	0.7415
2.0 - 2.49	37	0.0907	0.6544	0.9534
2.5 - 2.99	28	0.0686	0.7230	1.1652
3.0 - 3.49	18	0.0441	0.7671	1.3771
3.5 - 3.99	17	0.0417	0.8088	1.5890
4.0 - 4.49	12	0.0294	0.8382	1.8008
4.5 - 4.99	13	0.0319	0.8701	2.0127
5.0 - 5.49	20	0.0490	0.9191	2.2246
5.5 - 5.99	5	0.0122	0.9313	2.4364
6.0 - 6.49	8	0.0196	0.9509	2.6483
6.5 - 6.99	3	0.0073	0.9582	2.8602
7.0 - 7.49	4	0.0098	0.9680	3.0720
7.5 - 7.99	3	0.0073	0.9753	3.2839
8.0 - 8.49	0	0	0.9753	3.4958
8.5 - 8.99	3	0.0073	0.9826	3.7076
9.0 - 9.49	0	0	0.9826	3.9195
9.5 - 9.99	0	0	0.9826	4.1313
10.0 - 10.49	1	0.0024	0.9850	4.3432
10.5 - 10.99	2	0.0049	0.9899	4.5551
11.0 - 11.49	1	0.0024	0.9923	4.7669
11.5 - 11.99	0	0	0.9923	4.9788
12.0 - 12.49	0	0	0.9923	5.1907
12.5 - 12.99	0	0	0.9923	5.4025
13.0 - 13.49	0	0	0.9923	5.6144
13.5 - 13.99	0	0	0.9923	5.8263
14.0 - 14.49	0	0	0.9923	6.0381
14.5 - 14.99	0	0	0.9923	6.2500
15.0 - 15.49	1	0.0024	0.9947	6.4619
15.5 - 15.99	1	0.0024	0.9971	6.6737
16.0 - 16.49	0	0	0.9971	6.8856
16.5 - 16.99	1	0.0024	0.9995	7.0975
TOTAL	408	0.9995	-	-

GRAPH A.1 STOPPAGE DISTRIBUTION FOR SPOTWELDING GUNS

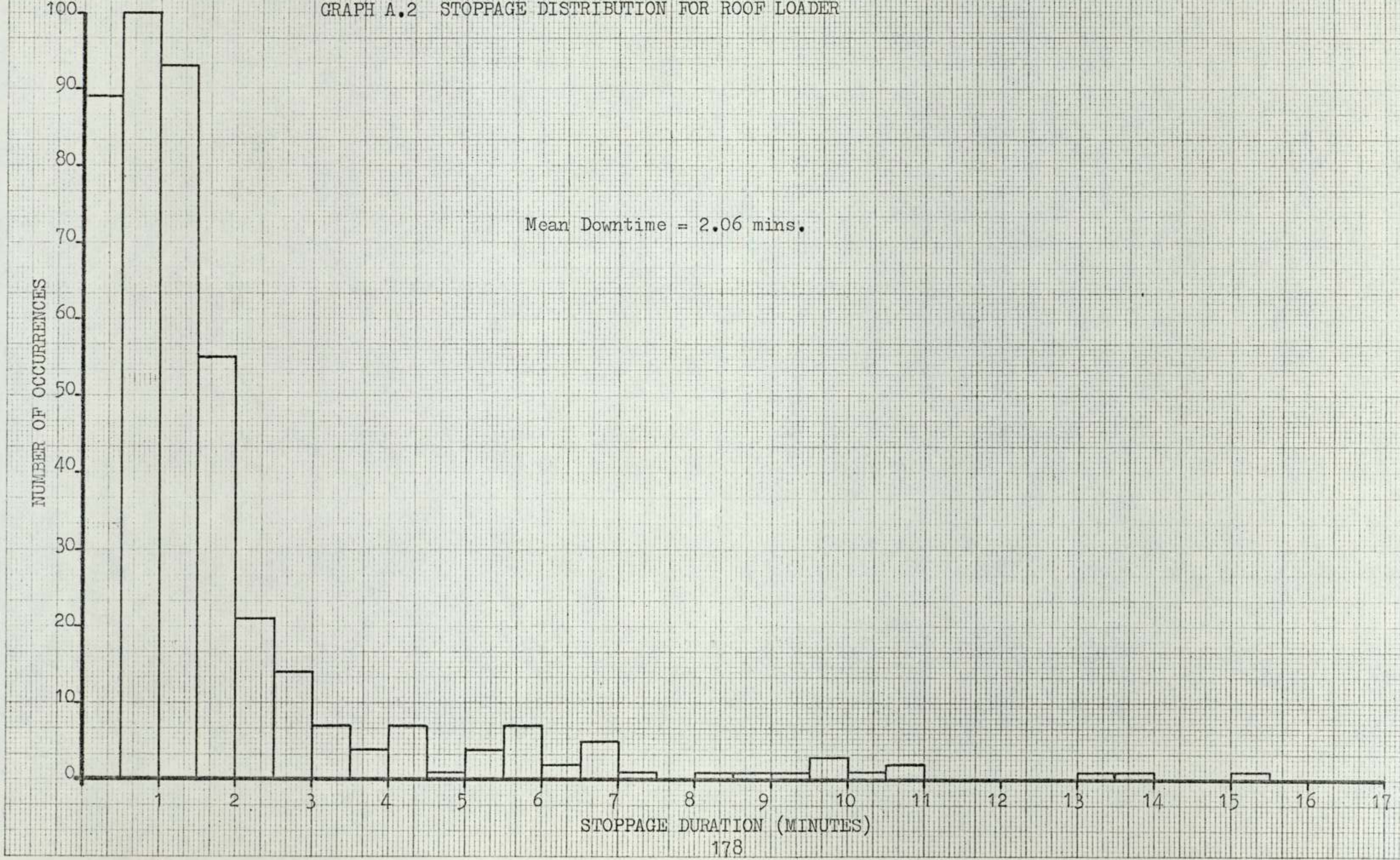

Mean Downtime = 2.36 mins.

A.6.2 Analysis of Roof Loader Breakdowns

Mean Stoppage Duration = 2.06 minutes

Interval t (mins)	Frequency f	Relative Frequency $f/\Sigma f$	Cumulative Frequency fc	$\frac{t_{mean}}{2.06}$
0.0 - 0.49	89	0.2109	0.2109	0.1214
0.5 - 0.99	100	0.2370	0.4479	0.3641
1.0 - 1.49	93	0.2204	0.6683	0.6068
1.5 - 1.99	55	0.1303	0.7986	0.8495
2.0 - 2.49	21	0.0498	0.8484	1.0922
2.5 - 2.99	14	0.0332	0.8816	1.3349
3.0 - 3.49	7	0.0166	0.8982	1.5777
3.5 - 3.99	4	0.0095	0.9077	1.8204
4.0 - 4.49	7	0.0166	0.9243	2.0631
4.5 - 4.99	1	0.0024	0.9267	2.3058
5.0 - 5.49	4	0.0095	0.9362	2.5485
5.5 - 5.99	7	0.0166	0.9528	2.7913
6.0 - 6.49	2	0.0047	0.9575	3.0340
6.5 - 6.99	5	0.0118	0.9693	3.2767
7.0 - 7.49	1	0.0024	0.9717	3.5194
7.5 - 7.99	0	0	0.9717	3.7621
8.0 - 8.49	1	0.0024	0.9741	4.0048
8.5 - 8.99	1	0.0024	0.9765	4.2476
9.0 - 9.49	1	0.0024	0.9789	4.4903
9.5 - 9.99	3	0.0071	0.9860	4.7730
10.0 - 10.49	1	0.0024	0.9884	4.9757
10.5 - 10.99	2	0.0047	0.9931	5.2184
11.0 - 11.49	0	0	0.9931	5.4617
11.5 - 11.99	0	0	0.9931	5.7039
12.0 - 12.49	0	0	0.9931	5.9466
12.5 - 12.99	0	0	0.9931	6.1893
13.0 - 13.49	1	0.0024	0.9955	6.4320
13.5 - 13.99	1	0.0024	0.9979	6.6748
14.0 - 14.49	0	0	0.9979	6.9175
14.5 - 14.99	0	0	0.9979	7.1602
15.0 - 15.49	1	0.0024	1.0003	7.4029
TOTAL	422	1.0003	-	-

GRAPH A.2 STOPPAGE DISTRIBUTION FOR ROOF LOADER



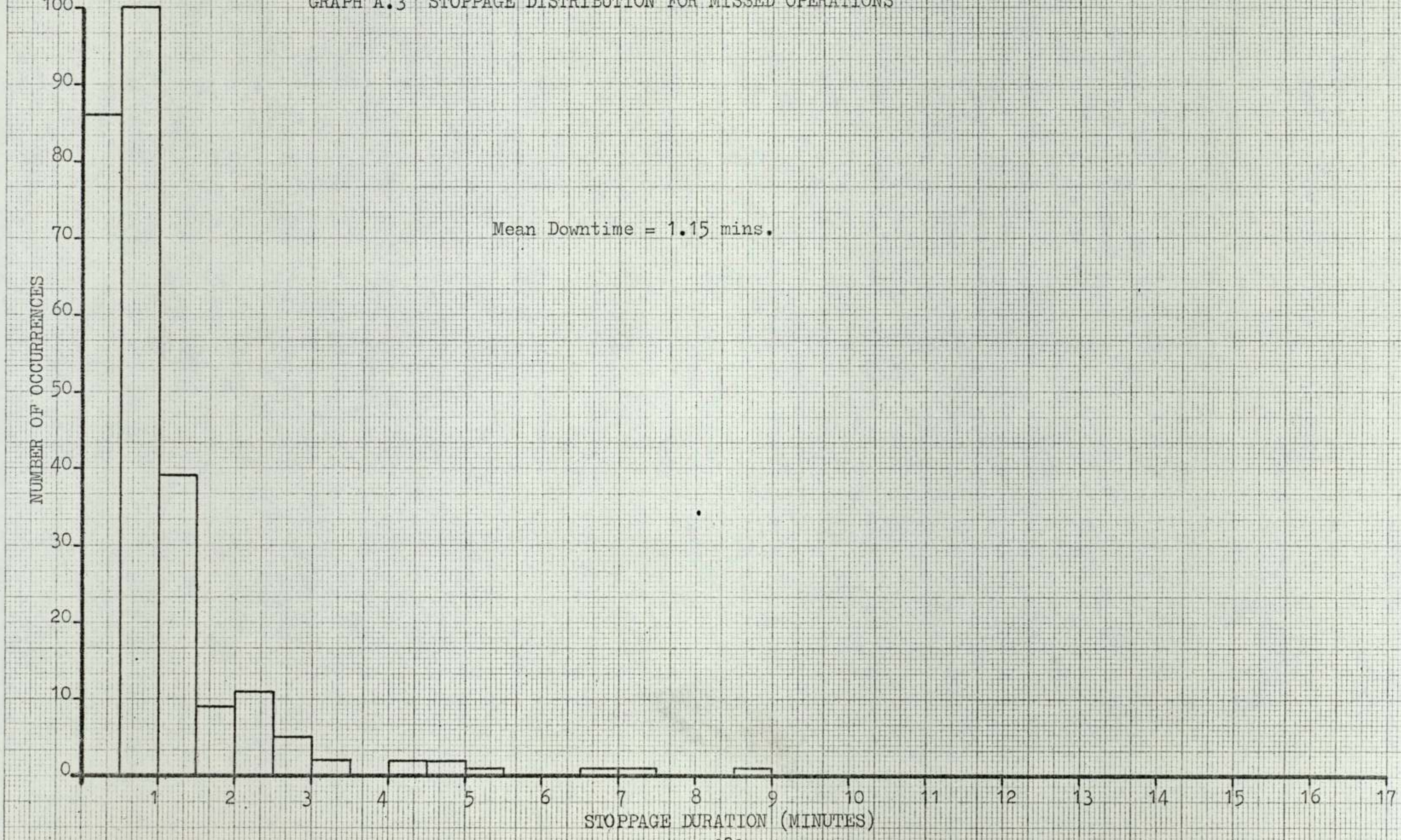
Mean Downtime = 2.06 mins.

A.6.3 Analysis of Stoppages due to Missed Operations

Mean Stoppage Duration = 1.15 minutes

Interval t (mins)	Frequency f	Relative Frequency $f/\Sigma f$	Cumulative Frequency fc	$\frac{t_{mean}}{1.15}$
0.0 - 0.49	86	0.3308	0.3308	0.2174
0.5 - 0.99	100	0.3846	0.7154	0.6522
1.0 - 1.49	39	0.1500	0.8654	1.0870
1.5 - 1.99	9	0.0346	0.9000	1.5217
2.0 - 2.49	11	0.0423	0.9423	1.9565
2.5 - 2.99	5	0.0192	0.9615	2.3913
3.0 - 3.49	2	0.0077	0.9692	2.8261
3.5 - 3.99	0	0	0.9692	3.2609
4.0 - 4.49	2	0.0077	0.9767	3.6956
4.5 - 4.99	2	0.0077	0.9846	4.1304
5.0 - 5.49	1	0.0038	0.9884	4.5652
5.5 - 5.99	0	0	0.9884	5.0000
6.0 - 6.49	0	0	0.9884	5.4348
6.5 - 6.99	1	0.0038	0.9922	5.8696
7.0 - 7.49	1	0.0038	0.9960	6.3043
7.5 - 7.99	0	0	0.9960	6.7391
8.0 - 8.49	0	0	0.9960	7.1739
8.5 - 8.99	1	0.0038	0.9998	7.6087
TOTAL	260	0.9998	-	-

GRAPH A.3 STOPPAGE DISTRIBUTION FOR MISSED OPERATIONS



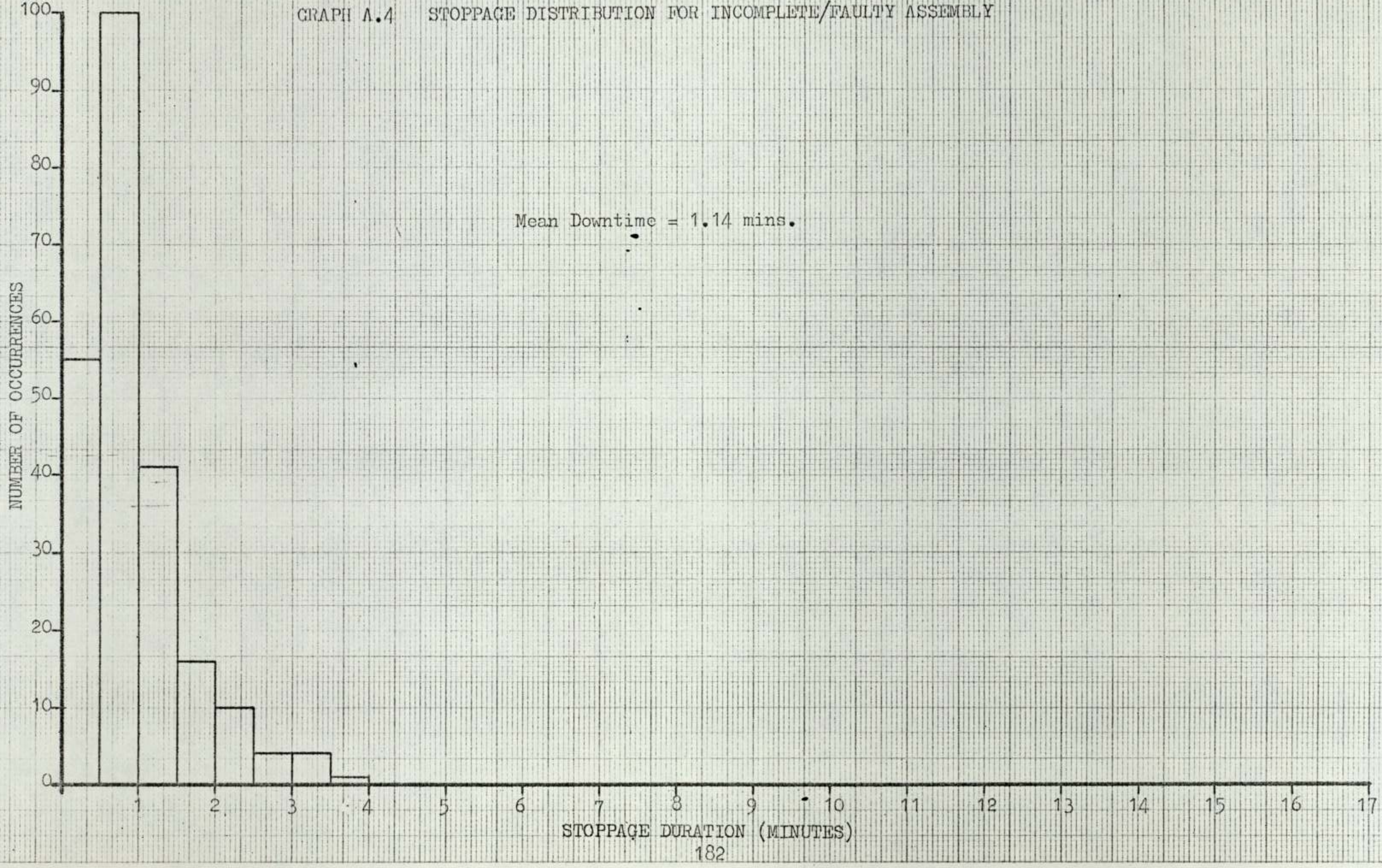
Mean Downtime = 1.15 mins.

A.6.4 Analysis of Stoppages due to Incomplete/Faulty Assemblies

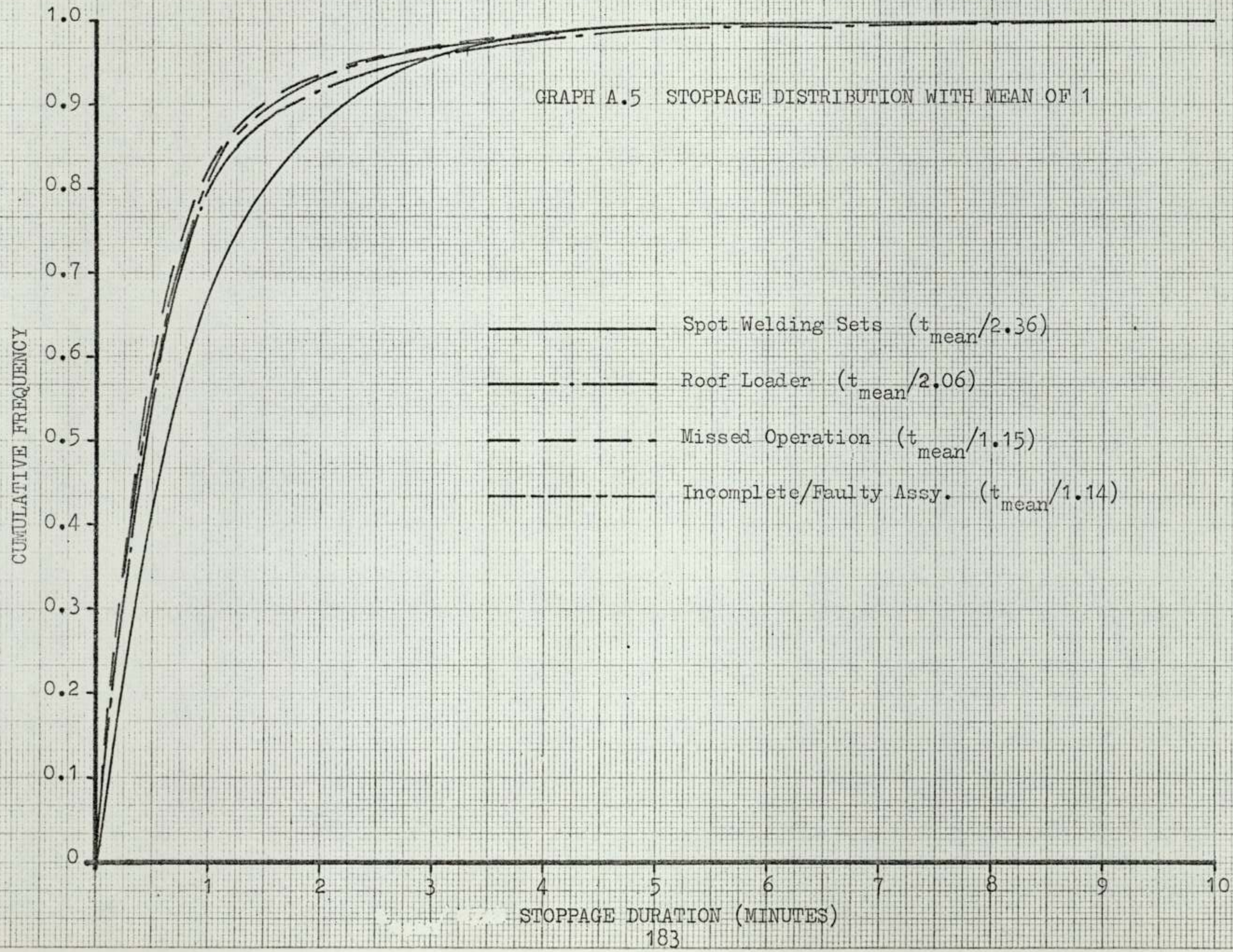
Mean Stoppage Duration = 1.14 minutes

Interval t (mins)	Frequency f	Relative Frequency $f/\Sigma f$	Cumulative Frequency fc	$\frac{t_{mean}}{1.14}$
0.0 - 0.49	55	0.2381	0.2381	0.2193
0.5 - 0.99	100	0.4329	0.6710	0.6579
1.0 - 1.49	41	0.1775	0.8485	1.0965
1.5 - 1.99	16	0.0693	0.9178	1.5351
2.0 - 2.49	10	0.0433	0.9611	1.9737
2.5 - 2.99	4	0.0173	0.9784	2.4123
3.0 - 3.49	4	0.0173	0.9957	2.8509
3.5.- 3.99	1	0.0043	1.0000	3.2895
TOTAL	231	1.0000	-	-

GRAPH A.4 STOPPAGE DISTRIBUTION FOR INCOMPLETE/FAULTY ASSEMBLY



Mean Downtime = 1.14 mins.



GRAPH A.5 STOPPAGE DISTRIBUTION WITH MEAN OF 1

A.7 Operator Work Rate Distribution

A.7.1 The Normal Distribution

x	.0013	.0016	.0019	.0023	.0026	.0030	.0035	.0040	.0047	.0054	.0062
y	-300	-295	-290	-285	-280	-275	-270	-265	-260	-255	-250
x	.0071	.0082	.0094	.0107	.0122	.0139	.0162	.0179	.0202	.0228	.0256
y	-245	-240	-235	-230	-225	-220	-215	-210	-205	-200	-195
x	.0287	.0322	.0359	.0401	.0446	.0495	.0548	.0606	.0668	.0749	.0808
y	-190	-185	-180	-175	-170	-165	-160	-155	-150	-145	-140
x	.0885	.0968	.1056	.1151	.1251	.1357	.1469	.1587	.1711	.1841	.1977
y	-135	-130	-125	-120	-115	-110	-105	-100	-95	-90	-85
x	.2119	.2266	.2420	.2578	.2743	.2912	.3085	.3264	.3446	.3632	.3821
y	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30
x	.4013	.4207	.4404	.4602	.4801	.5000	.5200	.5398	.5596	.5793	.5987
y	-25	-20	-15	-10	-5	0	5	10	15	20	25
x	.6179	.6368	.6554	.6736	.6915	.7088	.7257	.7422	.7580	.7734	.7881
y	30	35	40	45	50	55	60	65	70	75	80
x	.8023	.8159	.8289	.8413	.8531	.8643	.8729	.8849	.8944	.9032	.9115
y	85	90	95	100	105	110	115	120	125	130	135
x	.9192	.9265	.9332	.9394	.9452	.9505	.9554	.9599	.9641	.9678	.9713
y	140	145	150	155	160	165	170	175	180	185	190
x	.9744	.9772	.9798	.9821	.9842	.9861	.9878	.9883	.9906	.9918	.9929
y	195	200	205	210	215	220	225	230	235	240	245
x	.9938	.9946	.9953	.9960	.9965	.9970	.9974	.9977	.9981	.9984	.9987
y	250	255	260	265	270	275	280	285	290	295	300

The normal distribution tabulated on the previous page is presented in the form used to simulate operator work rate variability during the simulation exercises. The x-axis ranges from 0 to 1 to facilitate sampling using random numbers and the y-axis, representing time units in one hundredths of a minute, has a mean value of 0 and a spread of + and - 3 standard deviations. One standard deviation is equal to 100 hundredths of a minute or 1 minute.

The normal distribution in this form can be easily adapted to simulate any standard deviation with any mean cycle time by multiplying the sampled y-value by the appropriate standard deviation and adding to this the mean cycle time.

i.e. $$t = \bar{t} + s.(FN1)$$

where t = instantaneous cycle time

$\bar{t}$ = mean cycle time

s = standard deviation

$FN1$ = instantaneous y-value sampled from the distribution

A.7.2 Coefficient of Variation of Operator's Work Times

$$\text{Coefficient of Variation} = \frac{\text{Standard Deviation}}{\text{Mean Cycle Time}}$$

APPENDIX B

COMPUTER SIMULATION

B.1 Simulation Program Listings and Flow Diagrams

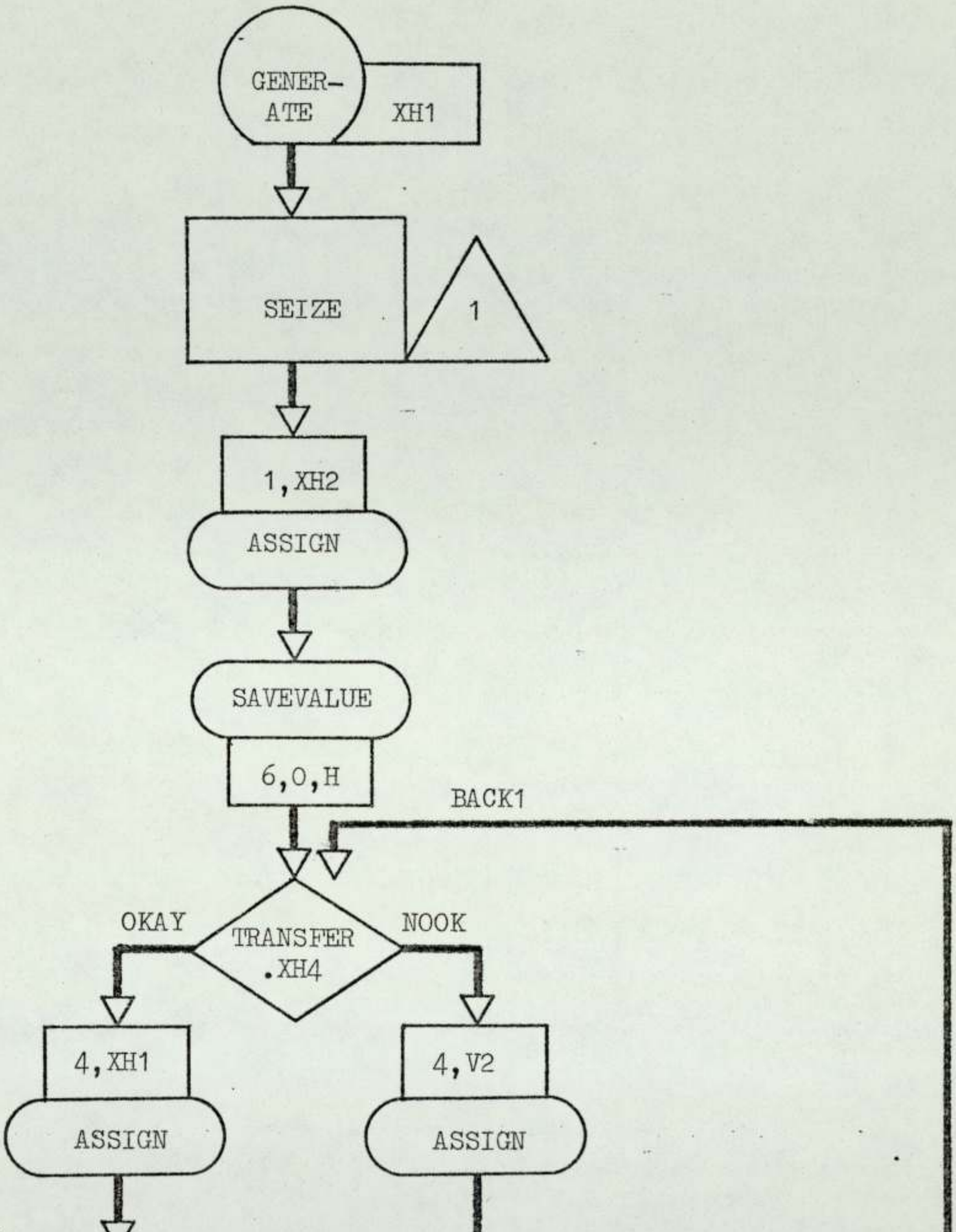
B.1.1 Area A - Tied without Interstation Storage Capacity

```
      GENERATE   XH1
      SEIZE      1
      ASSIGN     1,XH2
      SAVEVALUE  6,0,H
BACK1 TRANSFER   .XH4,OKAY,NOOK
OKAY  ASSIGN     4,XH1
      TRANSFER   ,FOR1
NOOK  ASSIGN     4,V2
FOR1  TEST G     P4,XH6,LOOP
      SAVEVALUE  6,P4,H
LOOP  LOOP       1,BACK1
      ADVANCE    XH6
      RELEASE    1
      TERMINATE
```

B.1.2 Area A - Untied without Interstation Storage Capacity

```
      GENERATE   XH1
      ASSIGN     5,1
      SEIZE      P5
      TRANSFER   .XH4,OKAY1,NOOK1
OKAY1 ADVANCE    XH1
      TRANSFER   ,FOR1
NOOK1 ADVANCE    V2
FOR1  ASSIGN     1,XH9
BACK1 ASSIGN     5+,1
      SEIZE      P5
      RELEASE    V4
      TRANSFER   .XH4,OKAY2,NOOK2
OKAY2 ADVANCE    XH1
      TRANSFER   ,FOR2
NOOK2 ADVANCE    V2
FOR2  LOOP       1,BACK1
      RELEASE    P5
      TERMINATE
```

B.1.1 Flow Diagram



cont......

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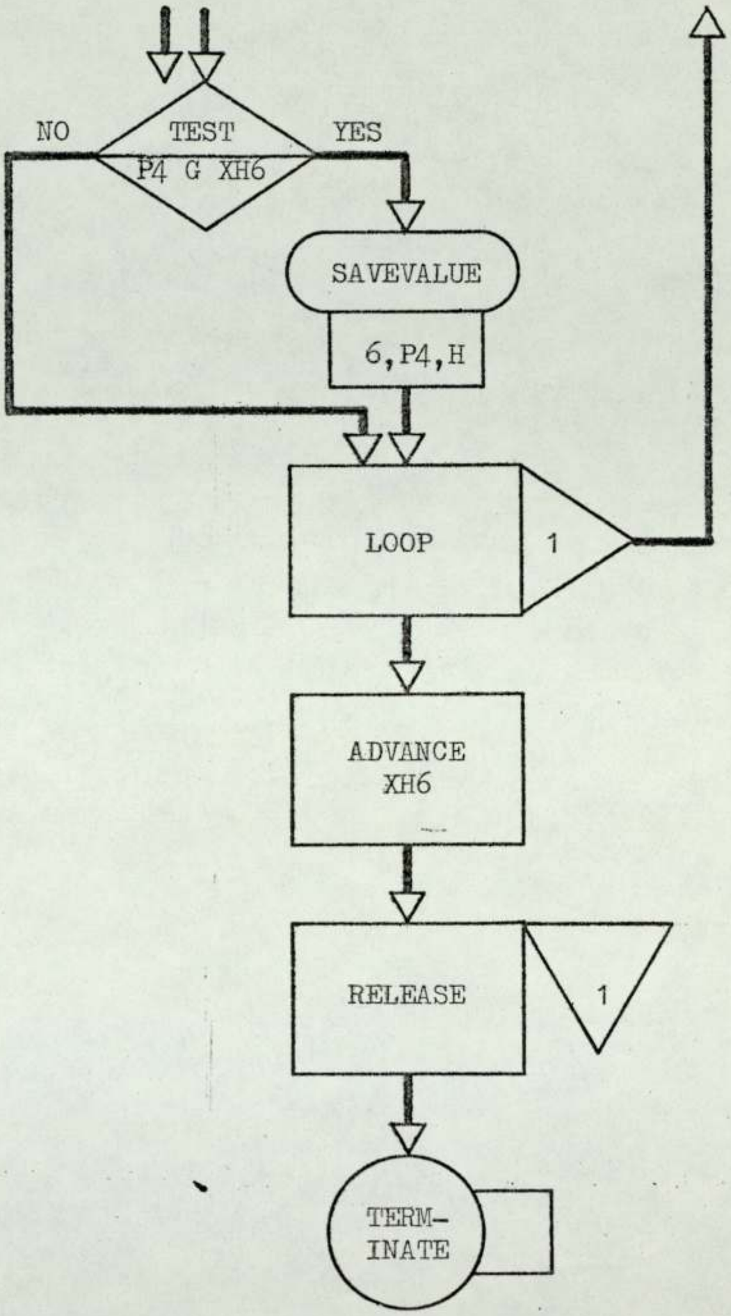
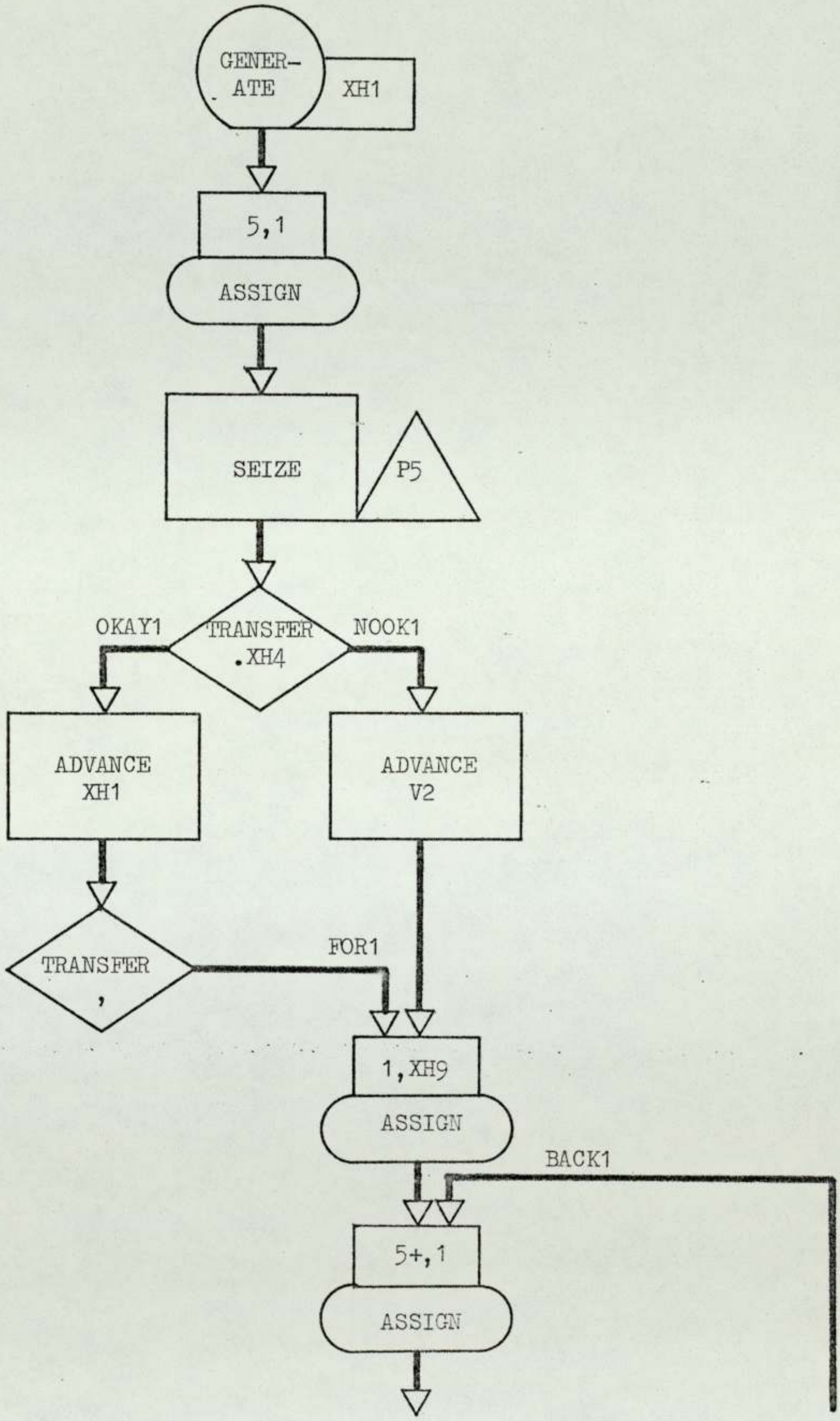
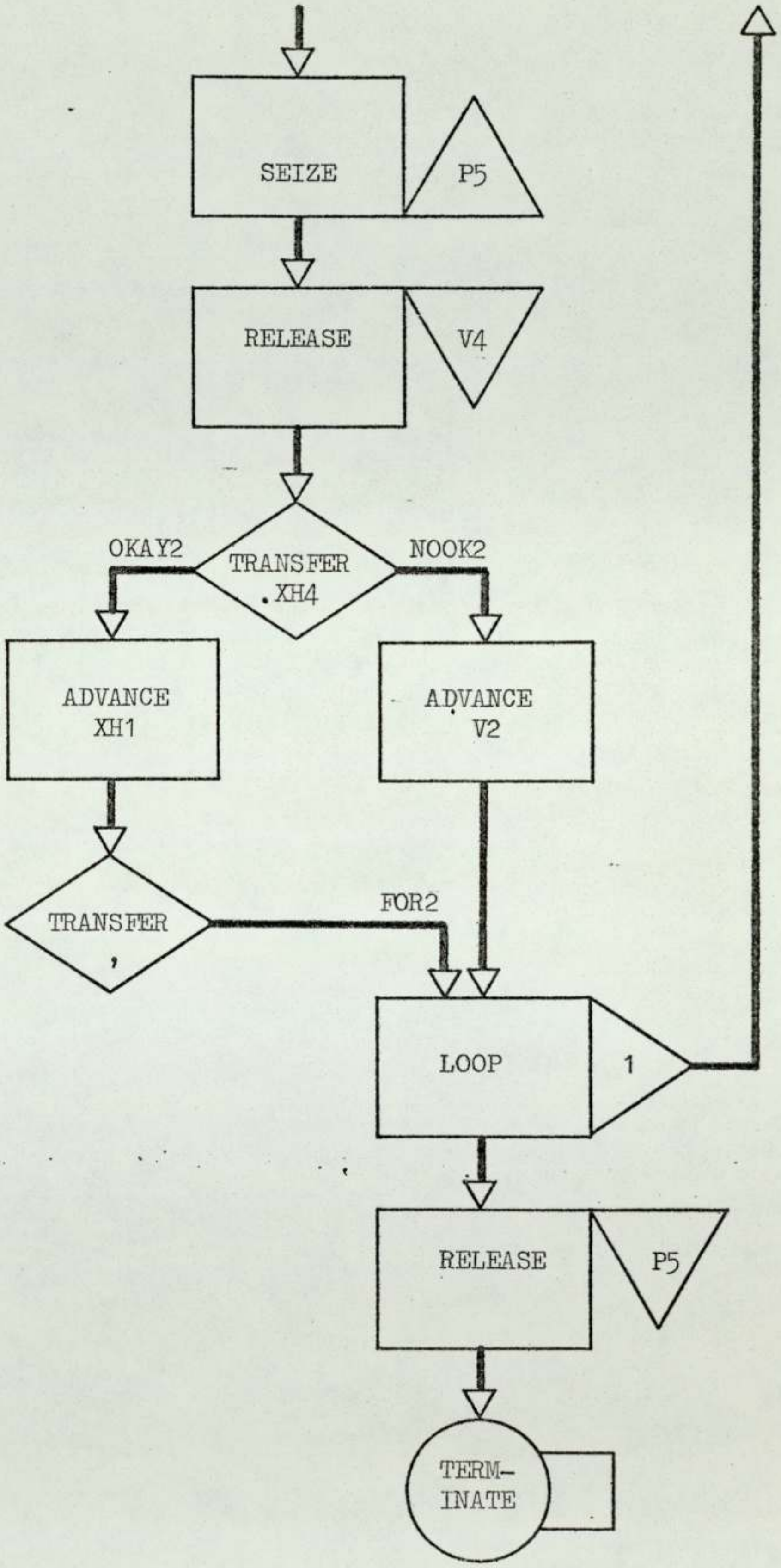

NO
TEST
YES
P4 G XH6
SAVEVALUE
6,P4,H
LOOP
1
ADVANCE
XH6
RELEASE
1
TERM-
INATE

B.1.2 Flow Diagram



cont......

......


SEIZE
P5
RELEASE
V4
OKAY2
TRANSFER
.XH4
NOOK2
ADVANCE
XH1
ADVANCE
V2
TRANSFER
,
FOR2
LOOP
1
RELEASE
P5
TERM-
INATE

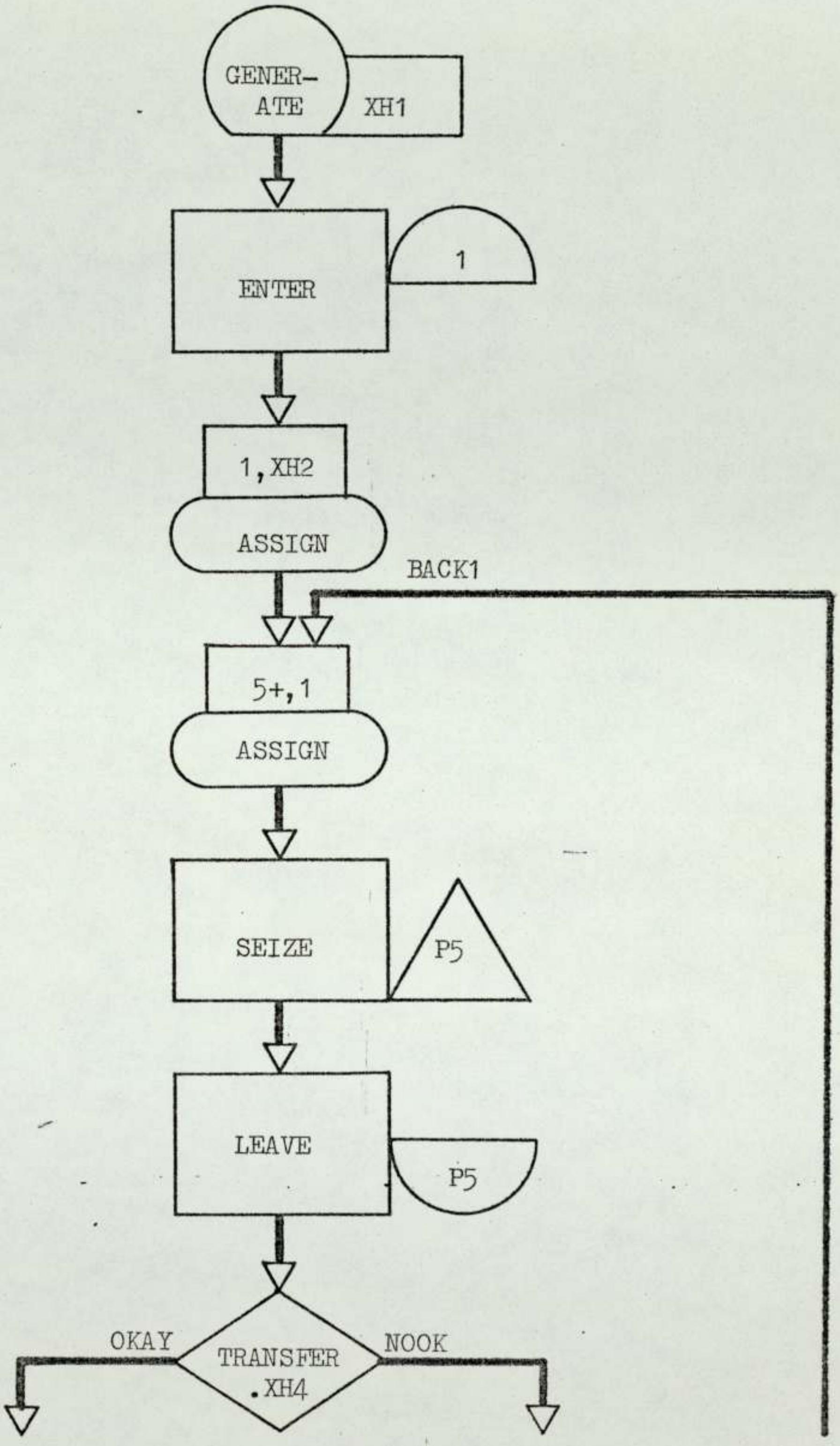
B.1.3 Area A - Untied with Interstation Storage Capacity

```
      GENERATE   XH1
      ENTER      1
      ASSIGN     1,XH2
BACK1 ASSIGN     5+,1
      SEIZE      P5
      LEAVE      P5
      TRANSFER   .XH4,OKAY,NOOK
OKAY  ADVANCE    XH1
      TRANSFER   ,FOR1
NOOK  ADVANCE    V2
FOR1  ENTER      V3
      RELEASE    P5
      LOOP       1,BACK1
      LEAVE      V3
      TERMINATE
```

B.1.4 Area B - Tied without Interstation Storage Capacity

```
      GENERATE   XH1
      SEIZE      1
      ASSIGN     1,XH8
      SAVEVALUE  7,0,H
BACK1 ASSIGN     4,V1
      TEST G     P4,XH7,FOR1
      SAVEVALUE  7,P4,H
FOR1  LOOP       1,BACK1
      ADVANCE    XH7
      RELEASE    1
      TERMINATE
```

B.1.3 Flow Diagram



cont......

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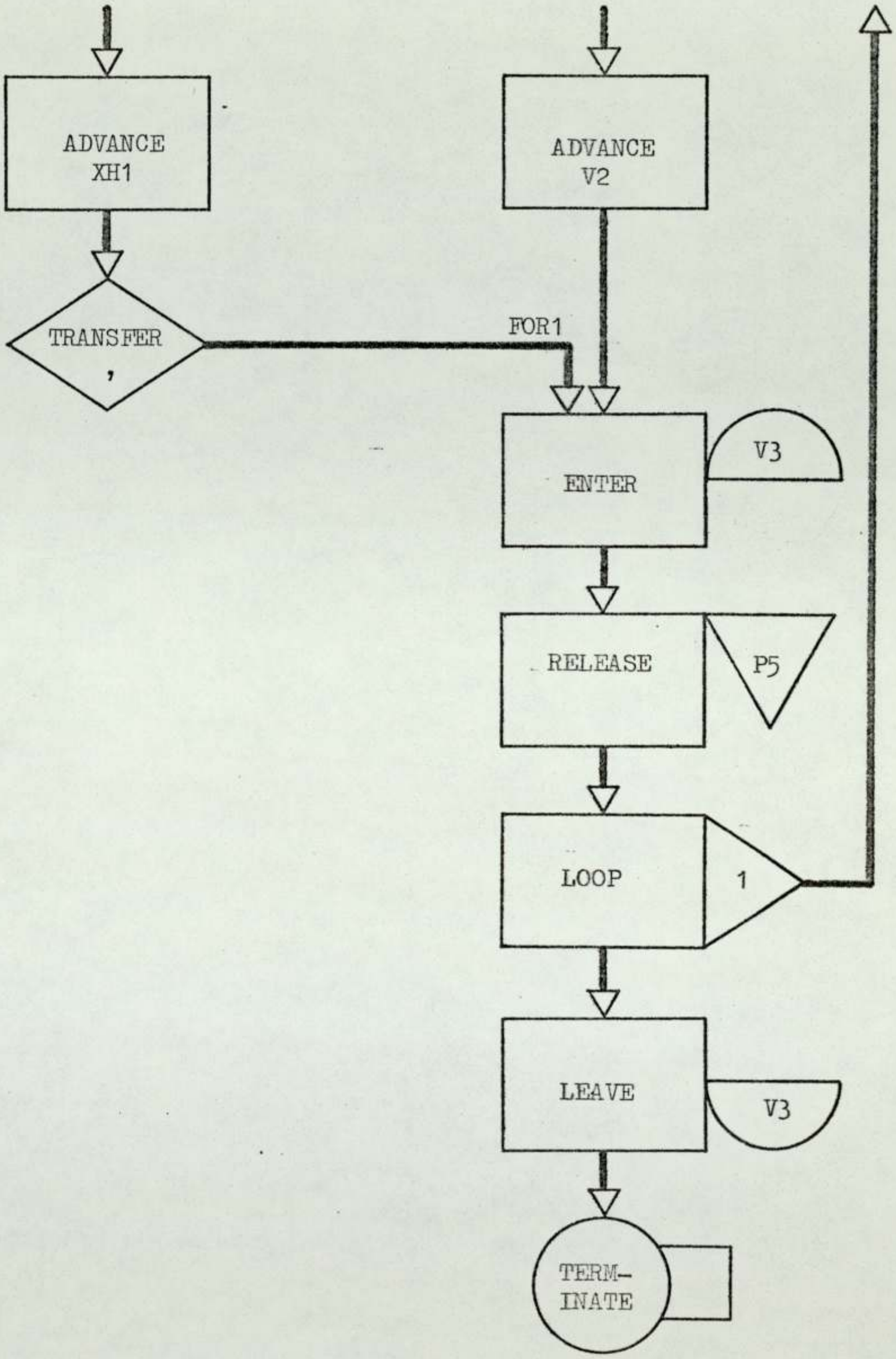
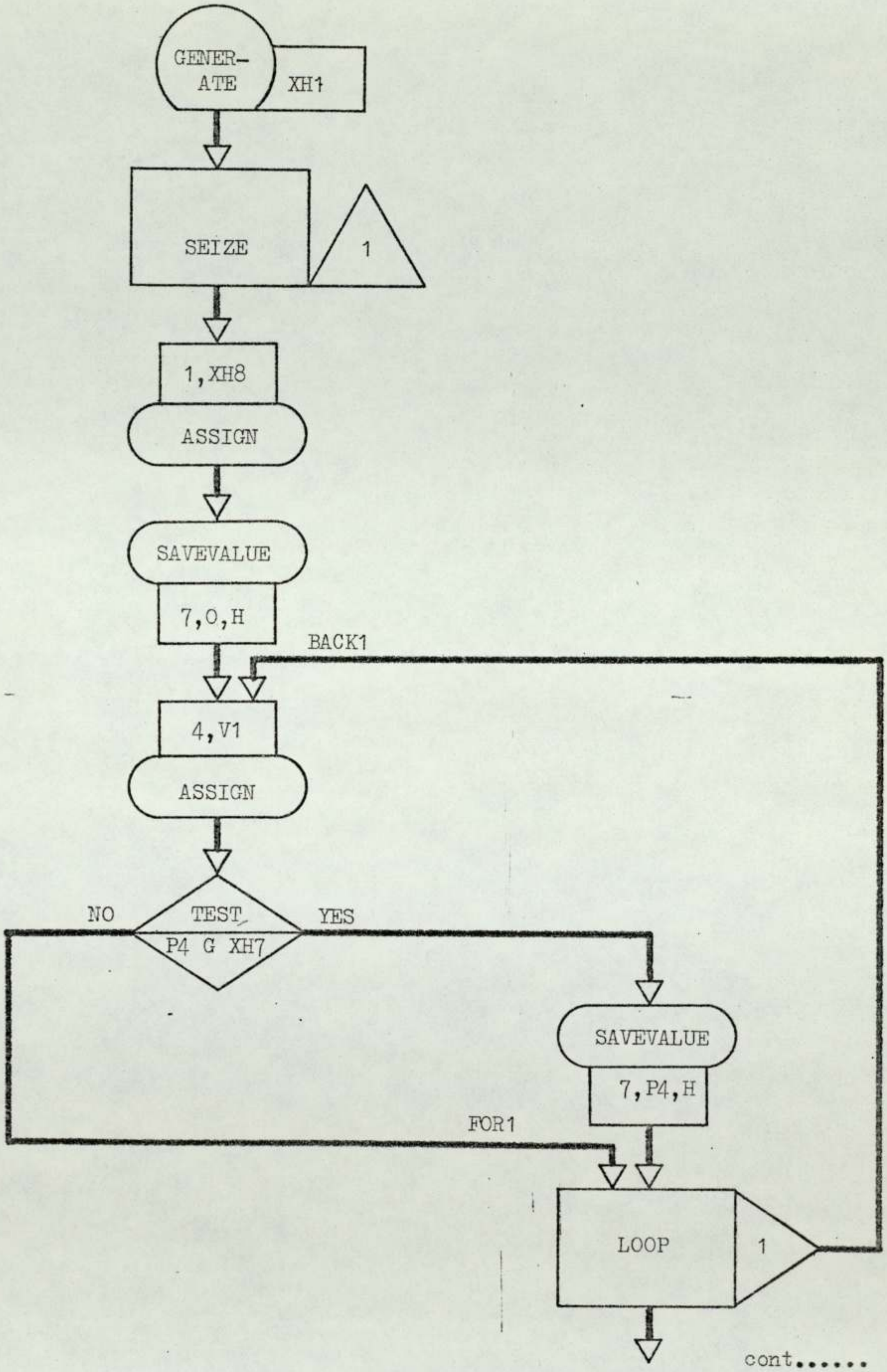

ADVANCE
XH1
TRANSFER
,
FOR1
ADVANCE
V2
ENTER
V3
RELEASE
P5
LOOP
1
LEAVE
V3
TERM-
INATE

B.1.4 Flow Diagram



cont......

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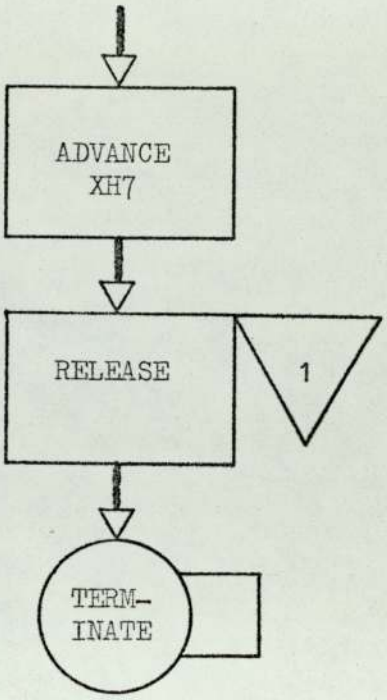

ADVANCE
XH7
RELEASE
1
TERM-
INATE

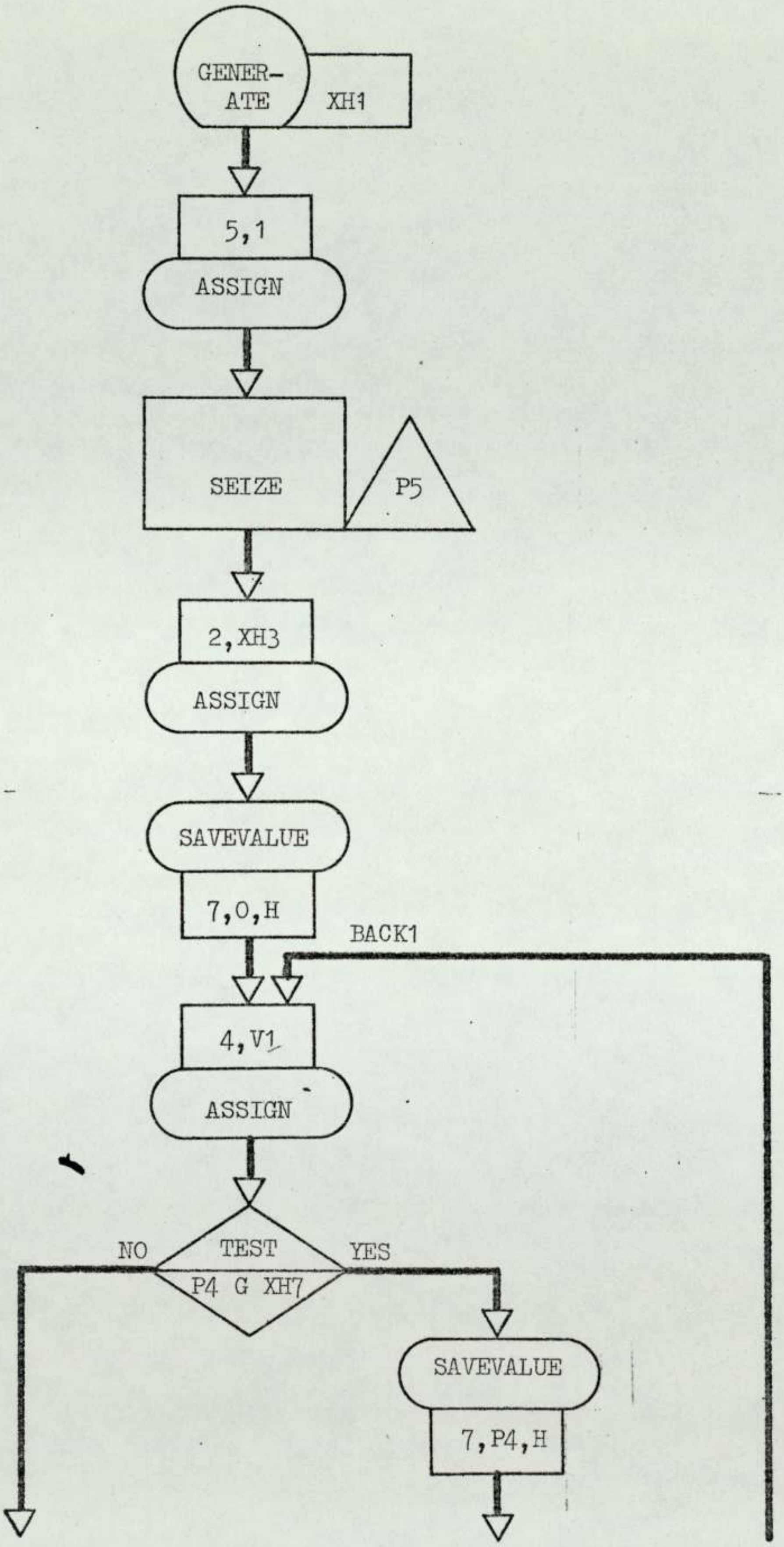
B.1.5 Area B - Untied without Interstation Storage Capacity

```
      GENERATE   XH1
      ASSIGN     5,1
      SEIZE      P5
      ASSIGN     2,XH3
      SAVEVALUE  7,0,H
BACK1 ASSIGN     4,V1
      TEST G     P4,XH7,FOR1
      SAVEVALUE  7,P4,H
FOR1  LOOP       2,BACK1
      ADVANCE    XH7
      ASSIGN     1,XH9
BACK2 ASSIGN     5+,1
      SEIZE      P5
      RELEASE    V4
      ASSIGN     2,XH3
      SAVEVALUE  7,0,H
BACK3 ASSIGN     4,V1
      TEST G     P4,XH7,FOR2
      SAVEVALUE  7,P4,H
FOR2  LOOP       2,BACK3
      ADVANCE    XH7
      LOOP       1,BACK2
      RELEASE    P5
      TERMINATE
```

B.1.6 Area B - Untied with Interstation Storage Capacity

```
      GENERATE   XH1
      ENTER      1
      ASSIGN     1,XH2
BACK1 ASSIGN     5+,1
      ASSIGN     2,XH3
      SEIZE      P5
      LEAVE      P5
      SAVEVALUE  7,0,H
BACK2 ASSIGN     4,V1
      TEST G     P4,XH7,FOR1
      SAVEVALUE  7,P4,H
FOR1  LOOP       2,BACK2
      ADVANCE    XH7
      ENTER      V3
      RELEASE    P5
      LOOP       1,BACK1
      LEAVE      V3
      TERMINATE
```

B.1.5 Flow Diagram



cont......

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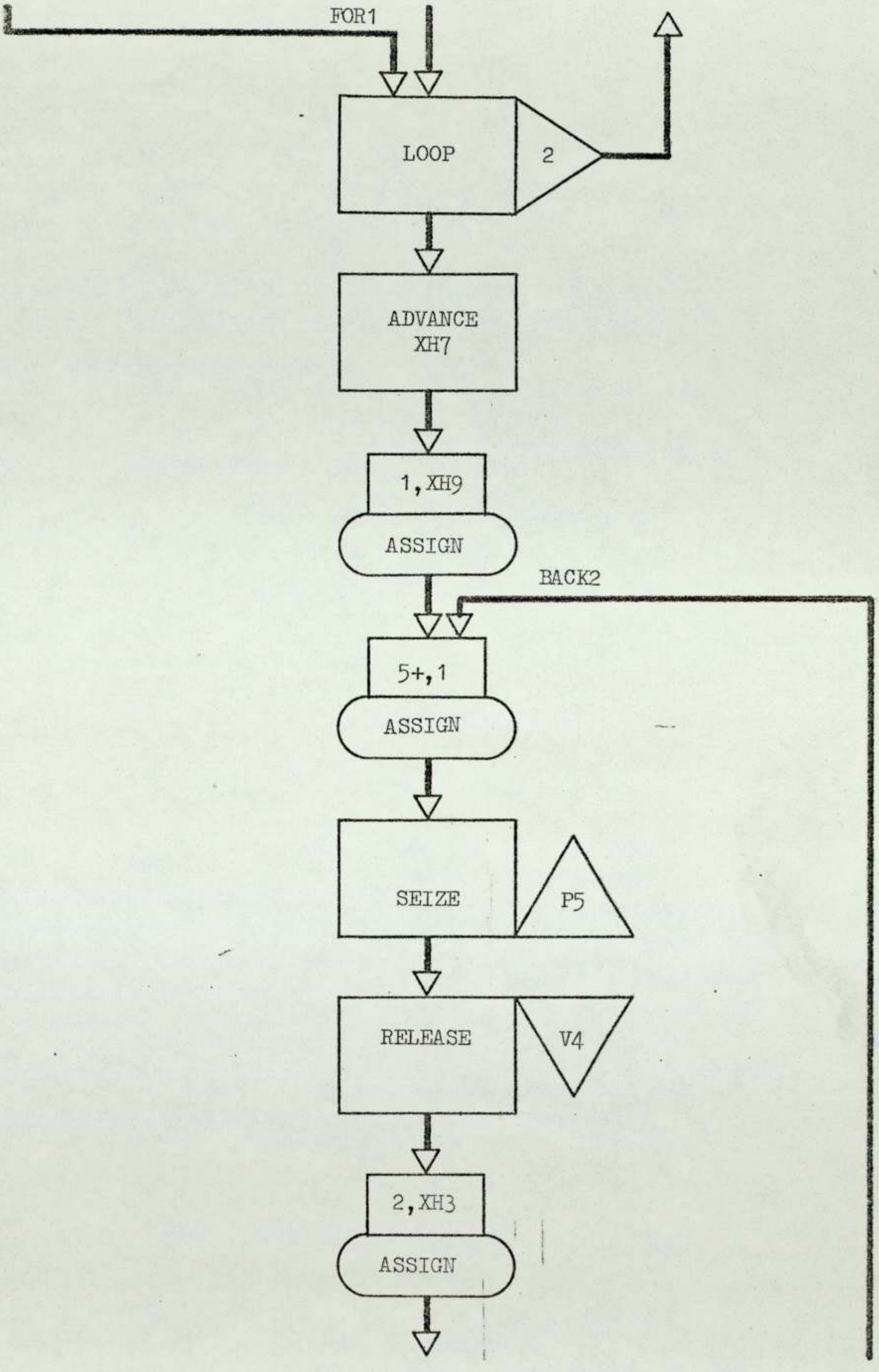
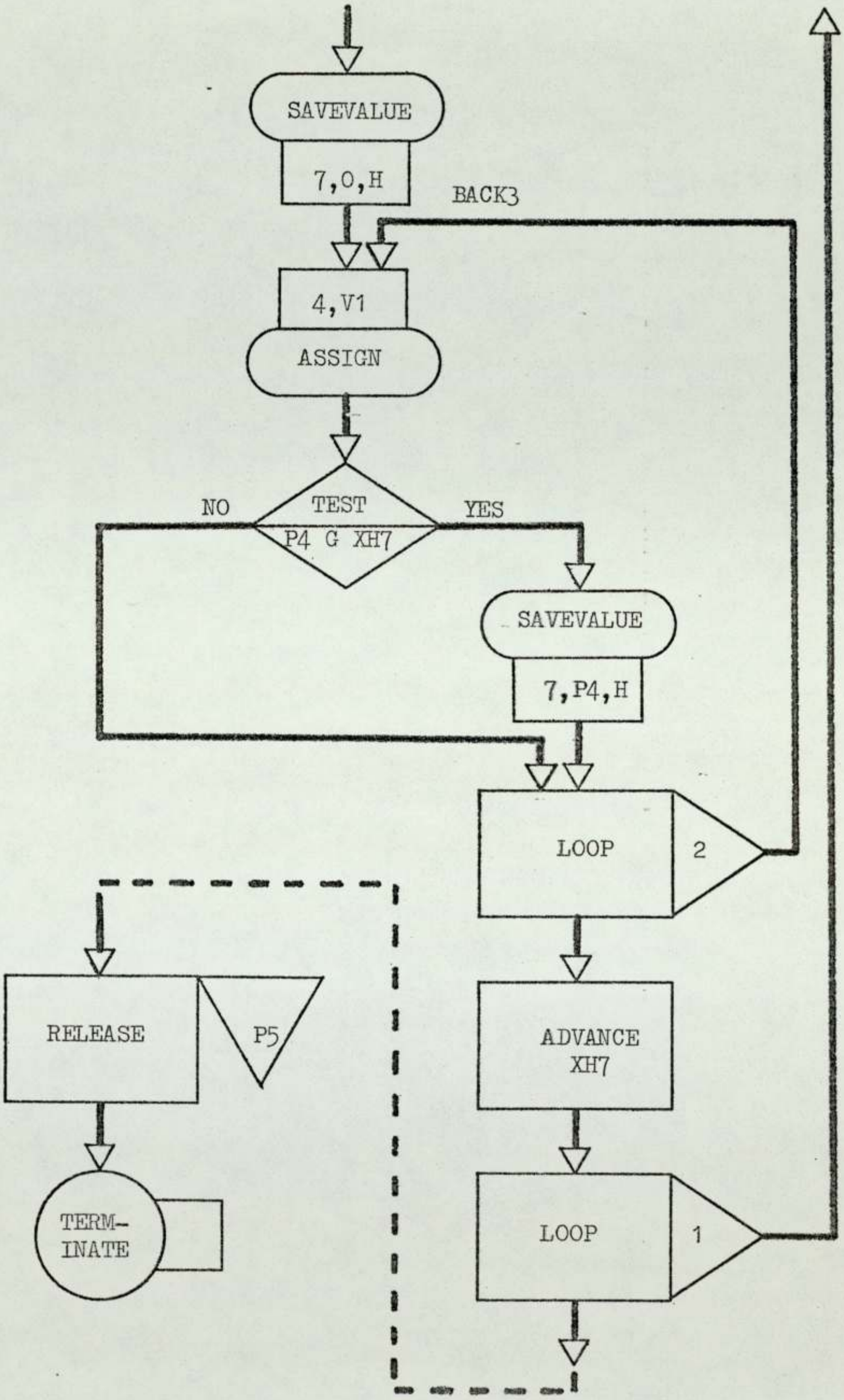
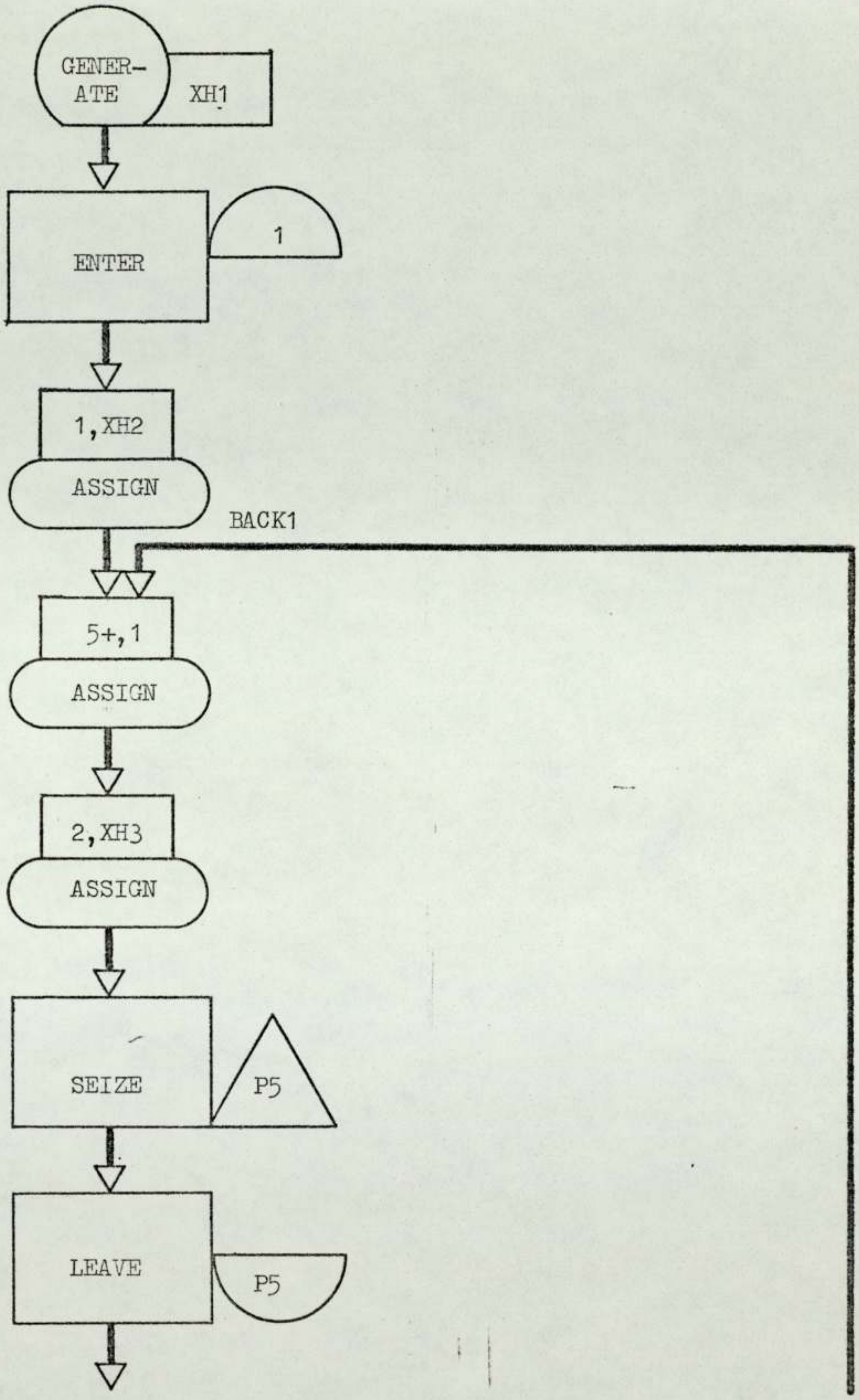

FOR1
LOOP
2
ADVANCE
XH7
1, XH9
ASSIGN
BACK2
5+, 1
ASSIGN
SEIZE
P5
RELEASE
V4
2, XH3
ASSIGN

cont......

......


SAVEVALUE
7,0,H
BACK3
4,V1
ASSIGN
NO
TEST
P4 G XH7
YES
SAVEVALUE
7,P4,H
LOOP
2
RELEASE
P5
ADVANCE
XH7
TERM-
INATE
LOOP
1

B.1.6 Flow Diagram



cont......

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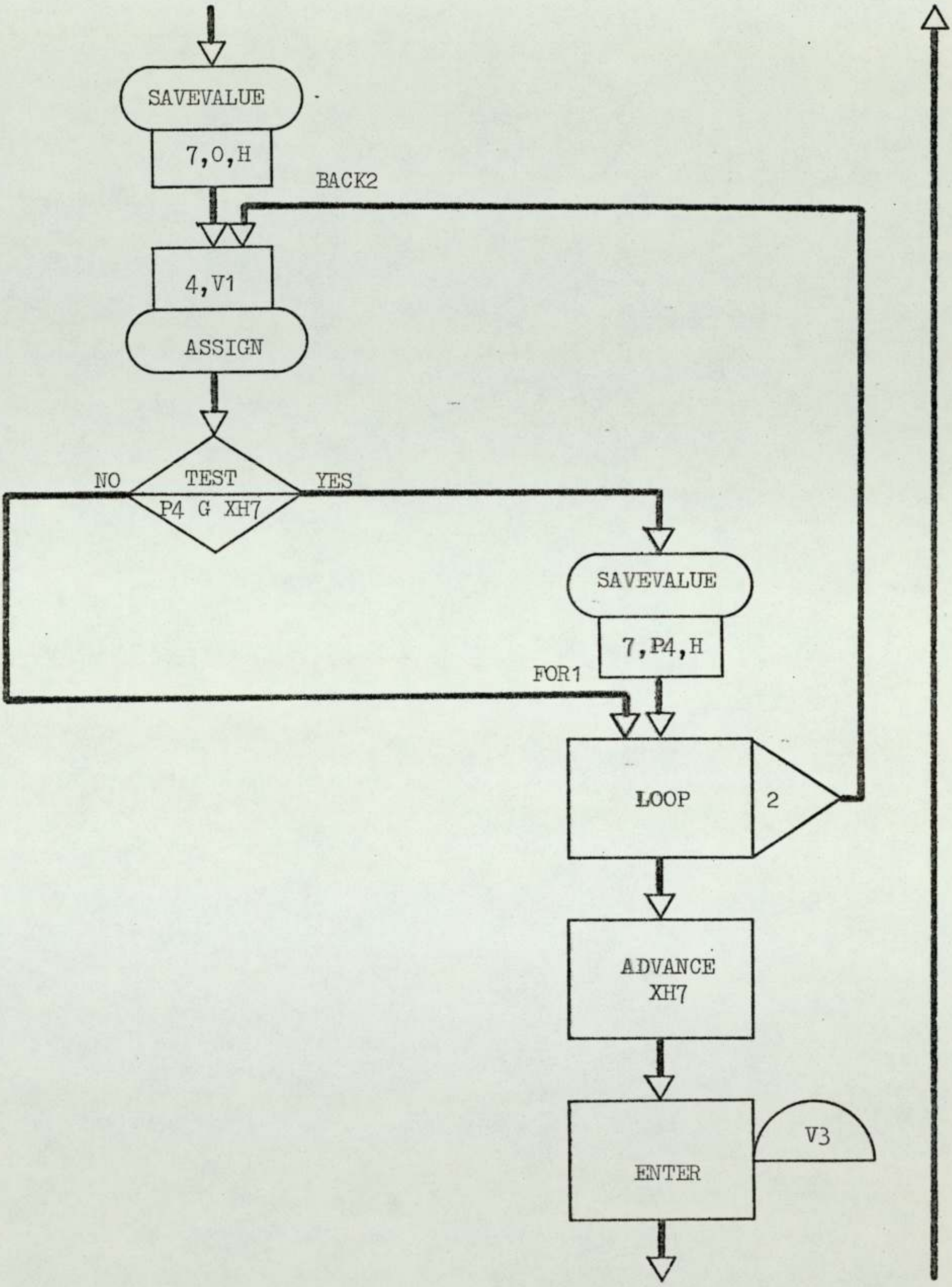
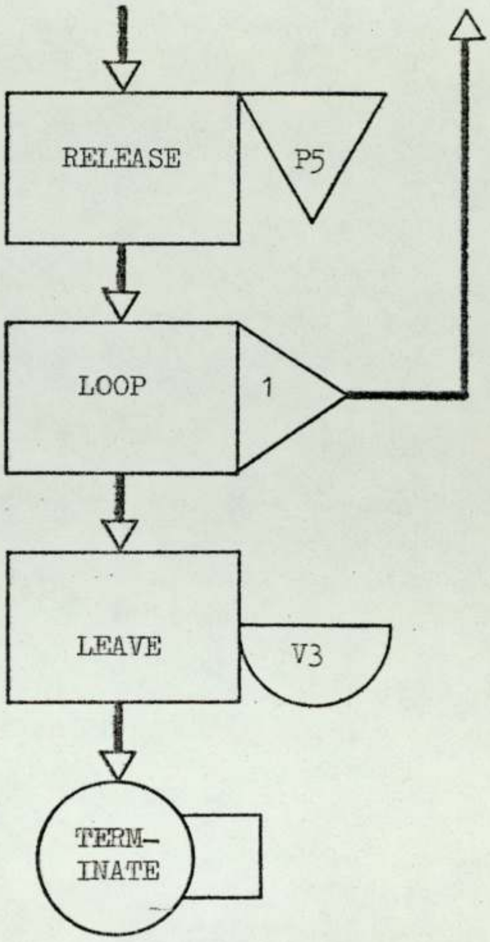

SAVEVALUE
7,0,H
BACK2
4,V1
ASSIGN
NO
TEST
P4 G XH7
YES
SAVEVALUE
7,P4,H
FOR1
LOOP
2
ADVANCE
XH7
ENTER
V3

cont……

......


RELEASE
P5
LOOP
1
LEAVE
V3
TERM-
INATE

B.2 Register of the Simulation Entities Used

B.2.1 Halfword Savevalues

Re-allocated Value = 10

NUMBER	USE IN THE MODEL
XH1	Mean Cycle Time
XH2	Number of stations
XH3	Number of operators per station
XH4	Stoppage probability in parts per 1,000
XH5	Mean stoppage duration
XH6	Cycle time plus stoppage time
XH7	Operator cycle time
XH8	Total number of operators
XH9	Number of stations minus one

B.2.2 Functions

Re-allocated Value = 5

NUMBER	USE IN THE MODEL
FN1	Operator's work rate distribution (Normal)
FN2	Downtime distribution (Negative exponential)

B.2.3 Variables

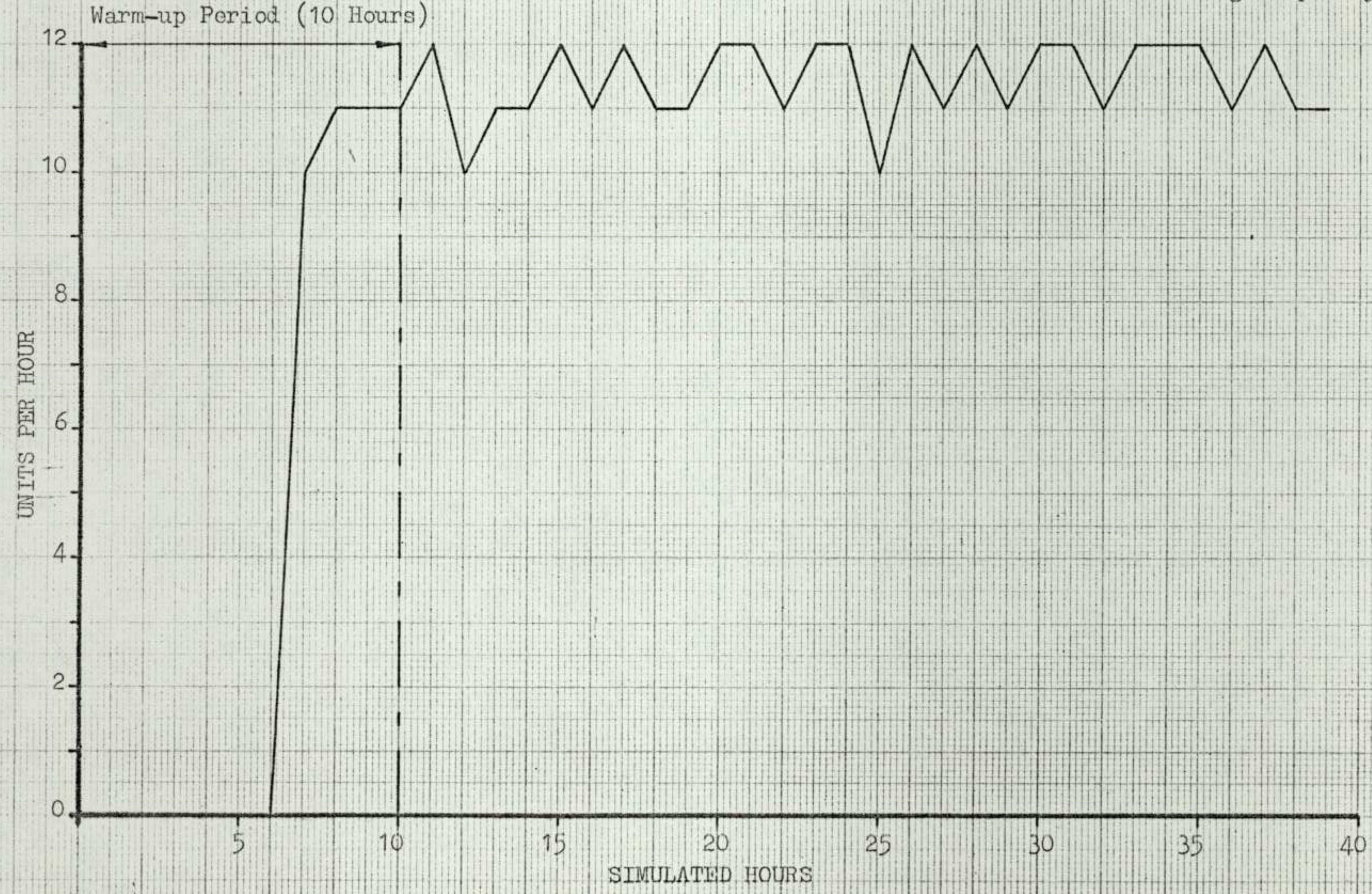
Re-allocated Value = 5

NUMBER	USE IN THE MODEL
V1	XH1 + (FN1)* (Coefficient of Variation)* XH1 Calculates operator's cycle time
V2	XH1 + FN2* XH5 Calculates cycle time + stoppage time
V3	P5 + 1 Calculates storage number
V4	P5 - 1 Calculates station number

B.3 WARM-UP TESTING

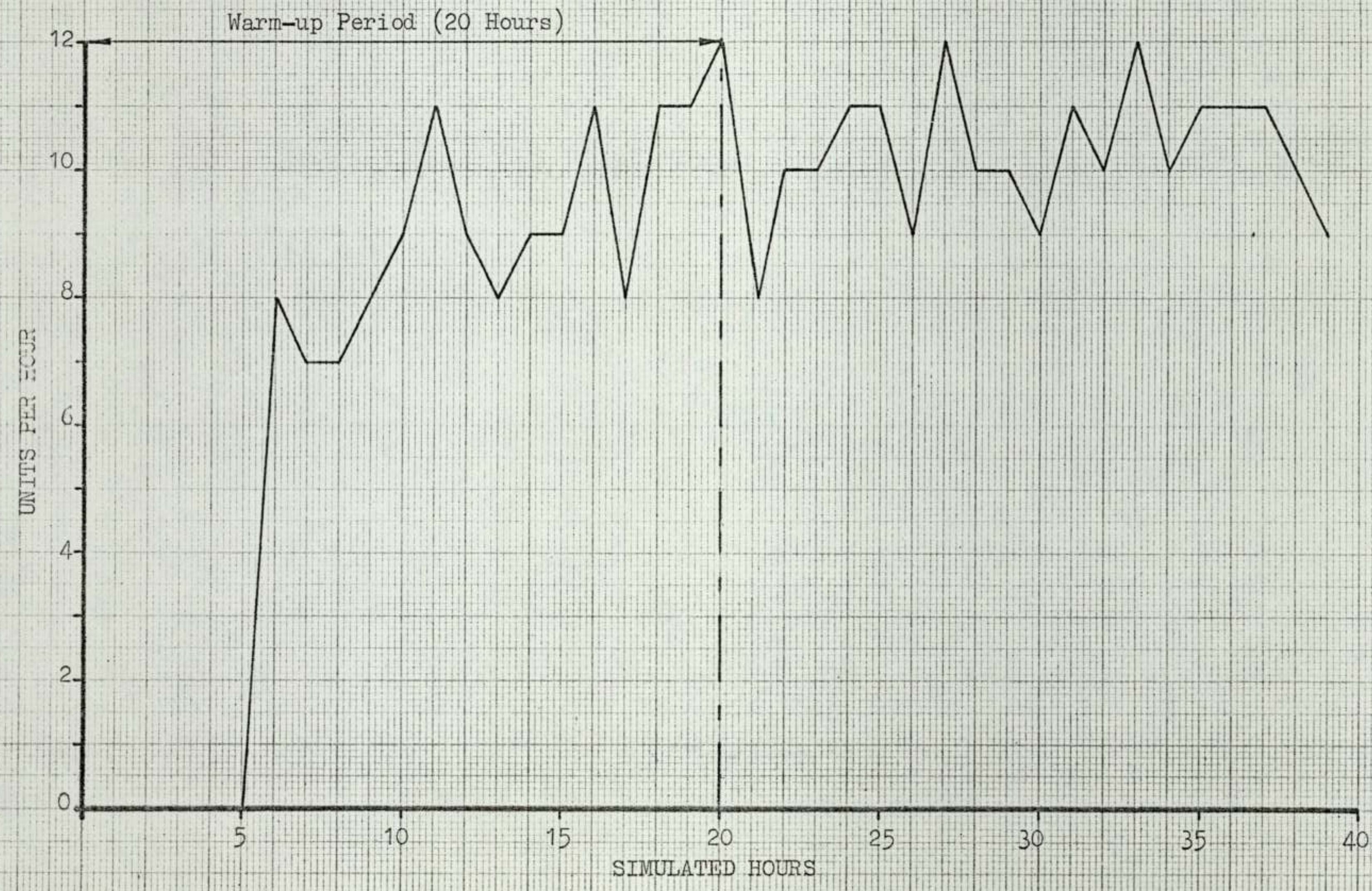
WARM-UP MONITORING FOR AREA A. DESIGN FACTOR EXPERIMENTS

Number of Stations = 50
Cycle Time = 5 mins.
Mean Downtime = 1 min.
Probability of a Stoppage = 0.10
Interstation Storage Capacity = 8

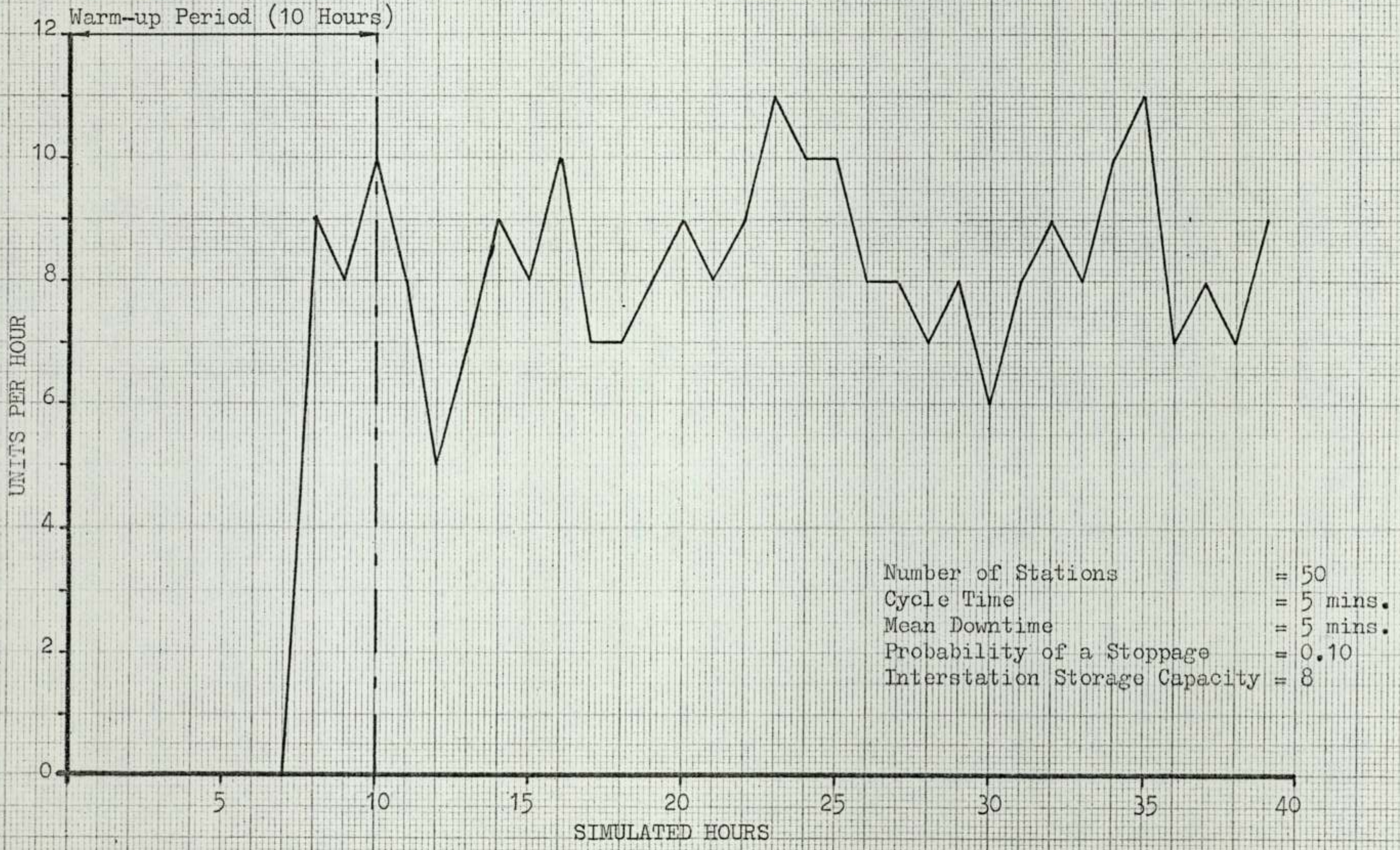


WARM-UP MONITORING FOR AREA B. DESIGN FACTOR EXPERIMENTS

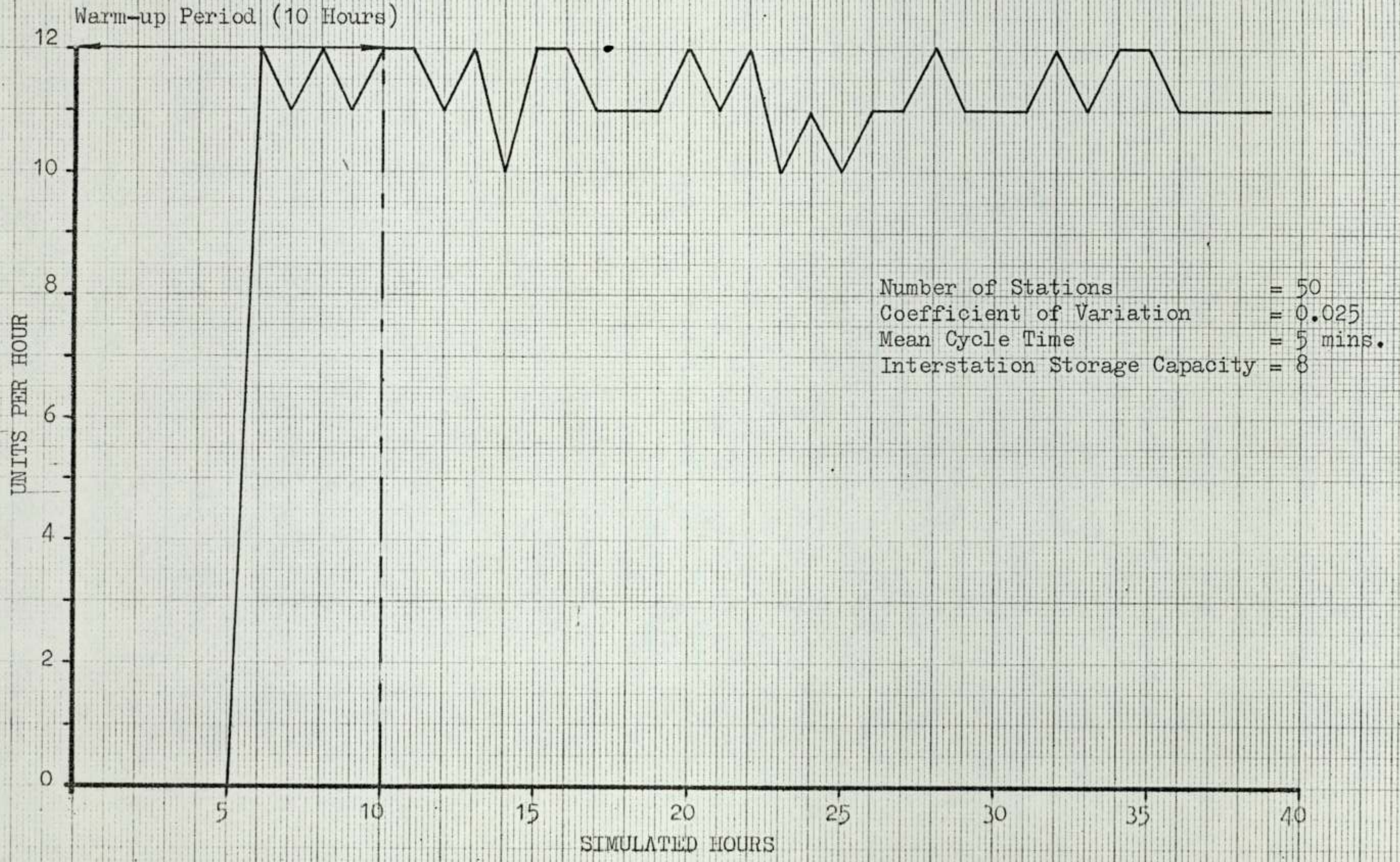
Number of Stations = 50
Coefficient of Variation = 0.133
Mean Cycle Time = 5 mins.
Interstation Storage Capacity = 8



WARM-UP MONITORING FOR SIMULATION STUDIES TO DETERMINE THE AREA A. EQUATION CONSTANTS



WARM-UP MONITORING FOR SIMULATION STUDIES TO DETERMINE THE AREA B. EQUATION CONSTANTS



APPENDIX C

RESULTS

C.1 Design Factor Experiments

Notation:

T = Tied System

U = Untied System

S = Interstation Storage Capacity

p = Log_{10}(probability of a stoppage per station)

q = Log_{10}(mean stoppage duration in minutes)

n = Log_{10}(number of stations)

t = Log_{10}(cycle time in minutes)

v = Log_{10}(coefficient of variation)

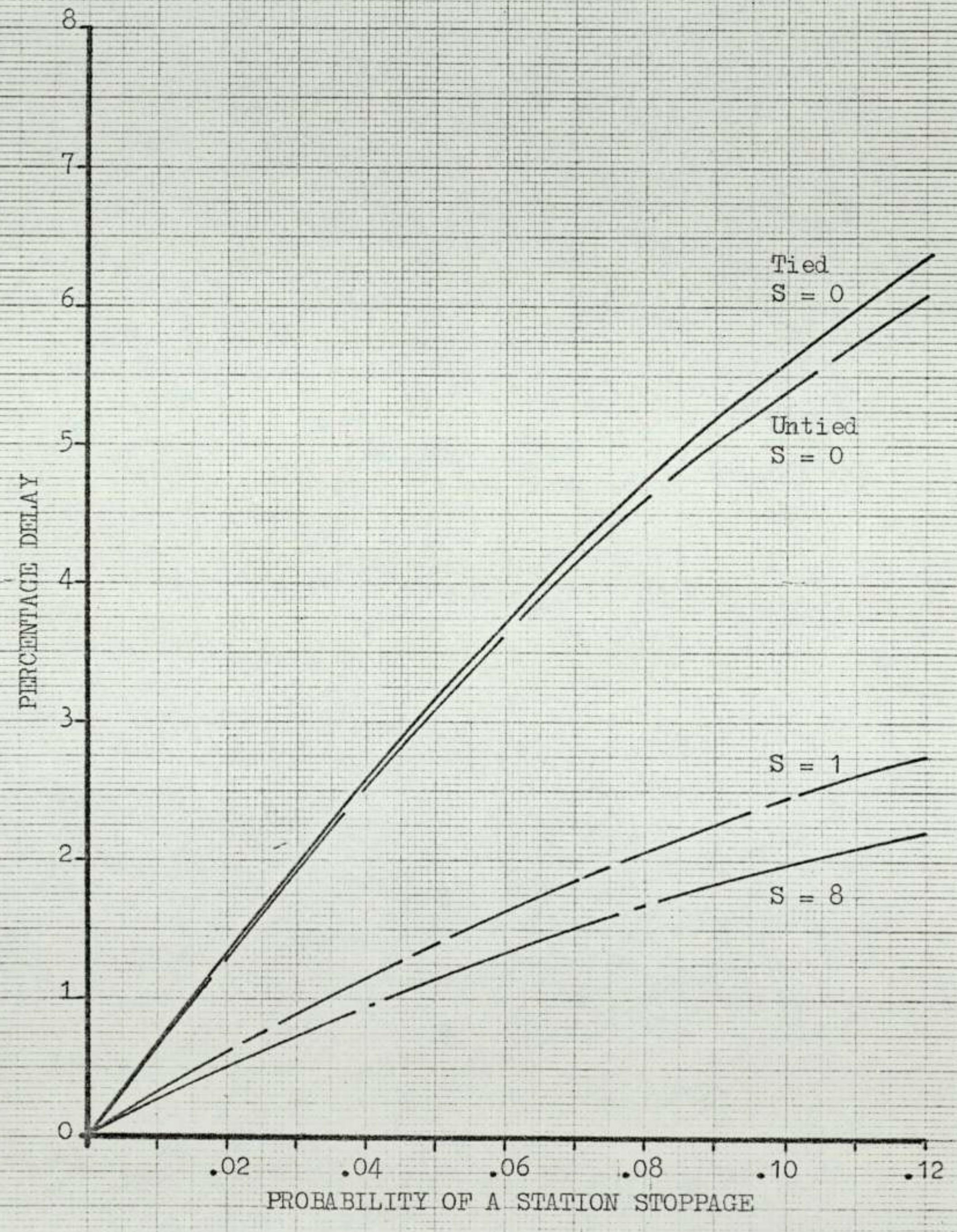
m = Log_{10}(number of operators per station)

C.1.1 Area A – Increasing Station Stoppage Probability (see Graph C.1)

Number of Stations = 4 Cycle Time = 5 mins. Mean Stoppage Duration = 1 min.

Prob. of a Station Stoppage	PERCENTAGE DELAY (100 – PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0.01	0.35	0.42	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
0.02	1.04	0.97	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
0.03	1.88	2.29	1.04	0.83	0.77	0.90	0.90	0.90	0.90	0.90
0.04	2.50	2.15	0.90	0.90	0.90	0.77	0.77	0.77	0.77	0.77
0.05	2.78	2.71	1.25	1.18	1.25	1.25	1.25	1.25	1.25	1.25
0.06	4.03	3.75	1.53	1.46	1.25	1.25	1.25	1.25	1.25	1.25
0.07	4.58	4.31	1.81	1.74	1.67	1.67	1.74	1.74	1.81	1.88
0.08	4.65	4.65	1.94	1.74	1.88	1.67	1.67	2.02	2.08	1.88
0.09	5.21	5.00	2.50	2.08	2.29	2.29	2.29	2.29	1.88	1.88
0.10	5.28	5.62	2.43	2.43	2.43	2.15	1.94	1.94	2.15	2.15
0.11	6.25	5.97	2.64	2.43	2.36	2.36	2.50	2.50	2.15	2.15
0.12	6.32	6.32	2.78	2.78	2.22	2.22	2.29	2.29	2.15	2.15

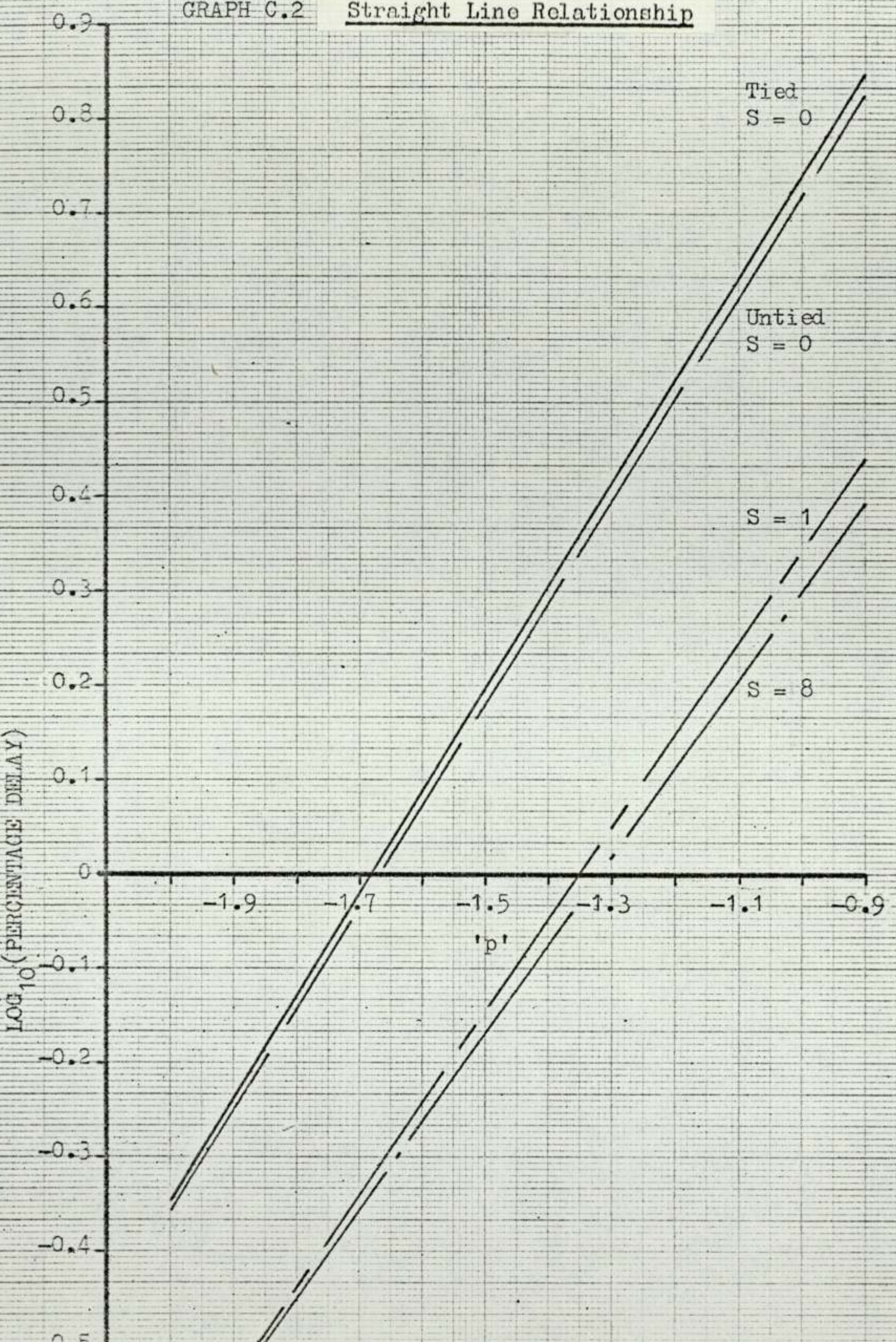
GRAPH C.1 Area A - Increasing Station Stoppage Probability



Straight Line Relationship (see Graph C.2)

p	LOG_{10}(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
-2.0000	-0.4584	-0.3799	-0.6440	-0.6440	-0.6440	-0.6440	-0.6440	-0.6440	-0.6440	-0.6440
-1.6990	0.0179	-0.0119	-0.2549	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560
-1.5229	0.2729	0.3602	0.0179	-0.0795	-0.1163	-0.0448	-0.0448	-0.0448	-0.0448	-0.0448
-1.3979	0.3979	0.3330	-0.0448	-0.0448	-0.0448	-0.1163	-0.1163	-0.1163	-0.1163	-0.1163
-1.3010	0.4438	0.4328	0.0969	0.0723	0.0969	0.0969	0.0969	0.0969	0.0969	0.0969
-1.2218	0.6051	0.5740	0.1838	0.1637	0.0969	0.0969	0.0969	0.0969	0.0969	0.0969
-1.1549	0.6613	0.6342	0.2567	0.2393	0.2219	0.2219	0.2393	0.2393	0.2567	0.2729
-1.0969	0.6678	0.6668	0.2865	0.2393	0.2729	0.2219	0.2219	0.3043	0.3187	0.0346
-1.0548	0.7167	0.6990	0.3979	0.3187	0.3602	0.3602	0.3602	0.3602	0.2729	0.2729
-1.0000	0.7225	0.7501	0.3858	0.3858	0.3858	0.3330	0.2887	0.2887	0.3330	0.3330
-0.9586	0.7959	0.7762	0.4216	0.3858	0.3729	0.3729	0.3979	0.3979	0.3330	0.3330
-0.9208	0.8007	0.8007	0.4436	0.4436	0.3470	0.3470	0.3602	0.3602	0.3330	0.3330

GRAPH C.2 **Straight Line Relationship**

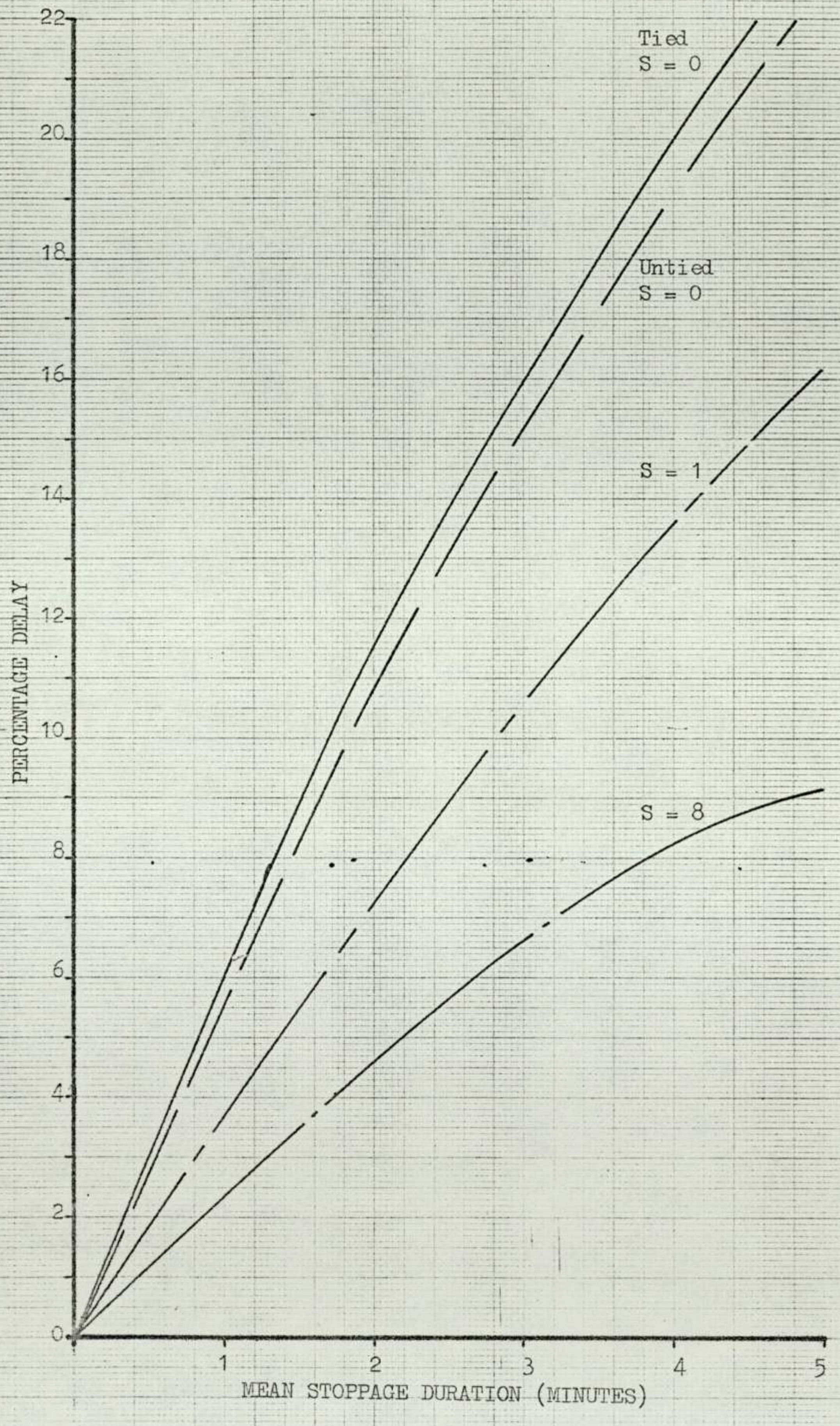


C.1.2 Area A - Increasing Mean Stoppage Duration (see Graph C.3)

Number of Stations = 4 Cycle Time = 5 mins. Probability of a Station Stoppage = 0.10

Mean Stoppage Duration (Mins.)	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S. = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
1	5.83	5.21	2.71	2.15	2.02	2.08	2.15	2.15	2.36	2.01
2	10.98	10.56	5.63	4.65	4.79	4.65	4.79	4.31	4.31	4.31
3	15.97	16.11	10.07	8.68	7.85	6.39	7.08	5.90	6.46	6.88
4	17.99	19.38	13.33	11.04	10.42	9.86	9.44	8.47	8.68	8.89
5	22.99	22.92	16.40	15.14	12.99	12.36	11.46	11.53	10.49	9.03

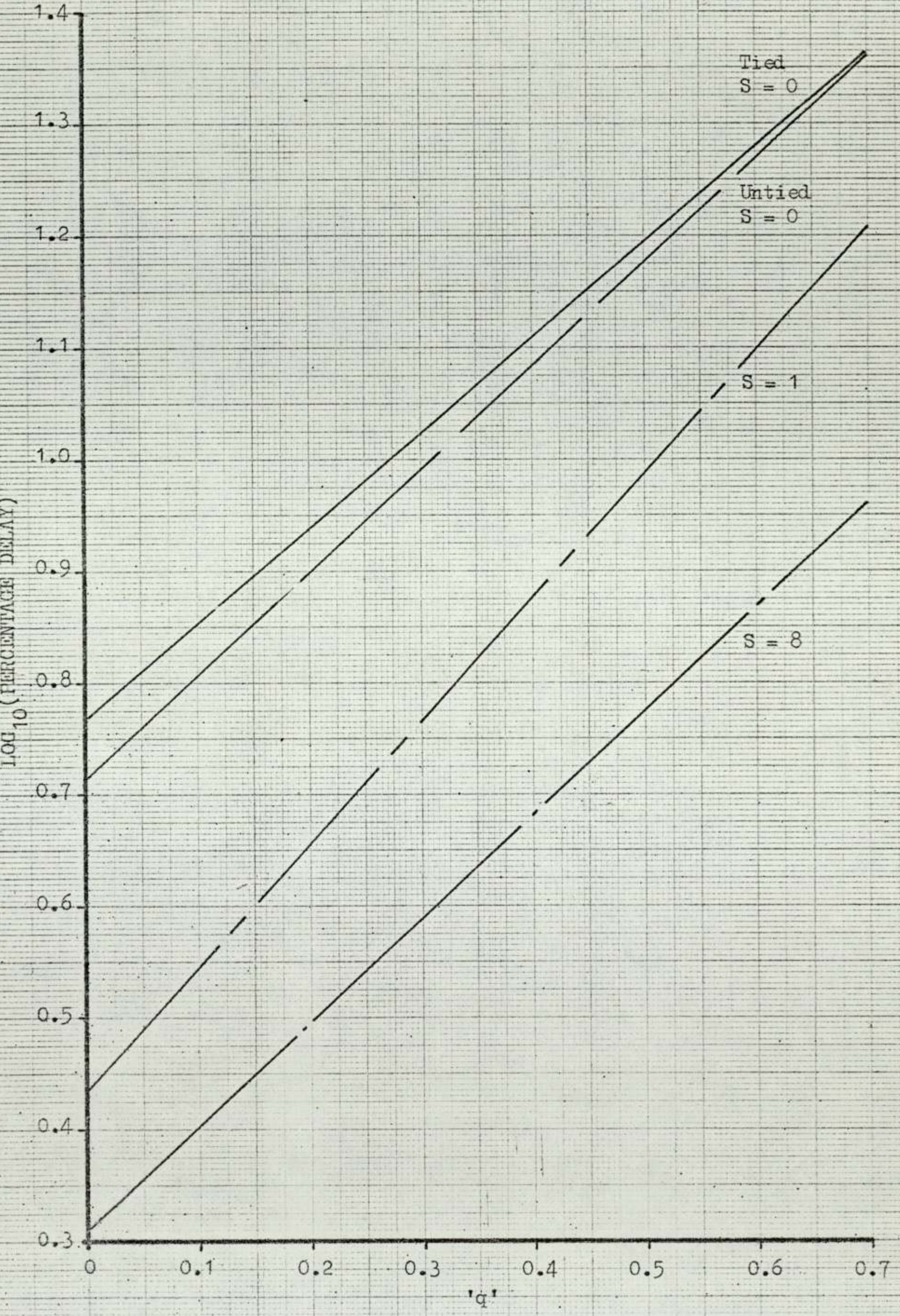
GRAPH C.3 **Area A - Increasing Mean Stoppage Duration**



<u>Straight Line Relationship</u> (see Graph C.4)

q	LOG_{10}(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0	0.7659	0.7168	0.4329	0.3328	0.3043	0.3187	0.3328	0.3328	0.3731	0.3040
0.3010	1.0406	1.0236	0.7501	0.6677	0.6805	0.6677	0.6805	0.6341	0.6341	0.6341
0.4771	1.2033	1.2071	1.0289	0.9386	0.8947	0.8055	0.8502	0.7711	0.8101	0.8373
0.6021	1.2551	1.2874	1.1249	1.0430	1.0179	0.9939	0.9752	0.9280	0.9386	0.9488
0.6990	1.3615	1.3602	1.2146	1.1801	1.1133	1.0920	1.0592	1.0618	1.0208	0.9556

GRAPH C.4 Straight Line Relationship

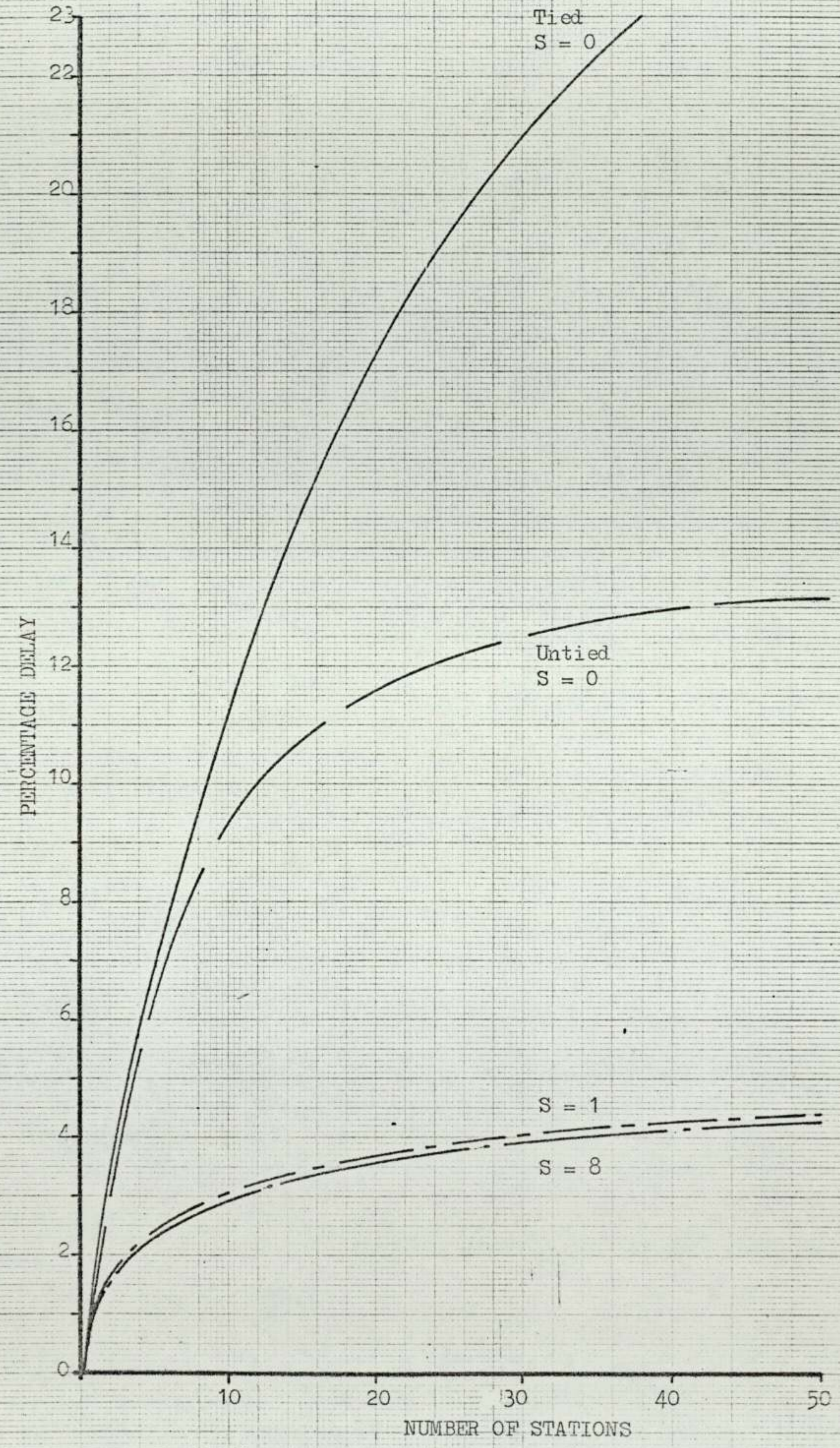


C.1.3 Area A – Increasing the Number of Stations (see Graph C.5)

Mean Stoppage Duration = 1 min. Cycle Time = 5 mins. Probability of a Station Stoppage = 0.10

Number of Stations	PERCENTAGE DELAY (100 – PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
2	2.64	2.50	1.74	1.94	1.46	1.60	1.60	1.60	1.60	1.60
4	6.60	6.25	2.85	2.57	2.43	2.50	2.50	2.50	2.50	2.50
6	7.29	7.29	2.71	2.78	2.43	2.50	2.57	2.50	2.43	2.43
8	9.10	8.13	2.64	2.22	2.29	2.50	2.22	2.78	2.22	2.22
10	10.97	9.31	2.64	2.85	2.71	2.85	2.85	2.29	2.57	2.57
15	15.49	10.83	3.61	3.13	2.92	3.47	3.26	2.85	2.99	2.99
20	16.81	11.67	3.33	3.47	3.26	3.40	3.06	3.26	3.40	3.40
30	21.39	11.74	3.75	3.96	3.89	3.68	3.89	3.54	3.82	3.82
40	23.19	12.99	3.96	4.51	4.31	4.58	4.10	4.24	4.03	4.03
50	27.57	13.19	4.65	4.65	5.00	4.86	4.31	4.51	4.38	4.38

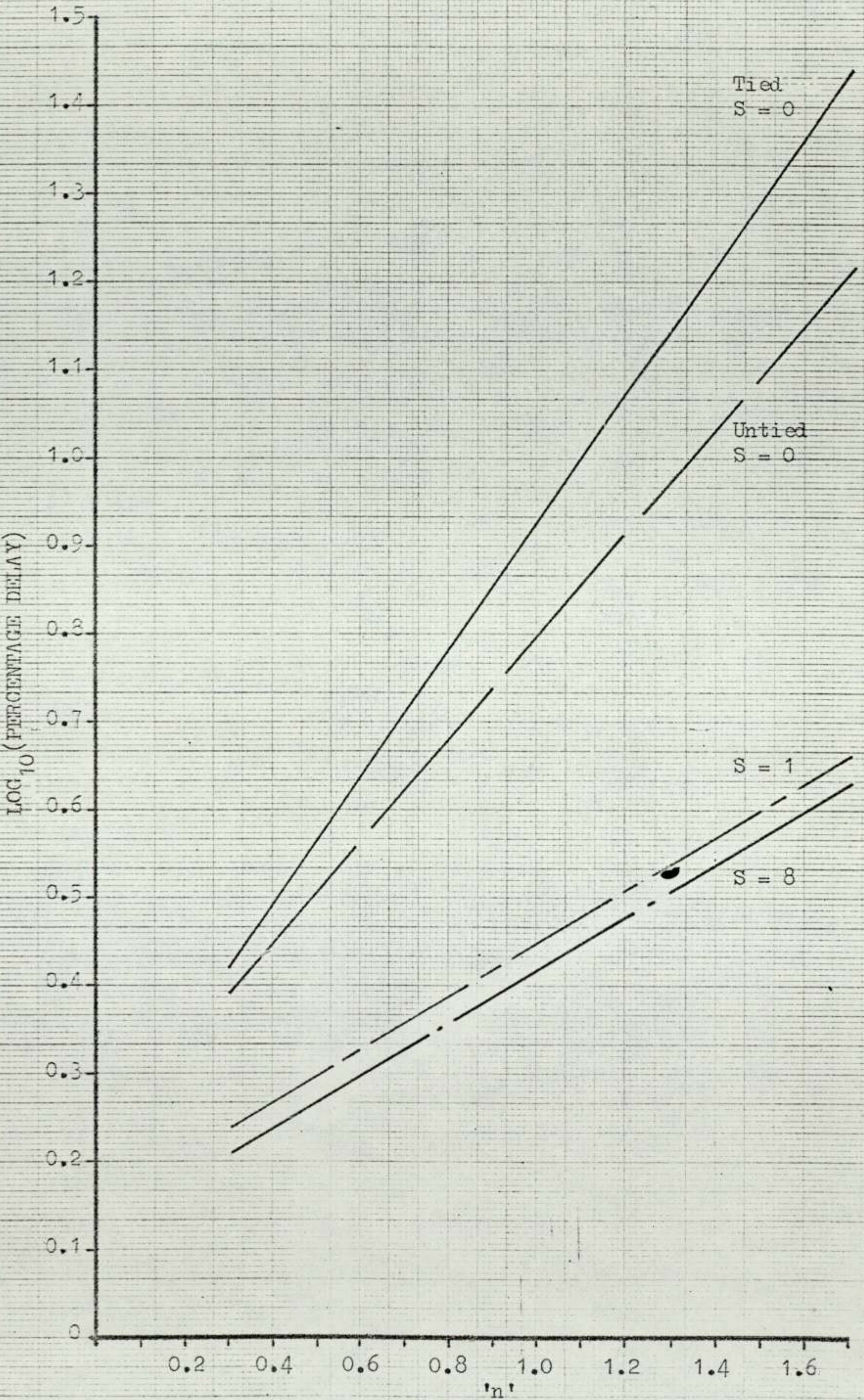
GRAPH C.5 **Area A - Increasing the Number of Stations**



Straight Line Relationship (see Graph C.6)

n	$\log_{10}$(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0.3010	0.4215	0.3979	0.2395	0.2887	0.1637	0.2033	0.2033	0.2033	0.2033	0.2033
0.6021	0.7797	0.7959	0.4544	0.4097	0.3858	0.3979	0.3979	0.3979	0.3979	0.3979
0.7782	0.8628	0.8629	0.4327	0.4438	0.3858	0.3979	0.4097	0.3979	0.3858	0.3858
0.9031	0.9589	0.9099	0.4215	0.3468	0.3602	0.3979	0.3468	0.4438	0.3468	0.3468
1.0000	1.0402	0.9688	0.4216	0.4545	0.4327	0.4544	0.4544	0.3602	0.4097	0.4097
1.1761	1.1901	1.0346	0.5576	0.4949	0.4649	0.5406	0.4544	0.4751	0.4751	0.4751
1.3010	1.2256	1.0671	0.5228	0.5406	0.5137	0.5319	0.4852	0.5137	0.5319	0.5319
1.4771	1.3302	1.0697	0.5740	0.5975	0.5898	0.5659	0.5898	0.5492	0.5819	0.5819
1.6021	1.3653	1.1137	0.5975	0.6546	0.6341	0.6612	0.6125	0.6269	0.6051	0.6051
1.6990	1.4404	1.1168	0.6678	0.6678	0.6990	0.6867	0.6341	0.6546	0.6410	0.6410

GRAPH C.6 Straight Line Relationship

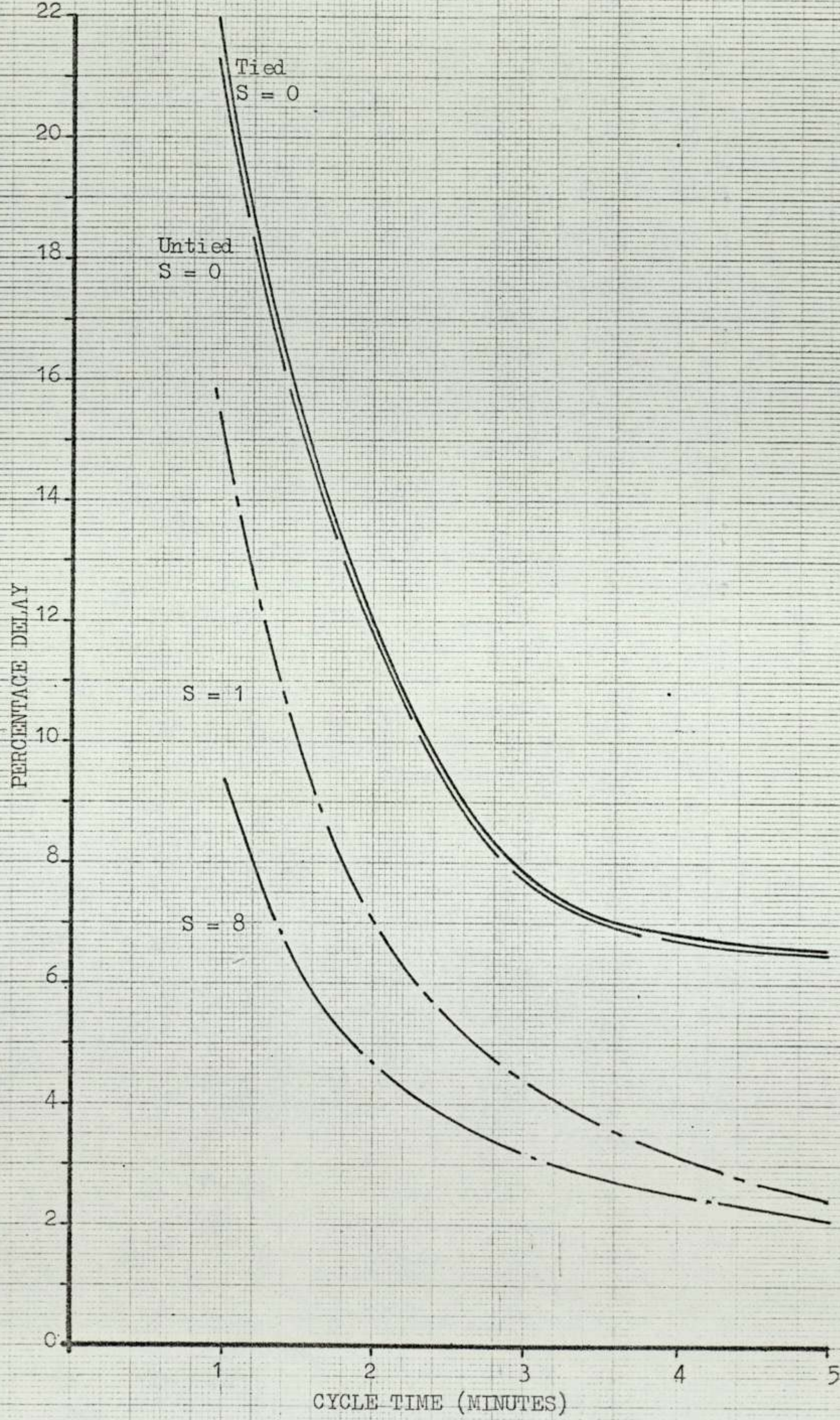


C.1.4 Area A - Increasing the Cycle Time (see Graph C.7)

Number of Stations = 4   Mean Stoppage Duration = 1 min.   Probability of a Station Stoppage = 0.10

Cycle Time (Mins.)	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
1	21.20	21.47	15.21	13.40	12.11	10.53	10.53	10.01	9.31	9.31
2	11.97	12.17	7.03	5.75	5.33	4.89	4.50	4.72	4.33	4.08
3	7.63	8.75	4.38	3.71	3.58	3.42	3.42	3.33	3.42	3.67
4	6.72	6.83	3.22	2.56	2.89	2.56	2.56	2.56	2.44	2.39
5	6.66	5.62	2.43	2.43	2.43	2.15	1.94	1.94	2.15	2.15

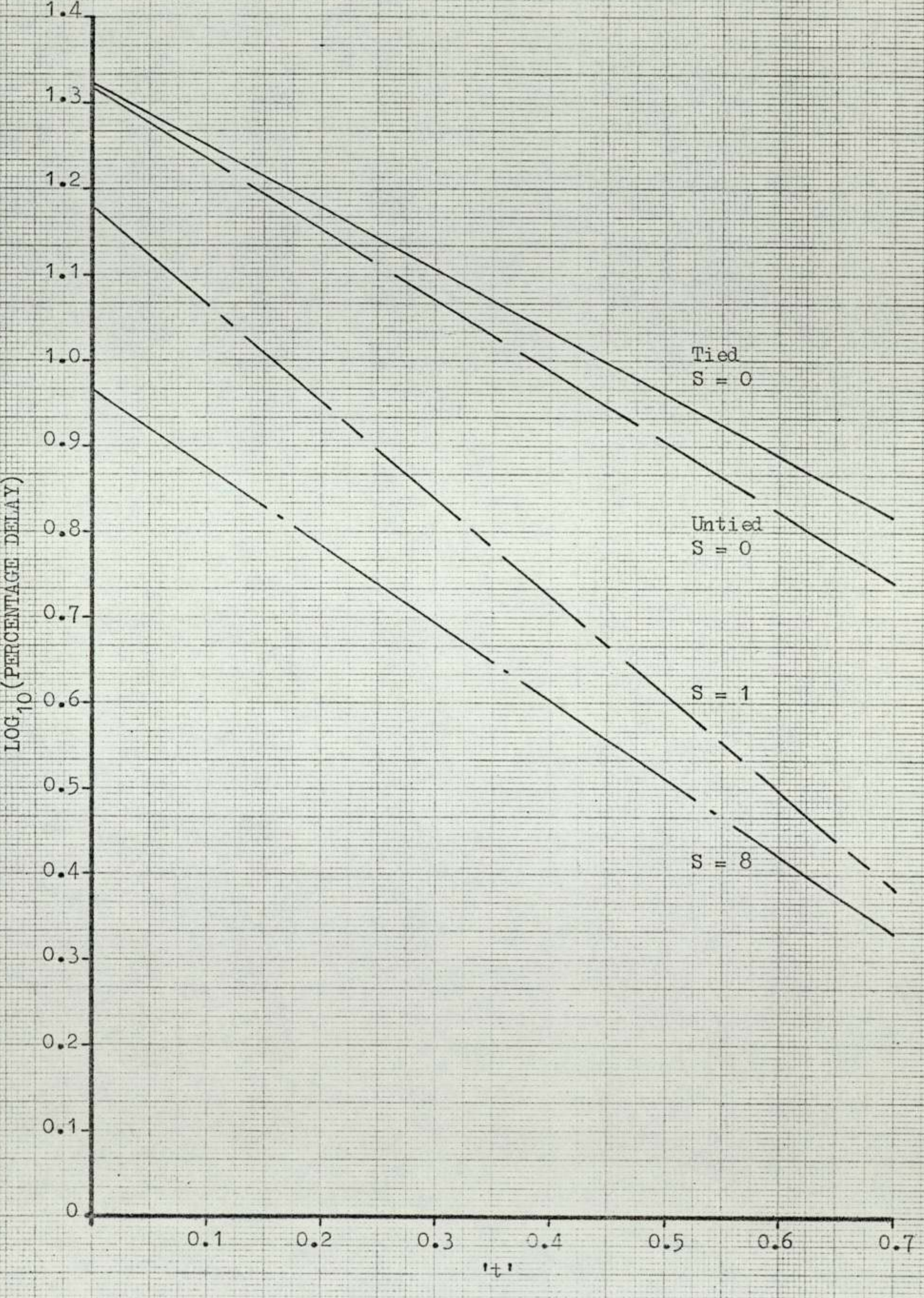
GRAPH C.7 Area A - Increasing the Cycle Time



Straight Line Relationship (see Graph C.8)

t	LOG_{10}(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0	1.3251	1.3318	1.1821	1.1271	1.0831	1.0224	1.0224	1.0050	0.9688	0.9688
0.3010	1.0781	1.0853	0.8468	0.7597	0.7269	0.6892	0.6532	0.6741	0.6368	0.6110
0.4771	0.8823	0.9420	0.6410	0.5691	0.5543	0.5337	0.5337	0.5228	0.5337	0.5643
0.6021	0.8276	0.8344	0.5082	0.4074	0.4608	0.4075	0.4075	0.4075	0.3881	0.3783
0.6990	0.8235	0.7497	0.3858	0.3858	0.3858	0.3328	0.2887	0.2887	0.3328	0.3328

GRAPH C.8 **Straight Line Relationship**

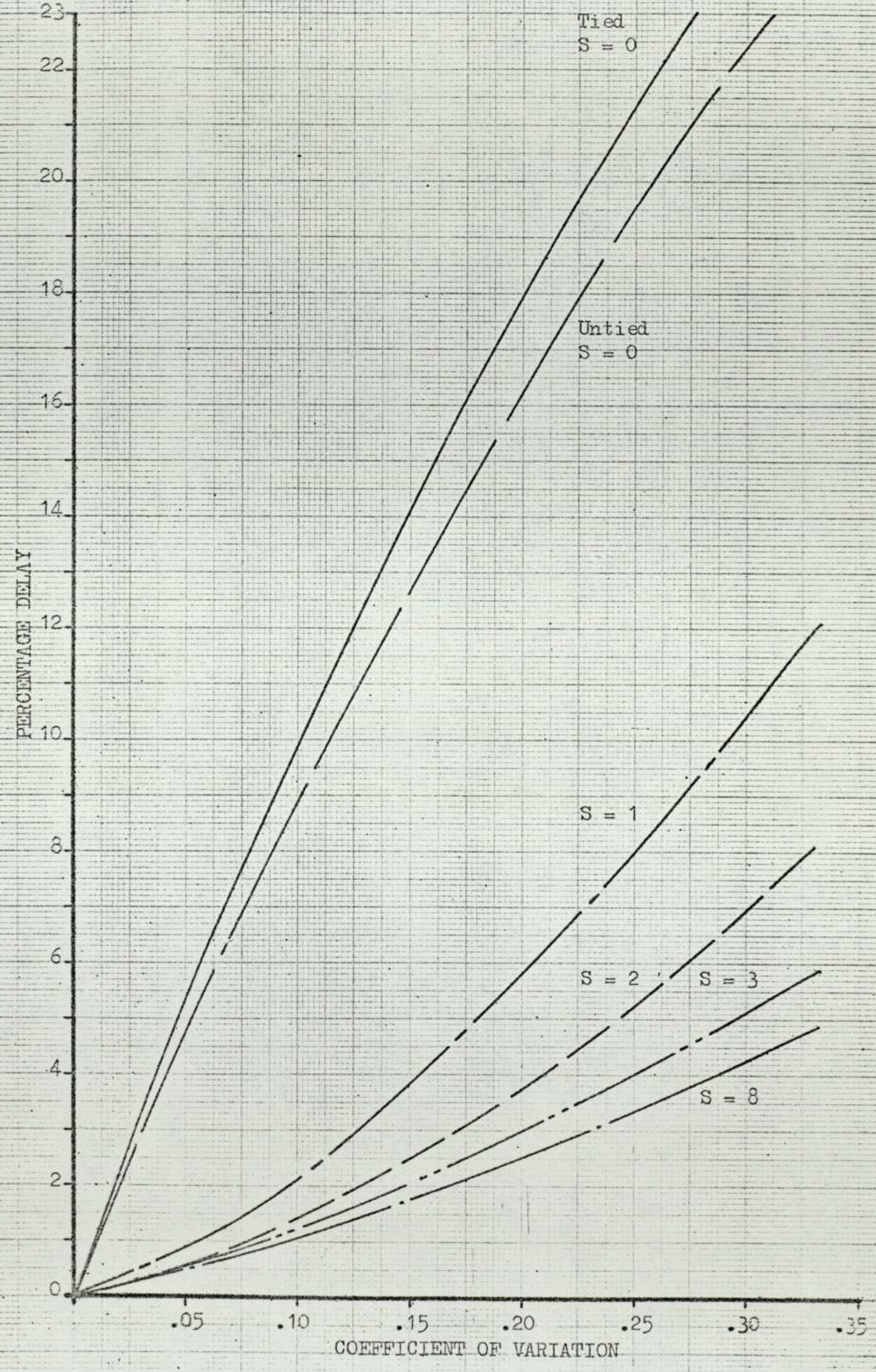


C.1.5 <u>Area B – Increasing the Coefficient of Variation</u> (see Graph C.9)

Number of Stations = 4 Number of Operators per Station = 1

Coef. of Variation	PERCENTAGE DELAY (100 – PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
.025	2.71	2.43	0.42	0.28	0.28	0.28	0.28	0.28	0.28	0.28
.033	3.54	3.13	0.63	0.56	0.42	0.42	0.42	0.42	0.42	0.42
.050	5.71	4.51	0.90	0.77	0.83	0.83	0.83	0.83	0.83	0.83
.066	6.81	6.04	1.04	0.90	0.90	0.83	0.83	0.83	0.83	0.83
.100	9.72	8.96	2.02	1.46	1.60	1.32	1.25	1.39	1.39	1.39
.133	12.43	11.39	3.06	2.29	1.94	2.36	1.18	1.88	1.94	1.88
.166	15.07	13.96	4.58	3.33	2.43	2.36	1.81	1.60	1.81	1.94
.200	17.64	16.18	5.83	4.17	3.26	3.13	3.13	3.06	2.92	3.06
.250	22.08	19.51	8.33	4.72	3.96	3.68	3.47	4.17	3.40	2.78
.300	24.17	22.57	10.07	7.78	5.28	4.65	4.51	4.31	4.38	4.58
.333	26.11	24.58	12.15	8.13	5.97	5.35	5.97	4.72	4.38	4.51

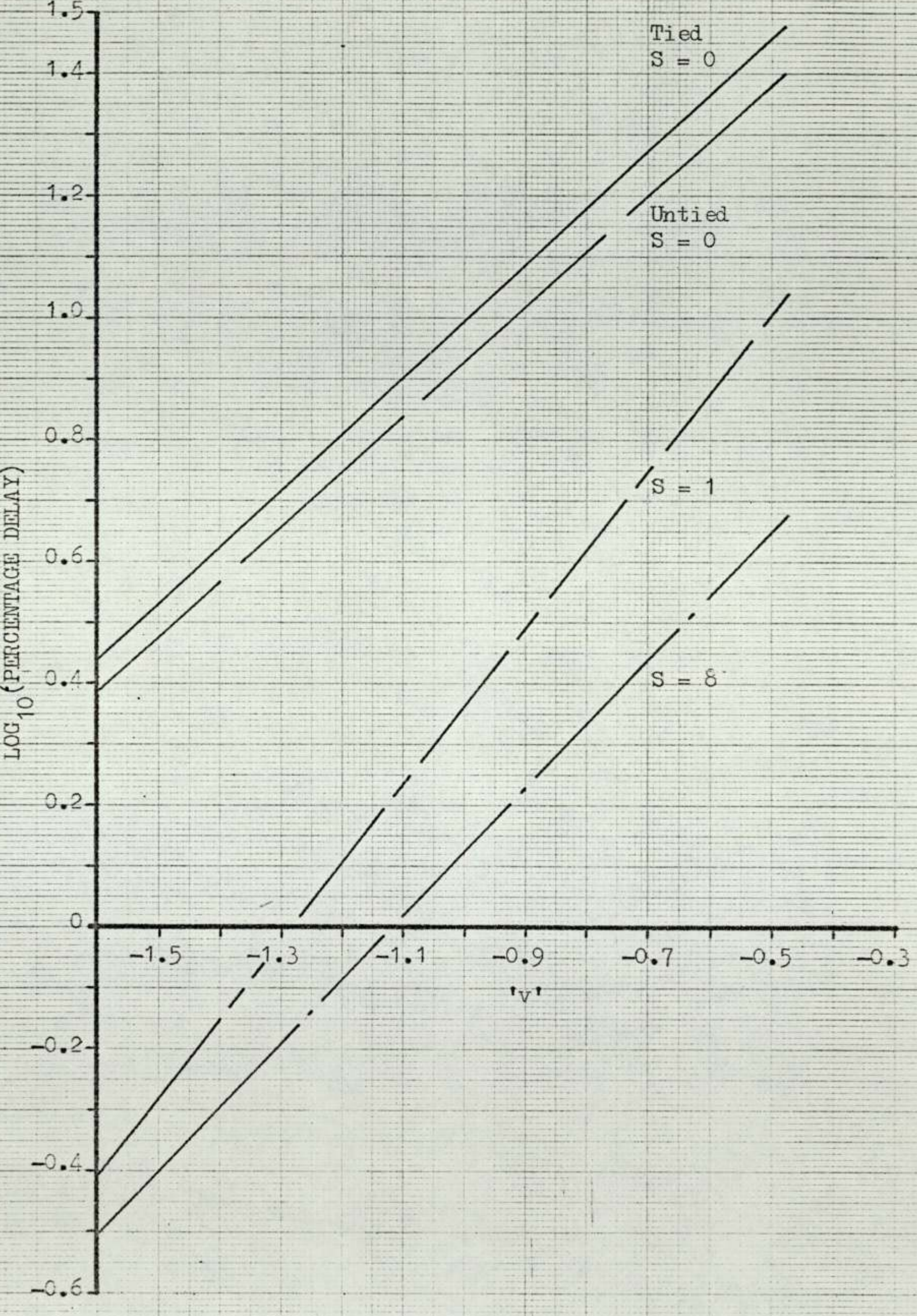
GRAPH C.9 **Area B - Increasing the Coefficient of Variation**



Straight Line Relationship (see Graph C.10)

v	$\log_{10}$(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
-1.6021	0.4327	0.3858	-0.3799	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560	-0.5560
-1.4771	0.5492	0.4949	-0.2041	-0.2541	-0.3799	-0.3799	-0.3799	-0.3799	-0.3799	-0.3799
-1.3011	0.7565	0.6546	-0.0443	-0.1163	-0.0794	-0.0794	-0.0794	-0.0794	-0.0794	-0.0794
-1.1762	0.8329	0.7811	0.0179	-0.0443	-0.0443	-0.0794	-0.0794	-0.0794	-0.0794	-0.0794
-1.0000	0.9878	0.9522	0.3043	0.1640	0.2033	0.1206	0.0969	0.1428	0.1428	0.1428
-0.8750	1.0945	1.0566	0.4853	0.3602	0.2887	0.3731	0.0723	0.2729	0.2887	0.2729
-0.7782	1.1781	1.1449	0.6613	0.5228	0.3858	0.3731	0.2567	0.2033	0.2567	0.2887
-0.6990	1.2465	1.2090	0.7660	0.6198	0.5137	0.4249	0.4949	0.4852	0.4649	0.4852
-0.6021	1.3439	1.2902	0.9208	0.6742	0.5975	0.5659	0.5406	0.6198	0.5319	0.4438
-0.5229	1.3832	1.3536	1.0030	0.8908	0.7225	0.6678	0.6536	0.6341	0.6410	0.6612
-0.4771	1.4168	1.3906	1.0846	0.9099	0.7761	0.7281	0.7761	0.6741	0.6410	0.6546

GRAPH C.10 Straight Line Relationship

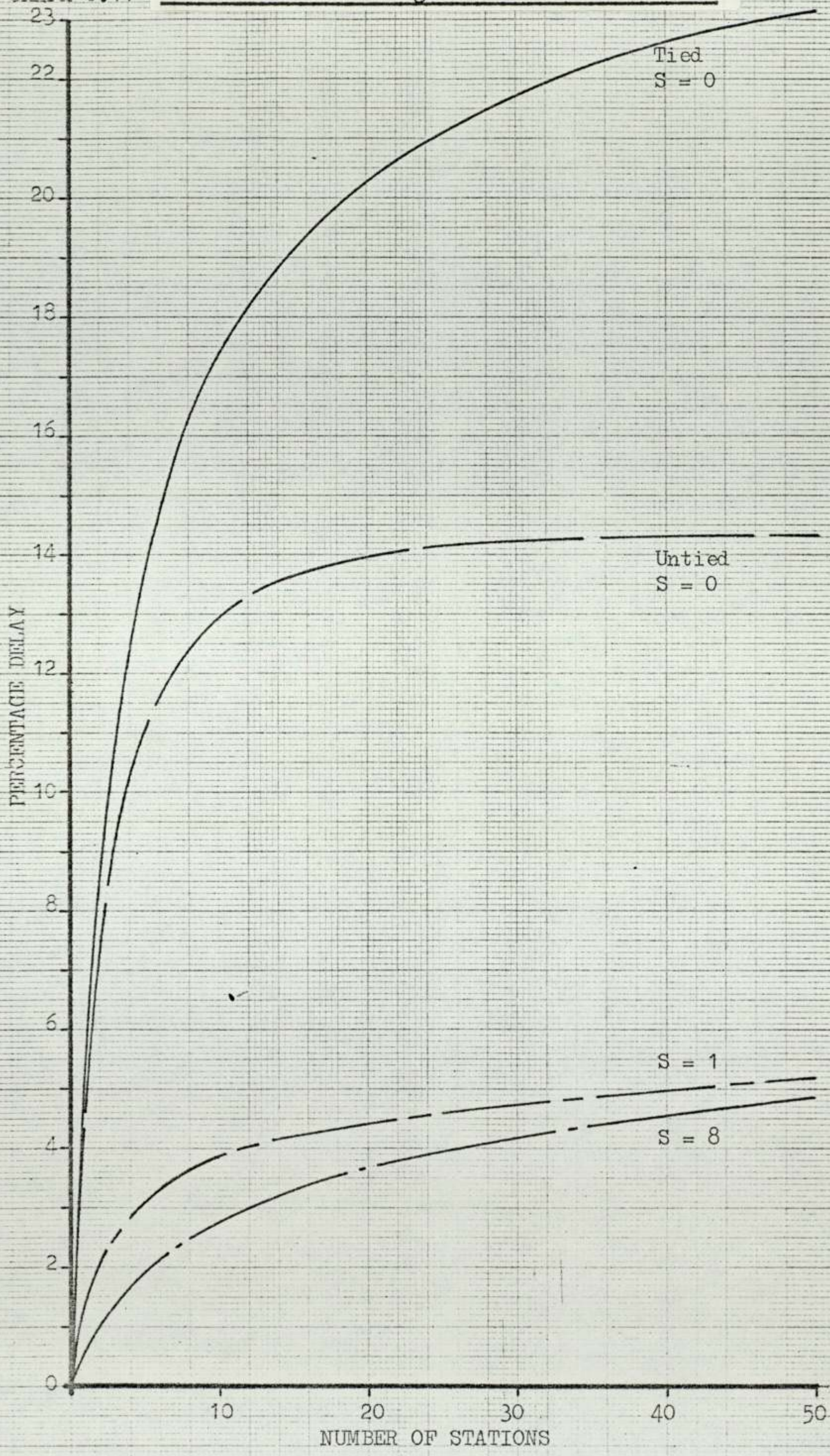


C.1.6 Area B - Increasing the Number of Stations (see Graph C.11)

Coefficient of Variation = 0.133 Number of Operators per Station = 1

Number of Stations	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
2	8.68	7.22	2.36	1.53	1.46	1.25	1.74	1.53	1.60	1.39
4	12.36	10.49	2.99	2.08	2.08	2.15	1.39	1.60	1.53	1.53
6	14.86	12.02	3.42	2.50	2.36	2.43	2.57	2.36	2.64	2.15
8	16.32	12.43	3.82	2.64	1.94	2.02	2.08	2.78	2.08	2.15
10	17.36	12.99	3.76	2.50	2.50	2.22	2.50	2.36	2.22	2.29
15	19.24	13.40	4.10	3.06	2.85	2.71	2.99	2.64	2.85	2.43
20	20.21	13.96	3.96	3.75	3.40	3.40	3.68	3.27	3.68	3.61
30	21.74	13.96	4.58	4.24	4.17	3.82	3.75	3.96	3.75	3.89
40	22.57	14.44	5.00	4.38	4.52	4.65	4.38	4.65	4.52	4.52
50	23.13	14.31	5.21	5.14	5.21	5.23	5.00	5.21	5.00	5.14

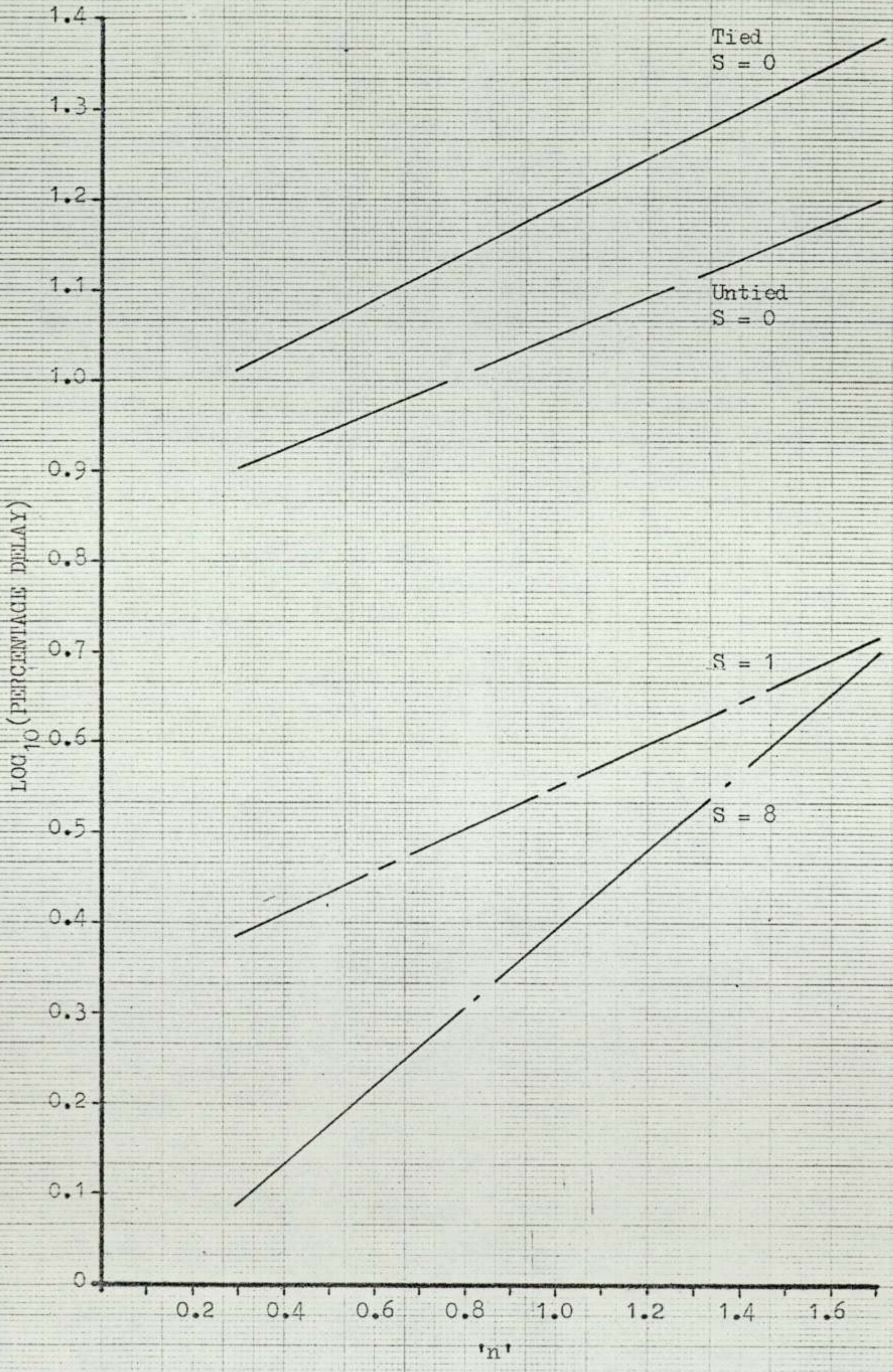
GRAPH C.11 Area B - Increasing the Number of Stations



Straight Line Relationship (see Graph C.12)

n	$\log_{10}$(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0.3010	0.9386	0.8587	0.3729	0.1838	0.1637	0.0969	0.2393	0.1838	0.2036	0.1430
0.6021	1.0920	1.0208	0.4749	0.3187	0.3187	0.3328	0.1430	0.2036	0.1838	0.1838
0.7782	1.1720	1.0799	0.5343	0.3979	0.3729	0.3858	0.4097	0.3729	0.4216	0.3328
0.9031	1.2128	1.0945	0.5819	0.4216	0.2887	0.3043	0.3187	0.4436	0.3187	0.3328
1.0000	1.2395	1.1137	0.5740	0.3979	0.3979	0.3470	0.3979	0.2036	0.3470	0.3602
1.1761	1.2842	1.1271	0.6126	0.4858	0.4548	0.4327	0.4749	0.4216	0.4545	0.3858
1.3010	1.3056	1.1449	0.5975	0.5740	0.5318	0.5318	0.5659	0.5139	0.5659	0.5575
1.4771	1.3373	1.1449	0.6612	0.6268	0.6198	0.5819	0.5740	0.5975	0.5740	0.5899
1.6021	1.3536	1.1596	0.6990	0.6410	0.6547	0.6677	0.6410	0.6677	0.6537	0.6537
1.6990	1.3638	1.1556	0.7167	0.7110	0.7167	0.7224	0.6990	0.7167	0.6990	0.7110

GRAPH C.12 **Straight Line Relationship**

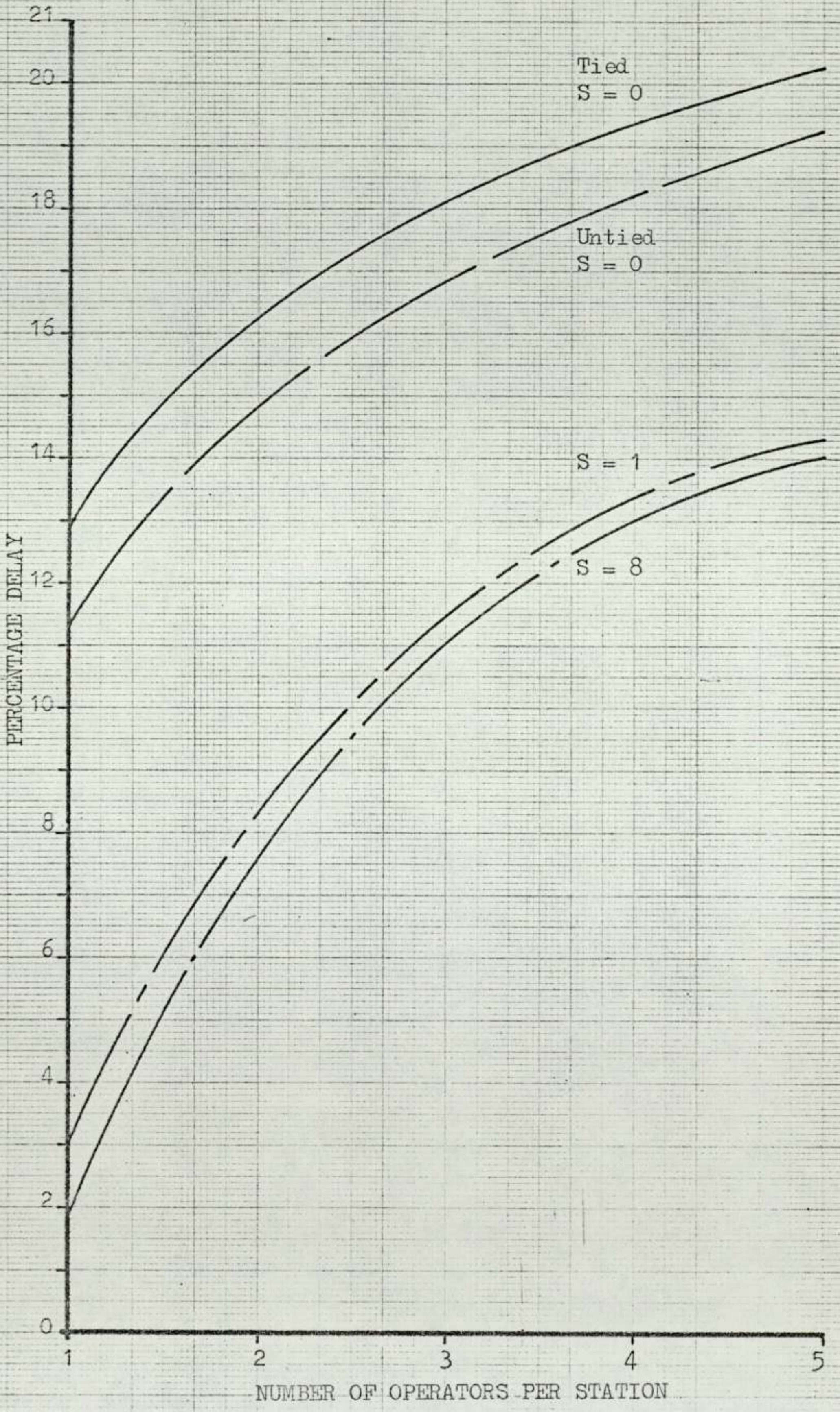


C.1.7 Area B - Increasing the Number of Operators per Station (see Graph C.13)

Coefficient of Variation = 0.133 Number of Stations = 4

Number of Operators per Station	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
1	12.36	11.39	3.06	2.36	1.95	1.88	2.29	1.88	1.95	1.88
2	16.32	14.79	8.33	7.92	7.64	7.50	7.50	7.50	7.50	7.50
3	18.13	17.08	11.04	10.90	10.97	11.04	11.18	11.18	11.18	11.18
4	19.45	18.19	13.06	12.71	12.50	12.57	12.64	13.57	12.71	12.71
5	20.21	19.31	14.31	14.10	14.24	13.96	14.10	14.10	14.03	14.10

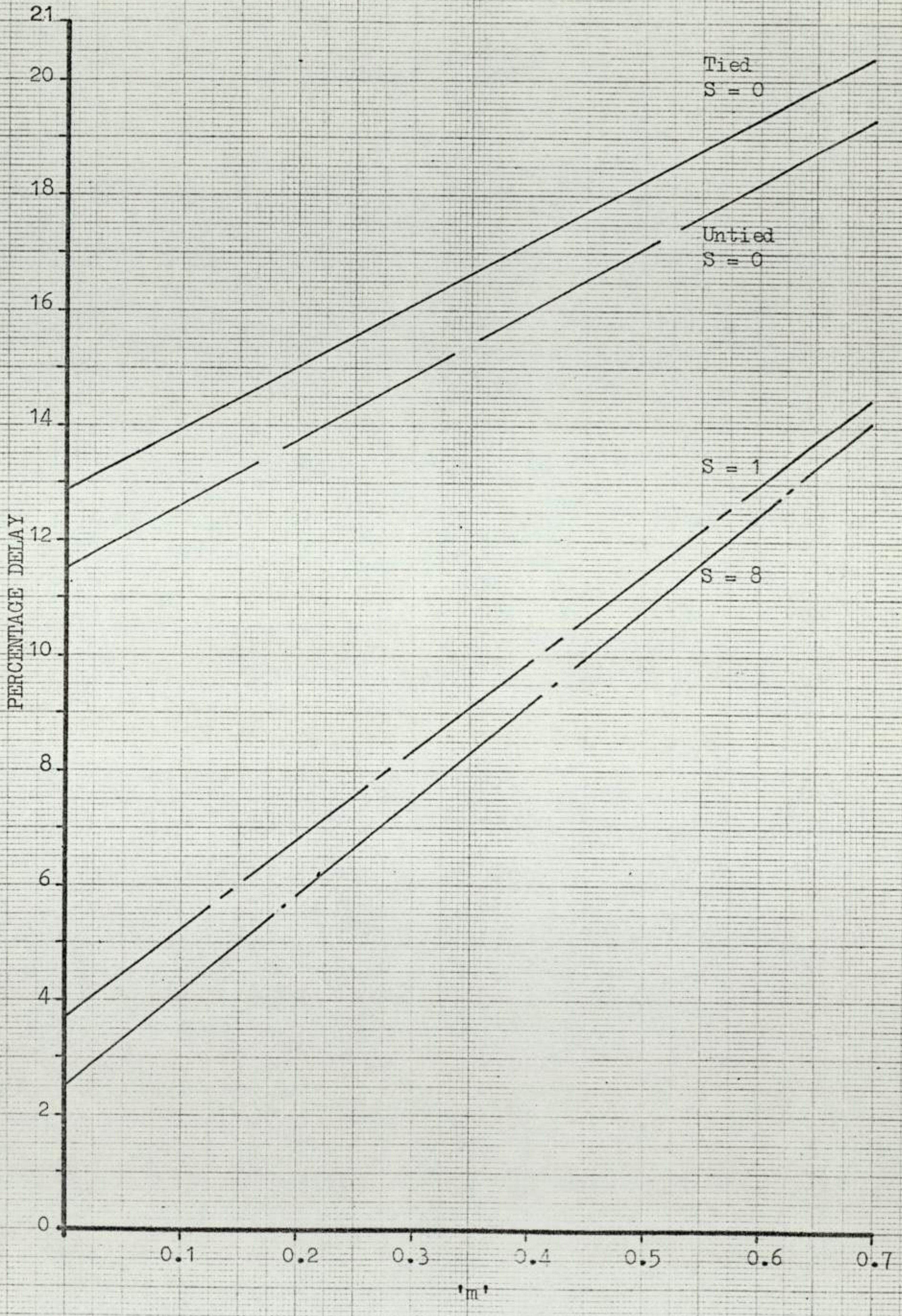
GRAPH C.13 **Area B - Increasing the Number of Operators per Station**



Straight Line Relationship (see Graph C.14)

m	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
0	12.36	11.39	3.06	2.36	1.95	1.88	2.29	1.88	1.95	1.88
0.3010	16.32	14.79	8.33	7.92	7.64	7.50	7.50	7.50	7.50	7.50
0.4771	18.13	17.08	11.04	10.90	10.97	11.04	11.18	11.18	11.18	11.18
0.6021	19.45	18.19	13.06	12.71	12.50	12.57	12.64	13.57	12.71	12.71
0.6990	20.21	19.31	14.31	14.10	14.24	13.96	14.10	14.10	14.03	14.10

GRAPH C.14 Straight Line Relationship



C.2 Determination of Efficiency Equation Constants

C.2.1 Study Area A

Notation:

T = Tied System

U = Untied System

S = Interstation Storage

p = $\log_{10}$(probability of a stoppage per station)

q = $\log_{10}$(mean stoppage duration in minutes)

t = $\log_{10}$(cycle time in minutes)

n = $\log_{10}$(number of stations)

Dx = Percentage Delay

Yx = $\log_{10}$(Dx)

The prefix 'x' identifies the combination simulated, these being:-

x	t	p	q	n
1	t_1	p_1	q_1	n_1
2	t_2	p_1	q_1	n_1
3	t_1	p_2	q_1	n_1
4	t_2	p_2	q_1	n_1
5	t_1	p_1	q_2	n_1
6	t_2	p_1	q_2	n_1
7	t_1	p_2	q_2	n_1
8	t_2	p_2	q_2	n_1
9	t_1	p_1	q_1	n_2
10	t_2	p_1	q_1	n_2
11	t_1	p_2	q_1	n_2
12	t_2	p_2	q_1	n_2
13	t_1	p_1	q_2	n_2
14	t_2	p_1	q_2	n_2
15	t_1	p_2	q_2	n_2
16	t_2	p_2	q_2	n_2

Let

$t_1 = \log_{10}1 = 0$

$t_2 = \log_{10}5 = 0.699$

$p_1 = \log_{10}0.02 = -1.699$

$p_2 = \log_{10}0.10 = -1.000$

$q_1 = \log_{10}1 = 0$

$q_2 = \log_{10}5 = 0.699$

$n_1 = \log_{10}6 = 0.778$

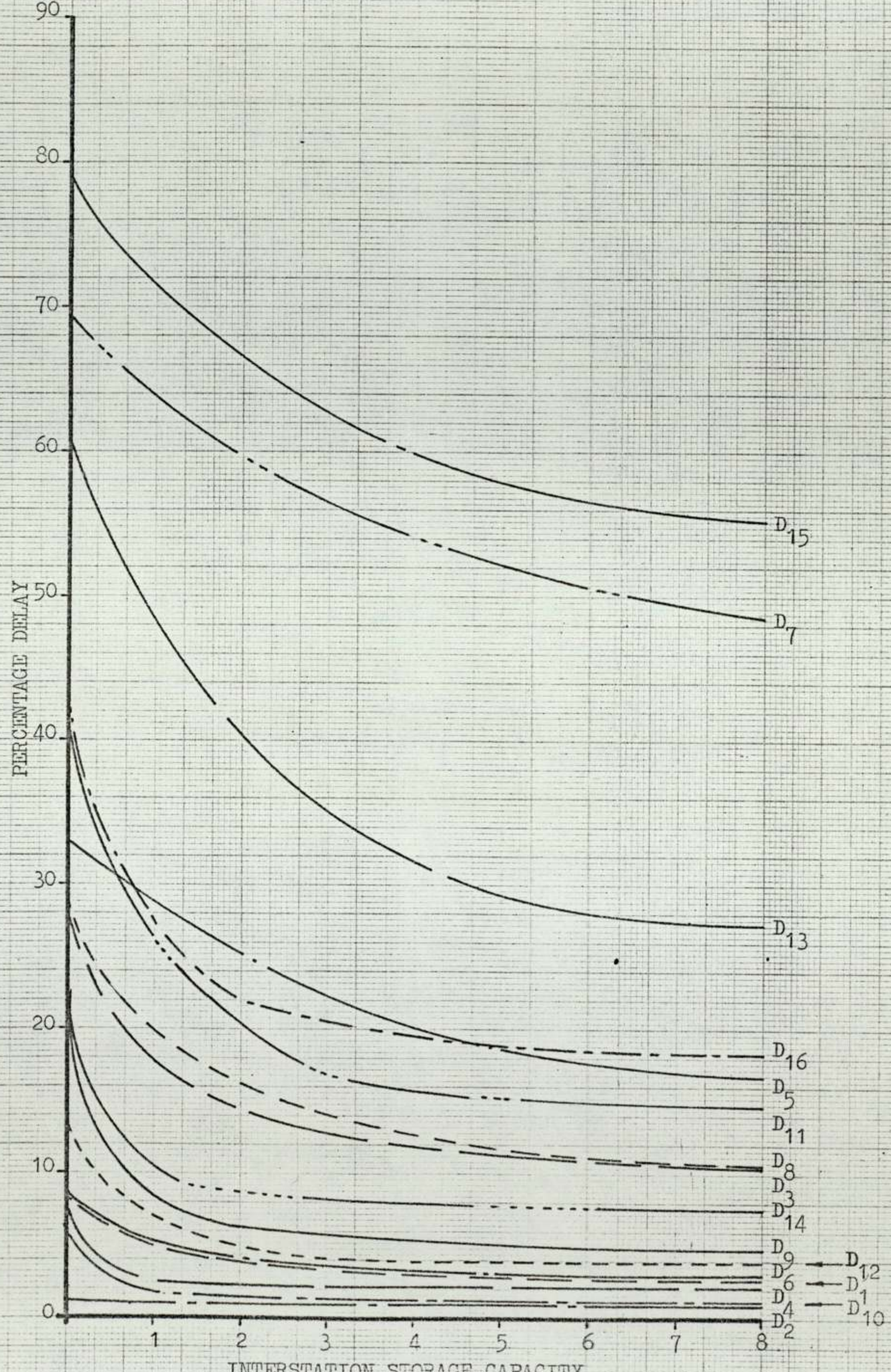
$n_2 = \log_{10}50 = 1.699$

Then the simulation results and values for Y_1 to Y_{16} to be used to calculate the efficiency equation constants are on the next two pages.

<u>Simulation Results</u> (see Graph C.15)

Dx	PERCENTAGE DELAY (100 - PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
D_1	7.88	8.23	4.90	4.03	3.54	3.20	2.95	2.88	2.88	2.88
D_2	1.74	1.70	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
D_3	30.04	27.71	17.95	14.48	12.88	12.01	11.35	10.87	10.63	10.45
D_4	7.94	7.19	2.57	2.15	2.12	2.12	2.12	2.12	2.12	2.12
D_5	33.85	32.99	28.75	25.10	22.33	20.35	18.85	17.67	16.70	15.90
D_6	8.54	8.30	5.10	4.10	3.61	3.26	3.02	2.92	2.92	2.92
D_7	67.85	69.39	63.65	59.58	56.70	54.34	52.50	50.94	49.86	49.24
D_8	30.00	27.81	19.55	16.35	14.27	12.88	11.88	11.08	10.52	10.07
D_9	38.26	22.37	8.33	6.46	5.73	5.42	5.10	4.90	4.72	4.69
D_{10}	10.94	5.80	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
D_{11}	65.31	42.88	26.32	20.24	16.98	15.90	15.52	15.21	14.97	14.76
D_{12}	27.95	13.30	4.34	4.10	4.03	3.99	3.99	3.99	3.99	3.99
D_{13}	76.67	62.01	48.68	39.58	35.31	31.46	28.75	27.71	27.50	27.50
D_{14}	41.15	24.03	10.17	8.72	8.23	8.02	7.85	7.78	7.71	7.71
D_{15}	88.23	79.41	71.35	66.56	62.92	60.04	58.08	56.81	56.04	55.63
D_{16}	71.04	43.61	27.67	21.98	20.42	19.48	18.94	18.68	18.58	18.58

GRAPH C.15 **Simulation Results**



Logarithms of Simulation Results

Yx	LOG_{10}(PERCENTAGE DELAY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
Y_1	0.8966	0.9154	0.6898	0.6088	0.5492	0.5045	0.4699	0.4597	0.4597	0.4597
Y_2	0.2395	0.2307	-0.2832	-0.2832	-0.2832	-0.2832	-0.2832	-0.2832	-0.2832	-0.2832
Y_3	1.4775	1.4427	1.2541	1.1609	1.1099	1.0795	1.0551	1.0362	1.0261	1.0191
Y_4	0.9005	0.8566	0.4099	0.3330	0.3259	0.3259	0.3259	0.3259	0.3259	0.3259
Y_5	1.5295	1.5184	1.4587	1.3997	1.3489	1.3086	1.2753	1.2472	1.2227	1.2014
Y_6	0.9316	0.9191	0.7079	0.6126	0.5576	0.5137	0.4801	0.4649	0.4649	0.4649
Y_7	1.8315	1.8409	1.8038	1.7751	1.7536	1.7351	1.7202	1.7070	1.6977	1.6924
Y_8	1.4771	1.4442	1.2911	1.2136	1.1545	1.1099	1.0745	1.0445	1.0220	1.0030
Y_9	1.5828	1.3497	0.9208	0.8101	0.7581	0.7338	0.7079	0.6898	0.6741	0.6709
Y_{10}	1.0390	0.7634	0.1637	0.1637	0.1637	0.1637	0.1637	0.1637	0.1637	0.1637
Y_{11}	1.8150	1.6322	1.4203	1.3062	1.2300	1.2014	1.1909	1.1821	1.1749	1.1690
Y_{12}	1.4464	1.1239	0.6365	0.6126	0.6051	0.6013	0.6013	0.6013	0.6013	0.6013
Y_{13}	1.8846	1.7925	1.6873	1.5975	1.5479	1.4977	1.4587	1.4427	1.4393	1.4393
Y_{14}	1.6143	1.3807	1.0073	0.9402	0.9154	0.9043	0.8947	0.8909	0.8869	0.8869
Y_{15}	1.9456	1.8999	1.8534	1.8232	1.7988	1.7784	1.7640	1.7544	1.7485	1.7453
Y_{16}	1.8515	1.6396	1.4420	1.3420	1.3100	1.2896	1.2769	1.2713	1.2690	1.2690

C.2.2 Study Area B

Notation:

T = Tied System

U = Untied System

S = Interstation Storage

$m = \log_{10}$(number of operators per station)

$n = \log_{10}$(number of stations)

$v = \log_{10}$(coefficient of variation)

D_x = percentage delay

The prefix 'x' identifies the combination simulated, these being:

x	m	v	n
1	m_1	v_1	n_1
2	m_2	v_1	n_1
3	m_1	v_2	n_1
4	m_2	v_2	n_1
5	m_1	v_1	n_2
6	m_2	v_1	n_2
7	m_1	v_2	n_2
8	m_2	v_2	n_2

Let $m_1 = \log_{10}1 = 0$

$m_2 = \log_{10}5 = 0.699$

$v_1 = \log_{10}0.025 = -1.602$

$v_2 = \log_{10}0.333 = -0.477$

$n_1 = \log_{10}6 = 0.778$

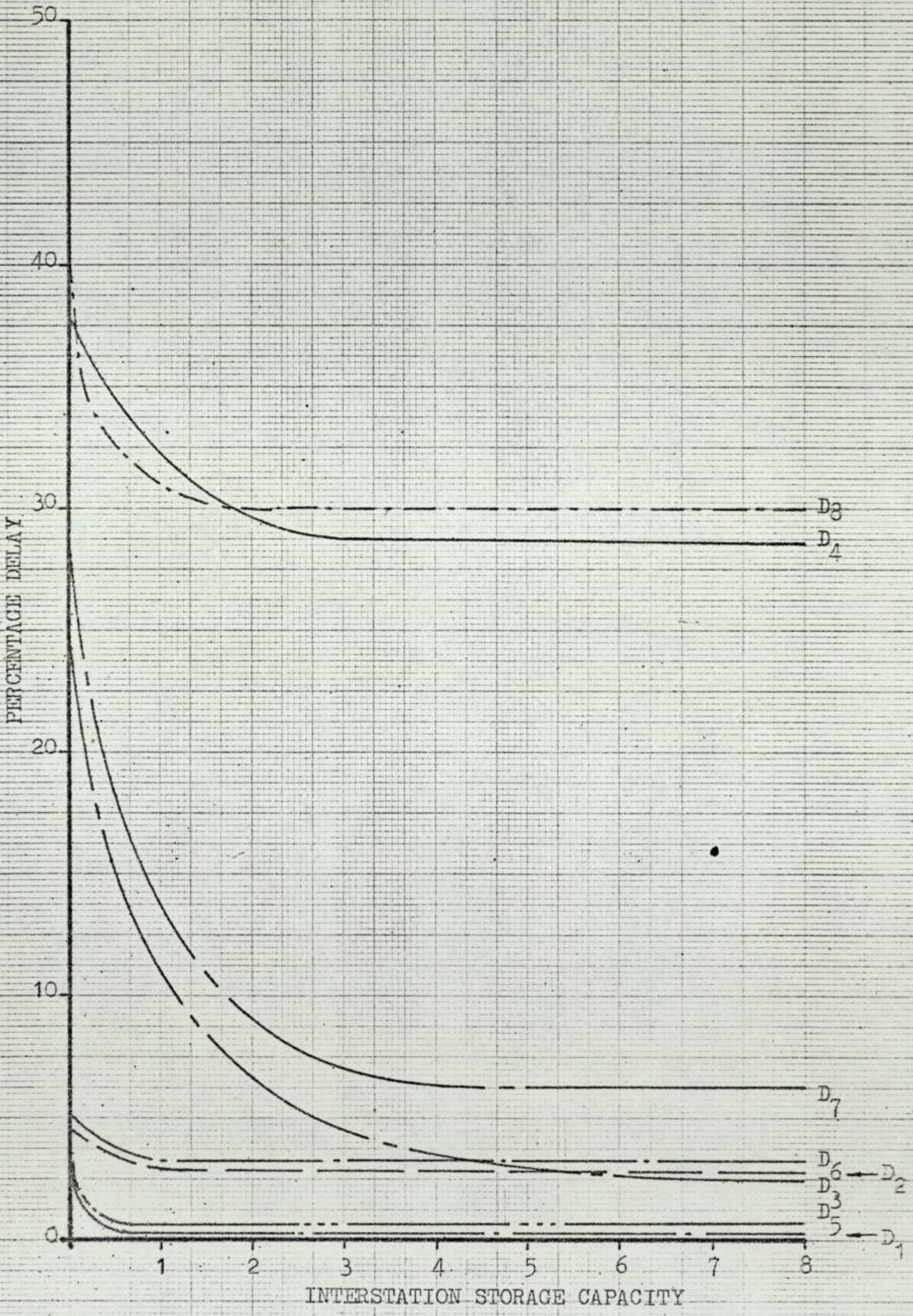
$n_2 = \log_{10}50 = 1.699$

Then the simulated results for D_1 to D_8 to be substituted in the efficiency equation are as follows.

Simulation Results (see Graph C.16)

Dx	PERCENTAGE DELAY (100 – PERCENTAGE EFFICIENCY)									
	T S = 0	U S = 0	U S = 1	U S = 2	U S = 3	U S = 4	U S = 5	U S = 6	U S = 7	U S = 8
D_1	2.99	2.47	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
D_2	4.72	4.41	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92
D_3	29.38	25.42	10.80	6.88	4.93	3.76	3.26	2.67	2.47	2.40
D_4	40.38	38.19	30.45	29.34	28.96	28.85	28.79	28.79	28.79	28.79
D_5	5.17	3.06	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
D_6	6.39	4.69	3.23	3.23	3.23	3.23	3.23	3.23	3.23	3.23
D_7	42.71	29.41	13.33	8.89	7.08	6.46	6.29	6.25	6.25	6.25
D_8	47.57	40.45	31.01	30.31	30.24	30.24	30.24	30.24	30.24	30.24

GRAPH C.16 Simulation Results



C.3 Validation of Efficiency Tables

C.3.1 Comparison with Actual Performance Figures

BUILD SYSTEMS	% SYSTEM EFFICIENCY		
	ACTUAL	TABULATED	DIFFERENCE
Maxi Gateline	75.8	77.7	-1.9
No.1 Marina Gateline	65.4	63.5	+1.9
No.2 Marina Gateline	70.0	73.5	-3.5
Allegro Gateline	78.2	77.7	+0.5
Cowley Intermittent	80.0	72.3	+7.7
Longbridge Intermittent	85.3	75.6	+9.7
Swindon Yo-Yo	79.7	72.6	+7.1

C.3.2 Comparison with Simulated Performance Figures

Validation of the tables by comparing actual production figures with the tabulated values is limited due to the number of existing production lines that can be analysed. Additional simulation exercises were, therefore, executed for a range of conditions to provide additional data to validate the tabulated values.

STRATEGY	1	2	3	4	5	6	7	8	9	10
No. of stations	4	6	8	10	15	20	30	40	50	4
No. of operators per station	1	2	3	4	5	1	2	3	4	5
Stoppage Probability per stn.	.008	.010	.012	.014	.016	.008	.010	.012	.014	.016
Mean downtime (minutes)	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
Coefficient of variation	.04	.08	.12	.16	.20	.24	.28	.32	.04	.08
Mean cycle time (minutes)	4	3	2	1	4	3	2	1	4	3

TIED SYSTEM – INTERSTATION STORAGE CAPACITY OF 0

% Efficiency (simulated)	95.3	85.9	76.4	63.5	63.0	66.4	57.4	39.9	71.8	84.3
% Efficiency (tabulated)	94.7	87.2	77.4	61.1	62.2	68.0	52.8	17.1	70.2	83.6
Difference	+0.6	-1.3	-1.0	+2.4	+0.8	-1.6	+4.6	+22.8	+1.6	+0.7

UNTIED SYSTEM – INTERSTATION STORAGE CAPACITY OF 0

% Efficiency (simulated)	95.8	89.3	79.9	65.3	68.2	76.1	68.7	56.2	83.8	84.5
% Efficiency (tabulated)	95.3	88.2	79.1	63.3	67.3	74.9	60.5	37.8	81.4	83.9
Difference	+0.5	+1.1	+0.8	+2.0	+0.9	+1.2	+8.2	+18.4	+2.4	+0.6

UNTIED SYSTEM – INTERSTATION STORAGE CAPACITY OF 1

% Efficiency (simulated)	98.8	94.0	87.7	77.2	77.2	91.4	80.7	67.0	92.2	89.7
% Efficiency (tabulated)	99.4	94.4	87.5	74.8	77.6	90.9	78.6	62.8	91.7	89.2
Difference	-0.6	-0.4	+0.2	+2.4	-0.4	-0.5	+2.1	+4.2	+0.5	+0.5

STRATEGY	1	2	3	4	5	6	7	8	9	10
UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4										
% Efficiency (simulated)	99.3	94.6	88.1	80.9	78.8	95.2	85.0	73.7	91.2	89.6
% Efficiency (tabulated)	99.4	95.1	89.0	78.7	78.6	95.1	82.9	70.0	92.3	89.9
Difference	-0.1	-0.5	-0.9	+2.2	+0.2	+0.1	+2.1	+3.7	-1.1	-0.3
UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8										
% Efficiency (simulated)	99.0	94.9	88.8	82.3	78.3	94.4	83.5	73.8	91.8	89.8
% Efficiency (tabulated)	99.5	95.3	89.6	80.7	79.0	95.9	83.6	71.4	94.4	90.3
Difference	-0.5	-0.4	-0.8	+1.6	-0.7	-1.5	-0.1	+2.4	-2.6	-0.5

To test the accuracy of the tables when large variancies occur in the conditions from station to station, the following simulation exercises were executed.

STRATEGY 1.

Mean Cycle Time = 3 minutes   Coefficient of Variation = 0.24

Station Number	1	2	3	4	5	6	7	8	9	10	Mean
Stoppage Probability per stn.	.006	.120	.120	.006	.006	.120	.006	.006	.006	.120	.052
Mean downtime (minutes)	1	5	5	1	1	5	1	1	1	5	2.6
No. of operators per stn.	1	5	5	1	1	5	1	1	1	5	2.6

Classification	S = 0 Tied	S = 0 Untied	S = 1 Untied	S = 4 Untied	S = 8 Untied
% Efficiency (simulated)	51.5	55.7	61.1	66.5	66.6
% Efficiency (tabulated)	49.5	55.6	71.6	75.9	77.5
Difference	+2.0	+0.1	-10.5	-9.4	-10.9

STRATEGY 2.

Mean Cycle Time = 2 minutes   Coefficient of Variation = 0.20

Station Number	1	2	3	4	5	6	7	8	9	10
Stoppage Probability per stn.	.100	.002	.003	.070	.008	.002	.009	.080	.009	.020
Mean downtime (minutes)	2	1	1	4	3	1	1	2	1	1
No. of operators per stn.	1	2	1	4	2	1	3	4	2	2

Station Number	11	12	13	14	15	16	17	18	19	20	Mean
Stoppage Probability per stn.	.050	.003	.007	.110	.050	.006	.030	.008	.008	.100	.034
Mean downtime (minutes)	3	4	2	1	1	1	1	3	2	2	1.85
No. of operators per stn.	2	3	1	1	3	2	4	1	1	1	2.05

Classification	S = 0 Tied	S = 0 Untied	S = 1 Untied	S = 4 Untied	S = 8 Untied
% Efficiency (simulated)	53.5	63.5	73.6	75.3	76.4
% Efficiency (tabulated)	51.6	61.9	79.4	81.8	84.5
Difference	+1.9	+1.6	-5.8	-6.5	-8.1

STRATEGY 3.

Mean Cycle Time = 1 minute   Coefficient of Variation = 0.28

Station Number	1	2	3	4	5	6	7	8	9	10	
Stoppage Probability per stn.	.100	.003	.020	.007	.008	.010	.001	.009	.015	.032	
Mean downtime (minutes)	2	2	1	4	3	1	2	1	1	2	
No. of operators per stn.	1	4	1	2	4	2	3	1	1	4	
Station Number	11	12	13	14	15	16	17	18	19	20	
Stoppage Probability per stn.	.080	.001	.001	.002	.005	.060	.006	.007	.001	.020	
Mean downtime (minutes)	4	3	1	2	1	2	2	1	3	4	
No. of operators per stn.	2	1	5	2	2	3	1	3	1	1	
Station Number	21	22	23	24	25	26	27	28	29	30	Mean
Stoppage Probability per stn.	.018	.008	.001	.001	.100	.020	.001	.002	.006	.090	.021
Mean downtime (minutes)	1	1	1	2	2	2	3	4	3	2	2.1
No. of operators per stn.	5	2	3	1	1	2	3	3	2	1	2.2

Classification	S = 0 Tied	S = 0 Untied	S = 1 Untied	S = 4 Untied	S = 8 Untied
% Efficiency (simulated)	41.3	50.3	67.3	74.7	75.5
% Efficiency (tabulated)	39.8	54.8	75.3	80.5	81.4
Difference	+1.5	-4.5	-8.0	-5.8	-5.9

APPENDIX D

THE EFFICIENCY EQUATIONS

D.1 Study Area A

Notation:

$p = \log_{10}$(probability of a stoppage per station)

$q = \log_{10}$(mean stoppage duration in minutes)

$t = \log_{10}$(cycle time in minutes)

$n = \log_{10}$(number of stations)

D = Percentage Delay

$$a = \frac{0.6990 - t}{0.6990}$$

$$b = \frac{-1.000 - p}{0.6990}$$

$$c = \frac{0.6990 - q}{0.6990}$$

$$d = \frac{1.6990 - n}{0.9208}$$

D.1.1 Tied System - Interstation Storage Capacity of 0

$$\begin{aligned}\mathrm{Log}_{10}D = {} & -0.1624abcd + 0.0547bcd - 0.0519acd + 0.0673abd \\ & -0.0735abc - 0.1715cd - 0.3083bd + 0.2603ad \\ & -0.1702bc + 0.2745ac + 0.1762ab - 0.3744d \\ & -0.4051c - 0.2372b + 0.0941a + 1.8515\end{aligned}$$

D.1.2 Untied System - Interstation Storage Capacity of 0

$$\begin{aligned}\mathrm{Log}_{10}D = {} & -0.0305abcd + 0.0008bcd - 0.0586acd + 0.0511abd \\ & -0.0735abc - 0.0719cd - 0.2662bd + 0.1364ad \\ & -0.1016bc + 0.2480ac + 0.1515ab + 0.1954d \\ & -0.5157c - 0.2589b + 0.2603a + 1.6396\end{aligned}$$

D.1.3 Untied System - Interstation Storage Capacity of 1

$$\begin{aligned}\mathrm{Log}_{10}D = {} & 0.1860abcd - 0.0718bcd - 0.0409acd - 0.0305abd \\ & -0.2953abc - 0.0757cd - 0.1485bd + 0.1013ad \\ & -0.0381bc + 0.3724ac + 0.2686ab + 0.1509d \\ & -0.8055c - 0.4347b + 0.4114a + 1.4420\end{aligned}$$

D.1.4 Untied System - Interstation Storage Capacity of 2

$$\begin{aligned}\mathrm{Log}_{10}D = {} & 0.0618abcd + 0.0319bcd + 0.0540acd + 0.0305abd \\ & -0.2233abc - 0.1512cd - 0.1992bd + 0.0803ad \\ & -0.0381bc + 0.2124ac + 0.1761ab - 0.1284d \\ & -0.7294c - 0.4018b + 0.4812a + 1.3420\end{aligned}$$

D.1.5 Untied System - Interstation Storage Capacity of 3

$$\begin{aligned}\log_{10}D = {} & 0.0304abcd + 0.0346bcd + 0.0488acd + 0.0048abd \\ & -0.1742abc - 0.1237cd - 0.2003bd + 0.1103ad \\ & -0.0468bc + 0.1361ac + 0.1437ab - 0.1555d \\ & -0.7049c - 0.3946b + 0.4888a + 1.3100\end{aligned}$$

D.1.6 Untied System - Interstation Storage Capacity of 4

$$\begin{aligned}\log_{10}D = {} & -0.0010abcd + 0.0394bcd + 0.0171acd + 0.0651abd \\ & -0.1346abc - 0.0096cd - 0.2109bd + 0.1364ad \\ & -0.0523bc + 0.1113ac + 0.1046ab - 0.1797d \\ & -0.6883c - 0.3853b + 0.4888a + 1.2896\end{aligned}$$

D.1.7 Untied System - Interstation Storage Capacity of 5

$$\begin{aligned}\log_{10}D = {} & -0.0033abcd + 0.0407bcd - 0.0190acd + 0.0726abd \\ & -0.1223abc - 0.0730cd - 0.2122bd + 0.1586ad \\ & -0.0554bc + 0.1025ac + 0.0769ab - 0.2024d \\ & -0.6756c - 0.3822b + 0.4871a + 1.2769\end{aligned}$$

D.1.8 Untied System - Interstation Storage Capacity of 6

$$\begin{aligned}\log_{10}D = {} & 0.0363abcd + 0.0276bcd - 0.0499acd + 0.0510abd \\ & -0.1235abc - 0.0486cd - 0.1991bd + 0.1794ad \\ & -0.0571bc + 0.0977ac + 0.0688ab - 0.2268d \\ & -0.6700c - 0.3805b + 0.4831a + 1.2713\end{aligned}$$

D.1.9 Untied System - Interstation Storage Capacity of 7

$$\begin{aligned}\mathrm{Log}_{10}D = {} & 0.0967abcd + 0.0035bcd - 0.0695acd + 0.0092abd \\ & -0.1361abc - 0.0284cd - 0.1750bd + 0.1962ad \\ & -0.0555bc + 0.0941ac + 0.0729ab - 0.2470d \\ & -0.6677c - 0.3821b + 0.4795a + 1.2690\end{aligned}$$

D.1.10 Untied System - Interstation Storage Capacity of 8

$$\begin{aligned}\mathrm{Log}_{10}D = {} & 0.1392abcd + 0.0155bcd - 0.0876acd - 0.0290abd \\ & -0.1366abc - 0.0094cd - 0.1560bd + 0.2131ad \\ & -0.0555bc + 0.0914ac + 0.0761ab - 0.2660d \\ & -0.6677c - 0.3821b + 0.4763a + 1.2690\end{aligned}$$

D.2 Study Area B

Notation:

$m = \log_{10}(\text{number of operators per station})$

$n = \log_{10}(\text{number of stations})$

$v = \log_{10}(\text{coefficient of variation})$

$D = \text{Percentage Delay}$

$$e = \frac{0.6990 - m}{0.6990}$$

$$f = \frac{-0.477 - v}{1.1250}$$

$$d = \frac{1.6990 - n}{0.9210}$$

D.2.1 Tied System - Interstation Storage Capacity of 0

$$\begin{aligned}
\mathrm{Log}_{10}D = {} & df\Big(\log_{10}\left[2.99e + 4.72(1-e)\right] - \log_{10}\left[29.37e + 40.38(1-e)\right] \\
& - \log_{10}\left[5.17e + 6.39(1-e)\right] + \log_{10}\left[42.71e + 47.57(1-e)\right]\Big) \\
& + d\Big(\log_{10}\left[29.37e + 40.38(1-e)\right] - \log_{10}\left[42.71e + 47.57(1-e)\right]\Big) \\
& + f\Big(\log_{10}\left[5.17e + 6.39(1-e)\right] - \log_{10}\left[42.71e + 47.57(1-e)\right]\Big) \\
& + \log_{10}\left[42.71e + 47.57(1-e)\right]
\end{aligned}$$

D.2.2 Untied System - Interstation Storage Capacity of 0

$$\begin{aligned}
\mathrm{Log}_{10}D = {} & df\big(\log_{10}[2.46e + 4.41(1-e)] - \log_{10}[25.42e + 38.19(1-e)] \\
& - \log_{10}[3.05e + 4.69(1-e)] + \log_{10}[29.41e + 40.45(1-e)]\big) \\
& + d\big(\log_{10}[25.42e + 38.19(1-e)] - \log_{10}[29.41e + 40.45(1-e)]\big) \\
& + f\big(\log_{10}[3.05e + 4.69(1-e)] - \log_{10}[29.41e + 40.45(1-e)]\big) \\
& + \log_{10}[29.41e + 40.45(1-e)]
\end{aligned}$$

D.2.3 Untied System - Interstation Storage Capacity of 1

$$\begin{aligned}
\mathrm{Log}_{10}D = {} & df\big(\log_{10}[0.11e + 2.92(1-e)] - \log_{10}[10.80e + 30.45(1-e)] \\
& - \log_{10}[0.66e + 3.23(1-e)] + \log_{10}[13.33e + 31.01(1-e)]\big) \\
& + d\big(\log_{10}[10.80e + 30.45(1-e)] - \log_{10}[13.33e + 31.01(1-e)]\big) \\
& + f\big(\log_{10}[0.66e + 3.23(1-e)] - \log_{10}[13.33e + 31.01(1-e)]\big) \\
& + \log_{10}[13.33e + 31.01(1-e)]
\end{aligned}$$

D.2.4 Untied System - Interstation Storage Capacity of 2

$$\begin{aligned}
\mathrm{Log}_{10}D = {} & df\big(\log_{10}[0.11e + 2.92(1-e)] - \log_{10}[6.87e + 29.34(1-e)] \\
& - \log_{10}[0.66e + 3.23(1-e)] + \log_{10}[8.89e + 30.31(1-e)]\big) \\
& + d\big(\log_{10}[6.87e + 29.34(1-e)] - \log_{10}[8.89e + 30.31(1-e)]\big) \\
& + f\big(\log_{10}[0.66e + 3.23(1-e)] - \log_{10}[8.89e + 30.31(1-e)]\big) \\
& + \log_{10}[8.89e + 30.31(1-e)]
\end{aligned}$$

D.2.5 Untied System - Interstation Storage Capacity of 3

$$\begin{aligned}
\mathrm{Log}_{10}D = {} & df\big(\log_{10}[0.11e + 2.92(1-e)] - \log_{10}[4.93e + 28.96(1-e)] \\
& - \log_{10}[0.66e + 3.23(1-e)] + \log_{10}[7.08e + 30.24(1-e)]\big) \\
& + d\big(\log_{10}[4.93e + 28.96(1-e)] - \log_{10}[7.08e + 30.24(1-e)]\big) \\
& + f\big(\log_{10}[0.66e + 3.23(1-e)] - \log_{10}[7.08e + 30.24(1-e)]\big) \\
& + \log_{10}[7.08e + 30.24(1-e)]
\end{aligned}$$

D.2.6 Untied System - Interstation Storage Capacity of 4

$$\begin{aligned}
\mathrm{Log}_{10}D = \; & df\Big(\log_{10}\left[0.11e + 2.92(1-e)\right] - \log_{10}\left[3.75e + 28.85(1-e)\right] \\
& - \log_{10}\left[0.66e + 3.23(1-e)\right] + \log_{10}\left[6.46e + 30.24(1-e)\right]\Big) \\
& + d\Big(\log_{10}\left[3.75e + 28.85(1-e)\right] - \log_{10}\left[6.46e + 30.24(1-e)\right]\Big) \\
& + f\Big(\log_{10}\left[0.66e + 3.23(1-e)\right] - \log_{10}\left[6.46e + 30.24(1-e)\right]\Big) \\
& + \log_{10}\left[6.46e + 30.24(1-e)\right]
\end{aligned}$$

D.2.7 Untied System - Interstation Storage Capacity of 5

$$\begin{aligned}
\mathrm{Log}_{10}D = \; & df\Big(\log_{10}\left[0.11e + 2.92(1-e)\right] - \log_{10}\left[3.26e + 28.78(1-e)\right] \\
& - \log_{10}\left[0.66e + 3.23(1-e)\right] + \log_{10}\left[6.46e + 30.24(1-e)\right]\Big) \\
& + d\Big(\log_{10}\left[3.75e + 28.85(1-e)\right] - \log_{10}\left[6.28e + 30.24(1-e)\right]\Big) \\
& + f\Big(\log_{10}\left[0.66e + 3.23(1-e)\right] - \log_{10}\left[6.28e + 30.24(1-e)\right]\Big) \\
& + \log_{10}\left[6.28e + 30.24(1-e)\right]
\end{aligned}$$

D.2.8 Untied System - Interstation Storage Capacity of 6

$$\begin{aligned}
\mathrm{Log}_{10}D = \; & df\Big(\log_{10}\left[0.11e + 2.92(1-e)\right] - \log_{10}\left[2.67e + 28.78(1-e)\right] \\
& - \log_{10}\left[0.66e + 3.23(1-e)\right] + \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + d\Big(\log_{10}\left[2.67e + 28.78(1-e)\right] - \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + f\Big(\log_{10}\left[0.66e + 3.23(1-e)\right] - \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + \log_{10}\left[6.25e + 30.24(1-e)\right]
\end{aligned}$$

D.2.9 Untied System - Interstation Storage Capacity of 7

$$\begin{aligned}
\mathrm{Log}_{10}D = \; & df\Big(\log_{10}\left[0.11e + 2.92(1-e)\right] - \log_{10}\left[2.46e + 28.78(1-e)\right] \\
& - \log_{10}\left[0.66e + 3.23(1-e)\right] + \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + d\Big(\log_{10}\left[2.46e + 28.78(1-e)\right] - \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + f\Big(\log_{10}\left[0.66e + 3.23(1-e)\right] - \log_{10}\left[6.25e + 30.24(1-e)\right]\Big) \\
& + \log_{10}\left[6.25e + 30.24(1-e)\right]
\end{aligned}$$

D.2.10 Untied System - Interstation Storage Capacity of 8

$$
\begin{aligned}
\mathrm{Log}_{10}D = {} & df\Big(\log_{10}\big[0.11e + 2.92(1-e)\big] - \log_{10}\big[2.40e + 28.78(1-e)\big] \\
& - \log_{10}\big[0.66e + 3.23(1-e)\big] - \log_{10}\big[6.25e + 30.24(1-e)\big]\Big) \\
& + d\Big(\log_{10}\big[2.40e + 28.78(1-e)\big] - \log_{10}\big[6.25e + 30.24(1-e)\big]\Big) \\
& + f\Big(\log_{10}\big[0.66e + 3.23(1-e)\big] - \log_{10}\big[6.25e + 30.24(1-e)\big]\Big) \\
& + \log_{10}\big[6.25e + 30.24(1-e)\big]
\end{aligned}
$$

APPENDIX E

THE EFFICIENCY TABLES

NOTATION:

M = Number of Operators per Station

N = Number of Stations

P = Probability of a Station Stoppage

Q = Mean Stoppage Duration in Minutes

T = Mean Cycle Time in Minutes

V = Coefficient of Variation .

Table A = Percentage Delays caused by Production Stoppages e.g. Equipment Breakdown, Material Shortage and Operator Error.

Table B = Percentage Delays caused by Operator Work Rate Variability.

TABLE A

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

T	N	4					6					8				
	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	4.96	5.85	6.76	7.68	8.60	6.26	7.33	8.42	9.22	10.60	7.45	8.76	10.09	11.43	12.77
	.010	5.80	6.87	7.88	8.91	9.94	7.28	8.48	9.35	10.61	12.07	8.64	10.09	11.54	12.98	14.43
	.012	6.71	6.84	8.95	10.07	11.19	7.83	9.18	10.85	12.15	13.44	9.76	11.32	12.87	14.42	15.95
	.014	7.52	8.74	9.96	11.16	11.38	9.16	10.22	11.96	13.34	14.71	10.82	12.48	14.12	15.75	17.36
	.016	8.31	9.62	10.92	12.21	13.49	10.03	11.53	13.01	14.46	15.91	11.83	13.58	15.30	17.00	18.68
2	.008	2.33	2.76	3.18	3.62	3.63	3.02	3.55	4.08	4.52	5.08	3.63	4.41	5.08	5.76	6.44
	.010	2.80	3.30	3.79	4.29	4.79	3.44	4.06	4.69	5.32	5.95	4.43	5.18	5.94	6.70	7.46
	.012	3.26	3.82	4.37	4.93	5.50	3.99	4.68	5.37	6.07	6.77	5.07	5.91	6.74	7.57	8.40
	.014	3.70	4.32	4.94	5.55	6.17	4.52	5.27	6.03	6.80	7.56	5.69	6.60	7.50	8.40	9.29
	.016	4.13	4.81	5.48	6.15	6.82	5.03	5.85	6.67	7.50	8.31	6.29	7.26	8.23	9.19	10.14
3	.008	1.50	1.77	2.05	2.33	2.61	1.97	2.32	2.67	3.03	3.38	2.50	2.95	3.40	3.86	4.32
	.010	1.82	2.15	2.47	2.80	3.13	2.36	2.77	3.17	3.58	3.99	2.99	3.51	4.02	4.54	5.07
	.012	2.14	2.51	2.88	3.25	3.63	2.73	3.19	3.65	4.11	4.57	3.46	4.04	4.61	5.19	5.77
	.014	2.44	2.86	3.28	3.69	4.11	3.09	3.60	4.11	4.62	5.15	3.91	4.55	5.18	5.82	6.45
	.016	2.75	3.21	3.66	4.12	4.58	3.43	4.00	4.57	5.14	5.71	4.35	5.04	5.72	6.41	7.09
4	.008	1.10	1.30	1.50	1.70	1.91	1.46	1.72	1.98	2.24	2.51	1.88	2.22	2.56	2.90	3.25
	.010	1.34	1.58	1.82	2.07	2.31	1.76	2.06	2.37	2.68	2.98	2.27	2.66	3.05	3.45	3.85
	.012	1.58	1.86	2.14	2.42	2.70	2.05	2.39	2.74	3.10	3.46	2.63	3.08	3.53	3.98	4.42
	.014	1.82	2.13	2.21	2.76	3.08	2.33	2.72	3.12	3.52	3.92	2.99	3.49	3.99	4.48	4.98
	.016	2.06	2.17	2.75	3.10	3.45	2.62	3.05	3.49	3.93	4.37	3.43	3.89	4.43	4.97	5.51

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

T	N	10					15					20				
	P Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	9.01	10.50	12.00	13.50	14.99	12.73	14.60	16.45	18.27	20.06	16.28	18.45	20.57	22.64	24.67
	.010	10.34	11.97	13.58	15.19	16.78	14.34	16.32	18.28	20.19	22.06	18.07	20.35	22.56	24.70	26.79
	.012	11.58	13.32	15.03	16.72	18.40	15.80	17.89	19.92	21.90	23.85	19.69	22.05	24.33	26.53	28.66
	.014	12.74	14.57	16.37	18.14	19.89	17.15	19.32	21.42	23.47	25.47	21.16	23.60	25.93	28.17	30.35
	.016	13.84	15.76	17.63	19.47	21.28	18.41	20.65	22.82	24.92	26.96	22.53	25.02	27.40	29.68	31.89
2	.008	4.60	5.38	6.17	6.96	7.75	6.67	7.72	8.77	9.80	10.84	8.68	9.97	11.25	12.51	13.75
	.010	5.38	6.25	7.13	8.01	8.65	7.66	8.82	9.96	11.09	12.21	9.84	11.24	12.62	13.97	15.30
	.012	6.11	7.08	8.03	8.98	9.93	8.58	9.83	11.05	12.26	13.46	10.91	12.40	13.86	15.29	16.69
	.014	6.81	7.85	8.88	9.90	10.91	9.49	10.77	12.07	13.35	14.61	11.90	13.47	15.01	16.50	17.97
	.016	7.48	8.59	9.69	10.77	11.84	10.25	11.66	13.03	14.37	15.69	12.83	14.48	16.08	17.63	19.15
3	.008	3.10	3.64	4.18	4.72	5.27	4.57	5.32	6.07	6.81	7.56	6.01	6.96	7.90	8.84	9.77
	.010	3.67	4.28	4.89	5.51	6.12	5.31	6.15	6.98	7.81	8.64	6.90	7.95	8.98	10.01	11.02
	.012	4.21	4.89	5.57	6.25	6.92	6.00	6.92	7.83	8.73	9.63	7.72	8.86	9.98	11.08	12.17
	.014	4.72	5.47	6.21	6.95	7.68	6.65	7.65	8.63	9.60	10.56	8.49	9.71	10.90	12.07	13.22
	.016	5.22	6.03	6.83	7.62	8.41	7.28	8.34	9.39	10.42	11.43	9.22	10.51	11.77	13.00	14.22
4	.008	2.35	2.76	3.17	3.59	4.00	3.50	4.08	4.67	5.26	5.85	4.63	5.39	6.15	6.91	7.67
	.010	2.80	3.27	3.74	4.22	4.70	4.09	4.76	5.43	6.09	6.76	5.36	6.21	7.06	7.90	8.74
	.012	3.23	3.76	4.29	4.83	5.36	4.66	5.40	6.13	6.86	7.59	6.04	6.98	7.90	8.81	9.72
	.014	3.64	4.23	4.82	5.40	5.99	5.20	6.00	6.80	7.59	8.38	6.69	7.69	8.69	9.67	10.64
	.016	4.04	4.69	5.32	5.96	6.59	5.71	6.58	7.44	8.29	9.13	7.30	8.37	9.43	10.47	11.50

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

N		30					40					50				
T	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	23.01	25.65	28.19	30.64	33.00	29.41	32.41	35.25	37.97	40.58	35.57	38.85	41.93	44.85	47.63
	.010	25.05	27.76	30.35	32.83	36.23	31.58	34.60	37.46	40.18	42.77	37.79	41.05	44.11	46.99	49.72
	.012	26.85	29.62	32.24	34.74	37.15	33.47	36.51	39.37	42.07	44.65	39.70	42.94	45.97	48.81	51.50
	.014	28.48	31.28	33.93	36.45	38.86	35.15	38.20	41.06	43.75	46.31	41.39	44.61	47.60	50.41	53.06
	.016	29.97	32.79	35.46	37.99	40.40	36.68	39.73	42.58	45.25	47.79	42.91	46.11	49.07	51.83	54.44
2	.008	12.59	14.31	15.99	17.62	19.23	16.40	18.49	20.51	22.48	24.40	20.12	22.55	24.89	27.15	29.35
	.010	14.02	15.85	17.62	19.34	21.03	18.02	20.21	22.32	24.36	26.35	21.89	24.41	26.82	29.14	31.39
	.012	15.31	17.22	19.07	20.86	22.62	19.46	21.74	23.92	26.02	28.06	23.46	26.04	28.51	30.88	33.16
	.014	16.49	18.48	20.40	22.25	24.06	20.78	23.12	25.36	27.51	29.59	24.87	27.51	30.02	32.42	34.74
	.016	17.58	19.64	21.62	23.53	25.37	21.99	24.39	26.67	28.86	30.98	26.16	28.84	31.39	33.83	31.16
3	.008	8.85	10.17	11.47	12.75	14.02	11.65	13.31	14.94	16.55	18.13	14.42	16.40	18.34	20.25	22.11
	.010	9.99	11.41	12.81	14.19	15.55	12.98	14.76	16.49	18.18	19.85	15.91	18.01	20.05	22.04	23.99
	.012	11.02	12.54	14.03	15.49	16.92	14.18	16.05	17.87	19.64	21.38	17.24	19.44	21.56	23.62	25.64
	.014	11.97	13.58	15.15	16.67	18.17	15.28	17.23	19.13	20.97	22.77	18.46	20.73	22.92	25.05	27.12
	.016	12.87	14.55	16.18	17.77	19.33	16.30	18.33	20.29	22.19	24.04	19.58	21.92	24.18	26.35	28.47
4	.008	6.89	7.98	9.06	10.14	11.21	9.14	10.55	11.93	13.31	14.68	11.38	13.09	14.77	16.44	18.09
	.010	7.85	9.04	10.22	11.39	12.55	10.28	11.80	13.30	14.78	16.24	12.68	14.51	16.31	18.08	19.82
	.012	8.73	10.01	11.28	12.53	13.77	11.32	12.94	14.53	16.09	17.63	13.86	15.79	17.68	19.53	21.36
	.014	9.54	10.92	12.26	13.59	14.89	12.28	13.99	15.66	17.30	18.90	14.94	16.96	18.93	20.86	22.75
	.016	10.31	11.76	13.18	14.57	15.94	13.18	14.97	16.71	18.41	20.08	15.94	18.04	20.09	22.08	24.02

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

N		4					6					8				
T	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	4.96	5.85	6.76	7.68	8.60	6.26	7.33	8.42	9.50	10.59	7.38	8.61	9.83	11.05	12.27
	.010	5.85	6.87	7.89	8.91	9.94	7.28	8.48	9.68	10.88	12.07	8.51	9.86	11.20	12.53	13.86
	.012	6.71	7.83	8.95	10.07	11.19	8.25	9.56	10.86	12.15	13.44	9.55	11.01	12.45	13.88	15.30
	.014	7.52	8.74	9.96	11.16	12.37	9.16	10.57	11.96	13.34	14.71	10.53	12.09	13.62	15.14	16.62
	.016	8.31	9.62	10.92	12.21	13.49	10.03	11.53	13.01	14.47	15.91	11.46	13.11	14.73	16.32	17.89
2	.008	2.33	2.76	3.18	3.62	4.05	3.02	3.55	4.08	4.62	5.15	3.63	4.25	4.87	5.49	6.11
	.010	2.80	3.30	3.79	4.29	4.79	3.58	4.18	4.79	5.40	6.01	4.25	4.95	5.65	6.35	7.05
	.012	3.26	3.82	4.37	4.93	5.50	4.11	4.78	5.46	6.13	6.80	4.84	5.62	6.39	7.15	7.92
	.014	3.70	4.32	4.94	5.55	6.17	4.62	5.36	6.10	6.83	7.56	5.40	6.24	7.08	7.91	8.73
	.016	4.13	4.81	5.48	6.15	6.82	5.11	5.91	6.71	7.50	8.29	5.94	6.84	7.74	8.63	9.51
3	.008	1.50	1.77	2.05	2.33	2.61	1.97	2.32	2.67	3.03	3.38	2.40	2.81	3.23	3.65	4.07
	.010	1.82	2.15	2.47	2.80	3.13	2.36	2.77	3.17	3.58	3.99	2.84	3.31	3.79	4.27	4.75
	.012	2.14	2.51	2.88	3.25	3.63	2.73	3.19	3.65	4.11	4.57	3.25	3.79	4.32	4.85	5.39
	.014	2.44	2.86	3.28	3.69	4.11	3.09	3.60	4.11	4.62	5.12	3.65	4.24	4.83	5.41	5.99
	.016	2.75	3.21	3.66	4.12	4.58	3.44	4.00	4.55	5.11	5.66	4.04	4.68	5.41	5.94	6.57
4	.008	1.09	1.30	1.50	1.70	1.91	1.46	1.72	1.98	2.24	2.51	1.79	2.10	2.41	2.73	3.05
	.010	1.34	1.58	1.82	2.07	2.31	1.76	2.06	2.37	2.68	2.99	2.13	2.49	2.85	3.22	3.59
	.012	1.58	1.86	2.14	2.42	2.70	2.05	2.39	2.74	3.09	3.45	2.45	2.86	3.27	3.68	4.10
	.014	1.82	2.13	2.45	2.76	3.08	2.33	2.72	3.11	3.50	3.89	2.77	3.22	3.68	4.13	4.59
	.016	2.06	2.40	2.75	3.10	3.45	2.60	3.03	3.46	3.89	4.32	3.07	3.57	4.07	4.56	5.06

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

T	N	10					15					20				
	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	8.39	9.74	11.09	12.43	13.76	10.59	12.21	13.80	15.38	16.95	12.50	14.32	16.13	17.90	19.65
	.010	9.59	11.07	12.53	13.98	15.42	11.94	13.67	15.38	17.07	18.73	13.94	15.88	17.79	19.66	21.50
	.012	10.70	12.29	13.85	15.39	16.92	13.16	14.99	16.80	18.57	20.32	15.23	17.28	19.27	21.22	23.13
	.014	11.73	13.42	15.07	16.70	18.30	14.28	16.22	18.11	19.95	21.76	16.42	18.55	20.63	22.64	24.61
	.016	12.71	14.48	16.22	17.92	19.59	15.34	17.36	19.32	21.23	23.10	17.53	19.74	21.87	23.95	25.97
2	.008	4.19	4.89	5.58	6.28	6.98	5.42	6.29	7.16	8.02	8.88	6.52	7.53	8.54	9.54	10.53
	.010	4.86	5.65	6.43	7.21	7.98	6.21	7.18	8.12	9.06	10.00	7.39	8.49	9.58	10.67	11.74
	.012	5.50	6.36	7.21	8.06	8.90	6.93	7.97	9.00	10.02	11.02	8.16	9.36	10.53	11.69	12.83
	.014	6.10	7.03	7.95	8.86	9.77	7.60	8.72	9.82	10.90	11.97	8.89	10.16	11.40	12.62	13.83
	.016	6.67	7.67	8.65	9.62	10.58	8.24	9.42	10.58	11.73	12.85	9.58	10.91	12.21	13.49	14.75
3	.008	2.79	3.26	3.74	4.21	4.69	3.67	4.27	4.88	5.48	6.08	4.45	5.17	5.89	6.60	7.31
	.010	3.27	3.81	4.35	4.89	5.43	4.23	4.91	5.59	6.26	6.93	5.09	5.88	6.67	7.46	8.24
	.012	3.72	4.33	4.92	5.52	6.12	4.76	5.51	6.25	6.98	7.71	5.67	6.53	7.39	8.24	9.08
	.014	4.16	4.82	5.47	6.12	6.77	5.26	6.06	6.86	7.65	8.44	6.21	7.14	8.06	8.97	9.86
	.016	4.57	5.28	5.99	6.69	7.38	5.73	6.59	7.44	8.29	9.12	6.72	7.71	8.69	9.65	10.60
4	.008	2.09	2.45	2.81	3.17	3.54	2.78	3.24	3.71	4.18	4.65	3.40	3.96	4.52	5.08	5.64
	.010	2.47	2.88	3.30	3.71	4.13	3.23	3.76	4.29	4.81	5.34	3.91	4.54	5.16	5.79	6.41
	.012	2.82	3.29	3.76	4.22	4.69	3.65	4.24	4.82	5.40	5.98	4.37	5.07	5.75	6.43	7.11
	.014	3.17	3.68	4.19	4.70	5.21	4.05	4.69	5.32	5.95	6.58	4.81	5.56	6.30	7.04	7.77
	.016	3.50	4.06	4.61	5.17	5.72	4.43	5.12	5.80	6.48	7.15	5.23	6.03	6.82	7.60	8.38

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF O

	N	30					40					50				
T	P Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	15.78	17.95	20.07	22.15	24.20	18.61	21.07	23.45	25.77	28.05	21.16	23.85	26.45	28.99	31.46
	.010	17.34	19.62	21.83	23.99	26.11	20.25	22.79	25.25	27.64	29.96	22.83	25.60	28.26	30.84	33.35
	.012	18.73	21.09	23.38	25.61	27.78	21.69	24.30	26.82	29.26	31.62	24.30	27.12	29.83	32.44	34.97
	.014	19.99	22.43	24.78	27.06	29.27	22.98	25.66	28.22	30.70	33.10	25.61	28.48	31.22	33.86	36.41
	.016	21.15	26.65	26.06	28.38	30.63	24.17	26.89	29.50	32.01	34.43	26.80	29.71	32.48	35.14	37.71
2	.008	8.45	9.71	10.95	12.18	13.40	10.15	11.62	13.06	14.49	15.89	11.70	13.36	14.98	16.57	18.14
	.010	9.41	10.77	12.10	13.42	14.71	11.19	12.75	14.29	15.79	17.26	12.80	14.54	16.25	17.91	19.55
	.012	10.29	11.73	13.14	14.52	15.88	12.12	13.77	15.37	16.94	18.48	13.77	15.59	17.36	19.09	20.78
	.014	11.09	12.60	14.08	15.52	16.94	12.97	14.68	16.35	17.98	19.57	14.64	16.53	18.36	20.14	21.88
	.016	11.83	13.41	14.95	16.45	17.92	13.75	15.52	17.25	18.93	20.56	15.48	17.39	19.27	21.10	22.89
3	.008	5.86	6.77	7.68	8.58	9.48	7.12	8.20	9.28	10.34	11.39	8.28	9.52	10.74	11.95	13.14
	.010	6.59	7.58	8.57	9.55	10.52	7.91	9.08	10.24	11.38	12.51	9.12	10.45	11.75	13.03	14.30
	.012	7.25	8.32	9.38	10.42	11.45	8.62	9.87	11.10	12.30	13.49	9.87	11.27	12.65	13.99	15.32
	.014	7.85	8.99	10.11	11.22	12.30	9.28	10.59	11.88	13.14	14.39	10.56	12.02	13.46	14.86	16.25
	.016	8.42	9.62	10.80	11.95	13.09	9.88	11.26	12.60	13.92	15.21	11.19	12.72	14.20	15.66	17.09
4	.008	4.52	5.25	5.97	6.70	7.42	5.53	6.41	7.28	8.14	9.00	6.47	7.48	8.48	9.47	10.46
	.010	5.11	5.91	6.71	7.50	8.29	6.19	7.14	8.08	9.02	9.95	7.17	8.26	9.34	10.40	11.46
	.012	5.65	6.52	7.38	8.23	9.08	6.77	7.80	8.80	9.81	10.79	7.80	8.96	10.10	11.23	12.35
	.014	6.15	7.08	8.00	8.91	9.80	7.32	8.40	9.47	10.52	11.57	8.37	9.59	10.80	11.98	13.15
	.016	6.62	7.60	8.57	9.53	10.48	7.82	8.96	10.08	11.19	12.28	8.90	10.18	11.44	12.67	13.89

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 1

	N	4					6					8				
T	p Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	3.46	4.21	4.98	5.77	6.60	3.92	4.78	5.67	6.59	7.54	4.29	5.23	6.21	7.23	8.29
	.010	4.10	4.95	5.82	6.73	7.65	4.62	5.58	6.58	7.62	8.67	5.02	6.08	7.18	8.32	9.48
	.012	4.70	5.64	6.62	7.62	8.63	5.27	6.34	7.44	8.57	9.73	5.72	6.89	8.09	9.32	10.59
	.014	5.28	6.32	7.38	8.46	9.57	5.90	7.06	8.26	9.48	10.72	6.38	7.64	8.94	10.27	11.62
	.016	5.84	6.96	8.11	9.27	10.45	6.50	7.75	9.03	10.33	11.66	7.01	8.37	9.75	11.16	12.59
2	.008	1.22	1.51	1.82	2.14	2.48	1.45	1.79	2.15	2.53	2.92	1.63	2.02	2.42	2.84	3.28
	.010	1.48	1.82	2.18	2.56	2.96	1.74	2.14	3.56	3.00	3.45	1.95	2.40	2.86	3.35	3.85
	.012	1.73	2.12	2.54	2.97	3.41	2.02	2.48	2.95	3.44	3.96	2.26	2.76	3.28	3.83	4.39
	.014	1.98	2.42	2.88	3.36	3.85	2.29	2.80	3.33	3.87	4.44	2.55	3.11	3.69	4.29	4.91
	.016	2.22	2.71	3.21	3.74	4.28	2.56	3.12	3.69	4.29	4.90	2.84	3.45	4.08	4.73	5.40
3	.008	0.66	0.83	1.01	1.20	1.40	0.81	1.01	1.22	1.44	1.68	0.93	1.15	1.39	1.65	1.91
	.010	0.81	1.02	1.45	1.71	1.98	0.98	1.22	1.47	1.74	2.01	1.12	1.39	1.67	1.97	2.28
	.012	0.96	1.20	1.45	1.71	1.98	1.15	1.43	1.72	2.02	2.34	1.31	1.62	1.94	2.28	2.63
	.014	1.11	1.38	1.66	1.96	2.27	1.32	1.63	1.96	2.30	2.65	1.49	1.84	2.20	2.57	2.96
	.016	1.26	1.56	1.87	2.20	2.54	1.49	1.83	2.19	2.56	2.96	1.67	2.05	2.45	2.86	3.29
4	.008	0.43	0.54	0.66	0.79	0.93	0.53	0.67	0.82	0.97	1.13	0.62	0.78	0.94	1.12	1.30
	.010	0.53	0.67	0.82	0.98	1.14	0.65	0.82	0.99	1.18	1.37	0.76	0.94	1.14	1.35	1.57
	.012	0.64	0.80	0.97	1.16	1.35	0.77	0.97	1.17	1.38	1.61	0.89	1.10	1.33	1.57	1.82
	.014	0.74	0.93	1.12	1.33	1.55	0.89	1.11	1.34	1.58	1.84	1.02	1.26	1.52	1.79	2.07
	.016	0.84	1.05	1.27	1.51	1.75	1.01	1.25	1.51	1.78	2.06	1.15	1.42	1.70	2.00	2.32

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 1

T	N	10					15					20				
	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	4.59	5.61	6.67	7.78	8.92	5.20	6.37	7.60	8.88	10.20	5.68	6.98	8.33	9.75	11.21
	.010	5.36	6.50	7.69	8.91	10.16	6.04	7.34	8.69	10.09	11.52	6.58	8.00	9.48	11.02	12.60
	.012	6.09	7.34	8.63	9.95	11.31	6.83	8.24	9.70	11.20	12.74	7.41	8.95	10.54	12.18	13.86
	.014	6.78	8.13	9.51	10.93	12.37	7.57	9.09	10.64	12.24	13.86	8.19	9.84	11.53	13.26	15.03
	.016	7.44	8.88	10.35	11.85	13.37	8.28	9.89	11.53	13.21	14.92	8.94	10.68	12.45	14.27	16.11
2	.008	1.79	2.21	2.65	3.12	3.60	2.13	2.62	3.14	3.68	4.24	2.40	2.95	3.53	4.13	4.76
	.010	2.13	2.62	3.12	3.65	4.20	2.51	3.07	3.66	4.27	4.90	2.81	3.44	4.09	4.77	5.47
	.012	2.46	3.00	3.57	4.16	4.76	2.87	3.50	4.15	4.82	5.52	3.20	3.90	4.62	5.36	6.13
	.014	2.77	3.37	3.99	4.64	5.30	3.21	3.90	4.61	5.35	6.11	3.57	4.33	5.11	5.92	6.75
	.016	3.07	3.72	4.40	5.10	5.82	3.55	4.29	5.06	5.85	6.66	3.93	4.74	5.59	6.45	7.34
3	.008	1.03	1.28	1.55	1.82	2.11	1.26	1.56	1.87	2.20	2.57	1.45	1.78	2.14	2.50	2.89
	.010	1.24	1.54	1.84	2.17	2.50	1.50	1.84	2.20	2.58	2.97	1.71	2.10	2.50	2.92	3.36
	.012	1.44	1.78	2.13	2.49	2.87	1.73	2.12	2.52	2.95	3.39	1.96	2.40	2.85	3.32	3.81
	.014	1.64	2.01	2.40	2.81	3.23	1.95	2.38	2.83	3.30	3.78	2.20	2.68	3.18	3.69	4.23
	.016	1.83	2.24	2.67	3.11	3.58	2.16	2.63	3.12	3.63	4.16	2.43	2.95	3.49	4.05	4.63
4	.008	0.70	0.87	1.05	1.25	1.45	0.87	1.08	1.29	1.52	1.76	1.01	1.25	1.50	1.75	2.02
	.010	0.85	1.05	1.27	1.50	1.73	1.04	1.28	1.54	1.81	2.09	1.20	1.48	1.77	2.07	2.38
	.012	0.99	1.23	1.48	1.74	2.01	1.21	1.48	1.77	2.08	2.39	1.39	1.69	2.02	2.36	2.71
	.014	1.13	1.40	1.68	1.97	2.27	1.36	1.68	2.00	2.34	2.69	1.56	1.91	2.27	2.64	3.03
	.016	1.27	1.56	1.87	2.20	2.53	1.52	1.86	2.22	2.59	2.98	1.73	2.11	2.50	2.92	3.34

UNTIED SYSTEM – INTERSTATION STORAGE CAPACITY OF 1

T N	P Q	30					40					50				
		1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	6.44	7.93	9.49	11.12	12.81	7.04	8.68	10.40	12.21	14.09	7.54	9.31	11.18	13.13	15.17
	.010	7.41	9.03	10.72	12.48	14.29	8.06	9.84	11.70	13.63	15.62	8.61	10.52	12.52	14.60	16.74
	.012	8.31	10.05	11.85	13.71	15.62	9.01	10.91	12.88	14.91	16.99	9.59	11.63	13.74	15.91	18.15
	.014	9.15	11.00	12.90	14.85	16.84	9.89	11.90	13.97	16.09	18.25	10.51	12.66	14.86	17.12	19.43
	.016	9.95	11.89	13.88	15.91	17.97	10.73	12.83	14.99	17.18	19.42	11.38	13.62	15.91	18.24	20.62
2	.008	2.85	3.49	4.17	4.88	5.61	3.21	3.94	4.70	5.49	6.31	3.53	4.32	5:15	6.01	6.90
	.010	3.31	4.04	4.79	5.58	6.39	3.71	4.52	5.36	6.23	7.13	4.06	4.94	5.85	6.80	7.77
	.012	3.74	4.54	5.37	6.23	7.11	4.18	5.06	5.98	6.92	7.89	4.55	5.58	6.49	7.51	8.56
	.014	4.15	5.01	5.91	6.83	7.75	4.61	5.56	6.54	7.56	8.59	5.01	6.03	7.09	8.18	9.29
	.016	4.54	5.47	6.42	7.40	8.40	5.03	6.04	7.09	8.16	9.25	5.44	6.53	7.65	3.80	9.97
3	.008	1.77	2.16	2.58	3.01	3.46	2.03	2.48	2.95	3.44	3.94	2.27	2.76	3.27	3.81	4.36
	.010	2.06	2.52	2.99	3.48	3.99	2.36	2.87	3.40	3.95	4.51	2.61	3.17	3.75	4.35	4.96
	.012	2.35	2.85	3.38	3.92	4.48	2.66	3.23	3.81	4.42	5.04	2.94	3.55	4.19	4.84	5.51
	.014	2.61	3.17	3.74	4.34	4.95	2.95	3.57	4.20	4.86	5.53	3.24	3.91	4.60	5.31	6.03
	.016	2.87	3.47	4.09	4.73	5.39	3.24	3.89	4.57	5.28	5.99	3.53	4.25	4.99	5.74	6.52
4	.008	1.26	1.54	1.83	2.14	2.46	1.47	1.79	2.12	2.47	2.82	1.65	2.01	2.37	2.75	3.14
	.010	1.48	1.80	2.14	2.50	2.86	1.71	2.08	2.46	2.86	3.26	1.91	2.32	2.73	3.16	3.61
	.012	1.68	2.05	2.43	2.83	3.23	1.94	2.35	2.77	3.21	3.66	2.16	2.60	3.07	3.55	4.04
	.014	1.88	2.29	2.71	3.14	3.59	2.15	2.60	3.07	3.55	4.05	2.38	2.88	3.38	3.90	4.44
	.016	2.07	2.51	2.97	3.44	3.93	2.35	2.85	3.35	3.87	4.41	2.60	3.13	3.68	4.24	4.82

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

T	N / P \ Q	4					6					8				
		1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	2.65	3.15	3.67	4.19	4.72	2.92	3.49	4.06	4.65	5.25	3.13	3.74	4.37	5.01	5.66
	.010	3.17	3.75	4.35	4.95	5.56	3.47	4.12	4.78	5.46	6.14	3.70	4.40	5.12	5.85	6.59
	.012	3.67	4.33	5.00	5.68	6.36	3.99	4.72	5.46	6.22	6.98	4.24	5.02	5.82	6.63	7.45
	.014	4.15	4.88	5.62	6.37	7.13	4.49	5.30	6.12	6.94	7.77	4.75	5.62	6.49	7.38	8.27
	.016	4.62	5.42	6.23	7.04	7.86	4.98	5.86	6.74	7.64	8.54	5.25	6.19	7.13	8.09	9.05
2	.008	1.11	1.31	1.52	1.72	1.93	1.28	1.52	1.76	2.00	2.25	1.42	1.69	1.96	2.23	2.51
	.010	1.34	1.58	1.82	2.07	2.31	1.54	1.82	2.10	2.38	2.67	1.69	2.00	2.32	2.64	2.98
	.012	1.57	1.84	2.12	2.40	2.68	1.78	2.10	2.42	2.75	3.07	1.95	2.31	2.66	3.02	3.38
	.014	1.79	2.10	2.41	2.72	3.04	2.02	2.38	2.74	3.10	3.46	2.21	2.60	2.99	3.39	3.79
	.016	2.00	2.35	2.69	3.04	3.39	2.25	2.65	3.04	3.44	3.83	2.45	2.88	3.31	3.75	4.19
3	.008	0.67	0.79	0.90	1.02	1.14	0.79	0.94	1.08	1.22	1.37	0.90	1.06	1.22	1.39	1.56
	.010	0.81	0.95	1.10	1.24	1.38	0.96	1.13	1.30	1.47	1.64	1.07	1.27	1.46	1.65	1.85
	.012	0.95	1.12	1.28	1.45	1.62	1.11	1.31	1.51	1.70	1.90	1.24	1.46	1.68	1.91	2.13
	.014	1.09	1.28	1.47	1.66	1.85	1.27	1.49	1.71	1.93	2.15	1.41	1.65	1.90	2.15	2.40
	.016	1.23	1.44	1.65	1.86	2.07	1.42	1.66	1.91	2.15	2.40	1.57	1.84	2.11	2.39	2.67
4	.008	0.47	0.55	0.63	0.71	0.79	0.56	0.66	0.76	0.86	0.96	0.65	0.76	0.88	0.99	1.11
	.010	0.57	0.67	0.76	0.86	0.96	0.68	0.80	0.92	1.04	1.15	0.78	0.91	1.05	1.19	1.33
	.012	0.67	0.79	0.90	1.01	1.13	0.80	0.94	1.07	1.21	1.35	0.90	1.06	1.22	1.38	1.54
	.014	0.77	0.90	1.03	1.16	1.30	0.91	1.07	1.22	1.38	1.54	1.02	1.20	1.38	1.56	1.74
	.016	0.87	1.02	1.16	1.38	1.46	1.02	1.19	1.37	1.55	1.72	1.14	1.34	1.54	1.74	1.94

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

	N	10					15					20				
T	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	3.30	3.96	4.62	5.31	6.01	3.64	4.37	5.13	5.90	6.68	3.90	4.70	5.51	6.35	7.21
	.010	3.88	4.63	5.39	6.17	6.96	4.25	5.08	5.93	6.80	7.68	4.53	5.43	6.35	7.28	8.24
	.012	4.44	5.27	6.11	6.97	7.84	4.83	5.75	6.68	7.64	8.60	5.13	6.11	7.12	8.14	9.19
	.014	4.96	5.88	6.80	7.73	8.68	5.38	6.38	7.39	8.42	9.47	5.69	6.76	7.85	8.95	10.08
	.016	5.47	6.46	7.45	8.46	9.47	5.90	6.98	8.07	9.17	10.29	6.22	7.37	8.54	9.71	10.91
2	.008	1.54	1.83	2.13	2.42	2.73	1.78	2.12	2.47	2.82	3.18	1.97	2.36	2.75	3.14	3.55
	.010	1.83	2.16	2.50	2.85	3.20	2.09	2.48	2.88	3.29	3.70	2.31	2.74	3.18	3.64	4.09
	.012	2.10	2.48	2.86	3.25	3.65	2.39	2.83	3.26	3.72	4.18	2.62	3.10	3.60	4.10	4.60
	.014	2.36	2.78	3.21	3.64	4.07	2.67	3.15	3.64	4.14	4.63	2.91	3.44	3.98	4.53	5.08
	.016	2.61	3.07	3.54	4.01	4.48	2.94	3.46	4.00	4.53	5.07	3.19	3.77	4.35	4.94	5.54
3	.008	0.99	1.17	1.35	1.53	1.72	1.17	1.39	1.61	1.83	2.06	1.33	1.57	1.83	2.08	2.34
	.010	1.17	1.39	1.60	1.81	2.02	1.38	1.63	1.89	2.15	2.41	1.55	1.84	2.13	2.42	2.72
	.012	1.35	1.60	1.84	2.08	2.33	1.58	1.87	2.15	2.45	2.74	1.76	2.08	2.41	2.74	3.07
	.014	1.53	1.80	2.07	2.34	2.62	1.77	2.09	2.41	2.73	3.05	1.97	2.32	2.68	3.04	3.40
	.016	1.70	1.99	2.29	2.59	2.89	1.95	2.30	2.65	3.00	3.35	2.16	2.55	2.94	3.33	3.72
4	.008	0.72	0.85	0.98	1.11	1.24	0.87	1.03	1.19	1.35	1.51	1.00	1.18	1.37	1.55	1.74
	.010	0.86	1.01	1.16	1.32	1.47	1.03	1.21	1.40	1.59	1.78	1.17	1.38	1.60	1.81	2.03
	.012	0.99	1.17	1.34	1.52	1.70	1.18	1.39	1.60	1.81	2.03	1.33	1.57	1.82	2.06	2.30
	.014	1.12	1.32	1.51	1.71	1.91	1.32	1.56	1.79	2.03	2.27	1.49	1.75	2.02	2.29	2.56
	.016	1.25	1.46	1.68	1.90	2.12	1.46	1.72	1.98	2.24	2.50	1.64	1.93	2.22	2.51	2.81

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

	N	30					40					50				
T	P Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	4.30	5.19	6.11	7.06	8.03	4.61	5.57	6.57	7.60	8.66	4.86	5.89	6.96	8.06	9.18
	.010	4.96	5.96	6.98	8.03	9.09	5.29	6.36	7.47	8.60	9.76	5.56	6.70	7.87	9.07	10.31
	.012	5.58	6.67	7.78	8.92	10.08	5.92	7.09	8.29	9.52	10.76	6.21	7.44	8.71	10.00	11.33
	.014	6.16	7.33	8.53	8.75	10.99	6.52	7.77	9.06	10.36	11.69	6.81	8.13	9.48	10.86	12.26
	.016	6.71	7.80	9.24	10.53	11.84	7.08	8.42	9.78	11.16	12.56	7.38	8.74	10.21	11.67	13.14
2	.008	2.28	2.73	3.19	3.66	4.13	2.53	3.03	3.55	4.07	4.61	2.74	3.29	3.85	4.43	5.02
	.010	2.64	3.15	3.67	4.19	4.73	2.91	3.47	4.05	4.64	5.23	3.14	3.75	4.38	5.01	5.67
	.012	2.98	3.53	4.11	4.69	5.27	3.26	3.88	4.51	5.15	5.81	3.50	4.17	4.86	5.55	6.26
	.014	3.29	3.90	4.52	5.15	5.78	3.59	4.26	4.95	5.64	6.34	3.84	4.57	5.30	6.05	6.81
	.016	3.59	4.25	4.91	5.59	6.26	3.90	4.62	5.35	6.09	6.84	4.17	4.94	5.72	6.52	7.32
3	.008	1.58	1.88	2.18	2.49	2.80	1.78	2.12	2.47	2.83	3.19	1.96	2.33	2.73	3.12	3.52
	.010	1.83	2.16	2.51	2.87	3.22	2.05	2.44	2.83	3.23	3.64	2.24	2.67	3.10	3.54	3.99
	.012	2.06	2.44	2.83	3.21	3.61	2.30	2.73	3.16	3.60	4.05	2.50	2.97	3.45	3.93	4.42
	.014	2.28	2.70	3.12	3.54	3.97	4.05	2.53	3.00	3.47	4.43	2.75	3.26	3.77	4.30	4.82
	.016	2.49	2.94	3.40	3.85	4.32	2.76	3.26	3.76	4.38	4.79	2.98	3.53	4.08	4.64	5.20
4	.008	1.21	1.44	1.66	1.90	2.13	1.39	1.65	1.91	2.18	2.45	1.54	1.84	2.13	2.43	2.74
	.010	1.41	1.66	1.92	2.19	2.46	1.60	1.90	2.20	2.50	2.81	1.77	2.10	2.43	2.77	3.11
	.012	1.59	1.88	2.17	2.46	2.76	1.80	2.12	2.46	2.79	3.13	1.97	2.34	2.71	3.08	3.46
	.014	1.76	2.08	2.40	2.72	3.04	1.98	2.34	2.70	3.07	3.44	2.17	2.56	2.96	3.37	3.78
	.016	1.92	2.27	2.61	2.96	3.31	2.15	2.54	2.93	3.33	3.72	2.35	2.78	3.21	3.64	4.08

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

T	N	4					6					8				
	P \ Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	1.93	2.29	2.64	3.00	3.37	2.18	2.59	3.00	3.42	3.85	2.37	2.82	3.28	3.75	4.23
	.010	2.31	2.73	3.15	3.58	4.01	2.59	3.07	3.59	4.05	4.55	2.81	3.33	3.87	4.42	4.97
	.012	2.67	3.16	3.64	4.13	4.63	2.98	3.53	4.08	4.64	5.21	3.22	3.82	4.43	5.04	5.66
	.014	3.03	3.57	4.11	4.66	5.22	3.36	3.97	4.59	5.21	5.84	3.62	4.28	4.96	5.64	6.33
	.016	3.37	3.97	4.57	5.18	5.79	3.73	4.40	5.08	5.76	6.45	4.01	4.73	5.47	6.21	6.97
2	.008	0.86	1.02	1.18	1.34	1.51	1.01	1.21	1.40	1.60	1.80	1.14	1.36	1.58	1.81	2.04
	.010	1.03	1.22	1.42	1.61	1.81	1.21	1.44	1.67	1.90	2.14	1.36	1.62	1.88	2.14	2.41
	.012	1.20	1.42	1.65	1.87	2.10	1.41	1.67	1.93	2.20	2.46	1.57	1.86	2.16	2.46	2.76
	.014	1.37	1.62	1.87	2.13	2.38	1.59	1.88	2.18	2.48	2.78	1.77	2.10	2.43	2.76	3.10
	.016	1.53	1.81	2.09	2.37	2.66	1.77	2.10	2.42	2.75	3.08	1.97	2.33	2.69	3.05	3.42
3	.008	0.53	0.63	0.74	0.84	0.94	0.65	0.77	0.90	1.02	1.15	0.75	0.89	1.03	1.18	1.33
	.010	0.65	0.77	0.89	1.01	1.14	0.78	0.93	1.07	1.22	1.38	0.89	1.06	1.23	1.40	1.58
	.012	0.76	0.89	1.04	1.18	1.32	0.91	1.07	1.24	1.42	1.59	1.03	1.22	1.42	1.61	1.81
	.014	0.86	1.02	1.18	1.34	1.51	1.03	1.22	1.41	1.60	1.80	1.17	1.38	1.60	1.82	2.04
	.016	0.97	1.44	1.32	1.50	1.68	1.15	1.66	1.57	1.78	2.00	1.30	1.84	1.77	2.01	2.26
4	.008	0.38	0.45	0.53	0.60	0.68	0.47	0.56	0.65	0.75	0.84	0.55	0.66	0.76	0.87	0.98
	.010	0.46	0.55	0.64	0.73	0.83	0.57	0.68	0.79	0.89	1.01	0.66	0.79	0.91	1.04	1.17
	.012	0.54	0.64	0.75	0.85	0.95	0.66	0.79	0.91	1.04	1.16	0.77	0.91	1.05	1.20	1.34
	.014	0.62	0.74	0.85	0.97	1.09	0.76	0.89	1.03	1.18	1.32	0.87	1.03	1.19	1.35	1.51
	.016	0.70	0.83	0.96	1.09	1.22	0.84	1.00	1.15	1.31	1.47	0.97	1.14	1.32	1.50	1.68

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

N		10					15					20				
T	P Q	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	2.53	3.02	3.52	4.03	4.55	2.85	3.42	4.00	4.59	5.20	3.10	3.73	4.37	5.04	5.71
	.010	2.99	3.55	4.13	4.72	5.32	3.34	4.00	4.66	5.34	6.03	3.63	4.34	5.07	5.82	6.58
	.012	3.42	4.06	4.71	5.37	6.04	3.81	4.54	5.28	6.04	6.80	4.12	4.92	5.73	6.56	7.40
	.014	3.84	4.55	5.27	5.99	6.73	4.26	5.06	5.87	6.70	7.53	4.59	5.46	6.35	7.25	8.16
	.016	4.24	5.01	5.80	6.59	7.39	4.69	5.56	6.44	7.33	8.23	5.04	5.98	6.94	7.90	8.89
2	.008	1.26	1.50	1.74	1.99	2.25	1.49	1.78	2.07	2.37	2.67	1.68	2.01	2.34	2.68	3.03
	.010	1.49	1.77	2.06	2.35	2.64	1.75	2.08	2.42	2.77	3.12	1.96	2.34	2.72	3.11	3.51
	.012	1.71	2.03	2.35	2.68	3.01	2.00	2.37	2.75	3.14	3.53	2.23	2.65	3.08	3.51	3.95
	.014	1.93	2.28	2.64	3.00	3.37	2.24	2.65	3.07	3.50	3.92	2.49	2.95	3.42	3.89	4.37
	.016	2.13	2.52	2.91	3.31	3.71	2.47	2.92	3.37	3.83	4.30	2.74	3.24	3.74	4.26	4.77
3	.008	0.83	0.99	1.15	1.32	1.48	1.02	1.21	1.41	1.61	1.81	1.17	1.40	1.62	1.86	2.09
	.010	0.99	1.18	1.37	1.56	1.75	1.20	1.42	1.65	1.88	2.12	1.37	1.63	1.89	2.16	2.43
	.012	1.14	1.35	1.57	1.78	2.00	1.37	1.63	1.88	2.14	2.41	1.56	1.85	2.14	2.44	2.74
	.014	1.29	1.52	1.76	2.00	2.25	1.54	1.82	2.10	2.39	2.68	1.74	2.06	2.38	2.71	3.04
	.016	1.43	1.99	1.95	2.21	2.48	1.69	2.30	2.31	2.62	2.94	1.91	2.55	2.61	2.96	3.32
4	.008	0.62	0.74	0.86	0.98	1.11	0.78	0.92	1.07	1.22	1.38	0.91	1.08	1.25	1.43	1.61
	.010	0.74	0.88	1.02	1.16	1.31	0.92	1.09	1.26	1.43	1.61	1.06	1.26	1.46	1.66	1.87
	.012	0.86	1.01	1.17	1.84	1.50	1.05	1.24	1.44	1.63	1.83	1.21	1.43	1.66	1.88	2.11
	.014	0.97	1.14	1.32	1.50	1.68	1.18	1.39	1.61	1.82	2.04	1.35	1.60	1.84	2.09	2.34
	.016	1.07	1.27	1.46	1.66	1.86	1.30	1.53	1.77	2.01	2.25	1.49	1.75	2.02	2.29	2.57

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

T \ N	P \ Q	30					40					50				
		1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50	1.50	1.75	2.00	2.25	2.50
1	.008	3.49	4.22	4.97	5.73	6.52	3.80	4.60	5.43	6.29	7.17	4.06	4.93	5.83	6.75	7.71
	.010	4.06	4.88	5.72	6.58	7.46	4.40	5.30	6.23	7.18	8.15	4.69	5.65	6.65	7.68	8.73
	.012	4.59	5.50	6.42	7.36	8.32	4.96	5.95	6.96	8.00	9.05	5.27	6.33	7.41	8.52	9.66
	.014	5.10	6.08	7.08	8.10	9.13	5.49	6.56	7.65	8.76	9.89	5.82	6.96	8.12	9.31	10.52
	.016	5.58	6.63	7.70	8.79	9.90	6.00	7.14	8.30	9.48	10.68	6.34	7.56	8.79	10.06	11.34
2	.008	1.99	2.38	2.78	3.19	3.61	2.24	2.67	3.14	3.61	4.09	2.46	2.95	3.46	3.97	4.50
	.010	2.31	2.76	3.21	3.67	4.14	2.59	3.09	3.61	4.13	4.66	2.83	3.38	3.95	4.52	5.11
	.012	2.61	3.10	3.61	4.12	4.63	2.92	3.47	4.03	4.61	5.19	3.18	3.78	4.40	5.03	5.66
	.014	2.89	3.43	3.98	4.54	5.10	3.22	3.82	4.43	5.05	5.68	3.50	4.15	4.82	5.50	6.18
	.016	3.17	3.75	4.34	4.93	5.53	3.51	4.16	4.81	5.48	6.15	3.80	4.51	5.22	5.94	6.67
3	.008	1.43	1.70	1.98	2.27	2.55	1.65	1.96	2.28	2.61	2.94	1.84	2.19	2.55	2.91	3.28
	.010	1.66	1.97	2.29	2.61	2.94	1.90	2.26	2.62	2.99	3.36	2.11	2.51	2.91	3.32	3.73
	.012	1.88	2.22	2.57	2.93	3.29	2.14	2.53	2.93	3.34	3.75	2.36	2.80	3.24	3.69	4.14
	.014	2.08	2.46	2.84	3.23	3.62	2.36	2.79	3.22	3.66	4.11	2.60	3.07	3.55	4.04	4.53
	.016	2.27	2.94	3.10	3.52	3.94	2.57	3.26	3.50	3.97	4.45	2.82	3.53	3.84	4.36	4.89
4	.008	1.13	1.34	1.56	1.78	2.00	1.32	1.57	1.82	2.07	2.33	1.49	1.77	2.05	2.34	2.63
	.010	1.31	1.56	1.80	2.05	2.30	1.53	1.81	2.09	2.38	2.67	1.71	2.03	2.34	2.66	2.99
	.012	1.48	1.75	2.03	2.30	2.58	1.71	2.02	2.34	2.65	2.97	1.91	2.26	2.61	2.96	3.32
	.014	1.64	1.94	2.24	2.54	2.84	1.89	2.23	2.57	2.92	3.26	2.10	2.48	2.86	3.24	3.63
	.016	1.80	2.12	2.44	2.77	3.09	2.06	2.42	2.79	3.16	3.54	2.29	2.69	3.10	3.51	3.92

TABLE B

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	4					6					8				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	4.09	5.17	5.81	6.26	6.61	4.52	5.58	6.19	6.63	6.97	4.85	5.89	6.49	6.91	7.24
.08	7.62	9.42	10.48	11.24	11.82	8.34	10.08	11.10	11.82	12.38	8.89	10.58	11.56	12.25	12.79
.12	10.95	13.38	14.81	15.82	16.61	11.92	14.25	15.61	16.57	17.32	12.66	14.91	16.21	17.13	17.84
.16	14.17	17.16	18.92	20.17	21.14	15.37	18.23	19.89	21.07	21.98	16.28	19.02	20.62	21.63	22.60
.20	17.31	20.81	22.88	24.35	25.50	18.71	22.05	24.00	25.38	26.45	19.78	22.97	24.82	26.13	27.14
.24	20.37	24.37	26.73	28.40	29.70	21.98	25.77	27.98	29.54	30.76	23.19	26.18	28.90	30.38	31.52
.28	23.39	27.85	30.48	32.35	33.81	25.18	29.39	31.85	33.60	34.95	26.54	30.54	32.87	34.51	35.78
.32	26.36	31.26	34.15	36.21	37.82	28.33	32.94	35.64	37.55	39.04	29.82	34.20	36.74	38.53	39.93

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	10					15					20				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	5.12	6.14	6.72	7.13	7.45	5.65	6.62	7.17	7.56	7.86	6.07	6.98	7.51	7.87	8.16
.08	9.34	10.98	11.93	12.60	13.12	10.22	11.76	12.64	13.25	13.73	10.89	12.34	13.16	13.74	14.19
.12	13.27	15.44	16.69	17.58	18.26	14.44	16.45	17.60	18.41	19.03	15.34	17.21	18.28	19.03	19.61
.16	17.02	19.66	21.18	22.26	23.08	18.46	20.88	22.27	23.25	24.00	19.55	21.80	23.08	23.98	24.67
.20	20.65	23.72	25.48	26.73	27.69	22.33	25.13	26.73	27.86	28.72	23.60	26.18	27.65	28.68	29.48
.24	24.18	27.64	29.64	31.05	32.13	26.09	29.23	31.02	32.29	33.26	27.53	30.41	32.05	33.21	34.09
.28	27.64	31.46	33.67	35.23	36.44	29.76	33.21	35.20	36.59	37.66	31.36	34.51	36.32	37.58	38.56
.32	31.03	35.20	37.61	39.31	40.63	33.35	37.10	39.26	40.77	41.94	35.10	38.51	40.46	41.84	42.89

TIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	30					40					50				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	6.70	7.53	8.01	8.34	8.60	7.19	7.95	8.38	8.69	8.93	7.59	8.28	8.69	8.97	9.20
.08	11.92	13.20	13.94	14.46	14.85	12.70	13.85	14.52	14.98	15.34	13.35	14.38	14.98	15.41	15.74
.12	16.69	18.34	19.28	19.94	20.44	17.73	19.18	20.02	20.60	21.06	18.58	19.86	20.61	21.14	21.55
.16	21.20	23.15	24.26	25.04	25.64	22.46	24.16	25.14	25.83	26.36	23.48	24.97	25.84	26.46	26.93
.20	25.52	27.74	29.00	29.84	30.57	26.98	28.90	30.00	30.78	31.38	28.16	29.83	30.80	31.48	32.02
.24	29.70	32.15	33.55	34.54	35.30	31.34	33.45	34.66	35.52	36.18	32.68	34.49	35.55	36.29	36.87
.28	33.76	36.43	37.96	39.03	39.86	35.57	37.85	39.16	40.09	40.80	37.05	38.99	40.13	40.93	41.55
.32	37.72	40.59	42.23	43.39	44.28	39.70	42.13	43.53	44.52	45.29	41.31	43.37	44.57	45.42	46.08

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	4					6					8				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	3.62	4.84	5.55	6.06	6.45	3.76	4.96	5.65	6.14	6.52	3.87	5.04	5.72	6.20	6.58
.08	6.79	8.82	10.00	10.84	11.49	7.03	9.02	10.17	10.99	11.63	7.21	9.16	10.29	11.10	11.72
.12	9.80	12.53	14.12	15.24	16.12	10.12	12.80	14.35	15.45	16.30	10.37	12.99	14.52	15.59	16.43
.16	12.71	16.07	18.03	19.41	20.49	13.12	16.40	18.32	19.67	20.72	13.42	16.65	18.52	19.85	20.88
.20	15.56	19.49	21.79	23.41	24.67	16.04	19.89	22.13	23.72	24.95	16.39	20.18	22.38	23.94	25.15
.24	18.35	22.83	25.44	27.29	28.72	18.91	23.28	25.83	27.64	29.04	19.31	23.61	26.12	27.90	29.27
.28	21.10	26.08	29.00	31.06	32.66	21.72	26.60	29.44	31.46	33.03	22.17	26.97	29.76	31.75	33.29
.32	23.82	29.28	32.48	34.75	36.51	24.50	29.85	32.97	35.19	36.91	24.99	30.26	33.33	35.51	37.20

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	10					15					20				
V M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	3.95	5.11	5.78	6.25	6.62	4.11	5.23	5.88	6.34	6.70	4.22	5.32	5.95	6.40	6.75
.08	7.35	9.27	10.39	11.18	11.79	7.61	9.48	10.57	11.33	11.93	7.80	9.63	10.69	11.44	12.02
.12	10.56	13.14	14.65	15.71	16.53	10.91	13.43	14.89	15.92	16.72	11.17	13.63	15.06	16:07	16.85
.16	13.65	16.84	18.69	19.99	21,01	14.09	17.19	18.99	20.26	21.25	14.41	17.44	19.20	20.45	21.41
.20	16.67	20.40	22.57	24.11	25.30	17.19	20.82	22.93	24.43	25.58	17.56	21.12	23.19	24.65	25.79
.24	19.62	23.87	26.34	28.09	29.45	20.21	24.35	26.75	28.46	29.78	20.64	24.69	27.05	28.72	30.01
.28	22.52	27.26	30.04	31.97	33.49	23.18	27.79	30.48	32.38	33.86	23.66	28.18	30.81	32.68	34.13
.32	25.38	30.58	33.61	35.76	37.43	36.10	31.17	34.12	36.22	37.84	26.63	31.60	34.49	36.55	38.14

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 0

N	30					40					50				
V M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	4.39	5.44	6.06	6.49	6.83	4.51	5.54	6.13	6.56	6.89	4.61	5.61	6.19	6.61	6.93
.08	8.08	9.85	10.87	11.60	12.16	8.28	10.00	11.00	11.71	12.26	8.45	10.13	11.10	11.80	12.34
.12	11.55	13.93	15.31	16.29	17.04	11.82	14.14	15.49	16.44	17.18	12.04	14.30	15.63	16.56	17.29
.16	14.88	17.81	19.51	20.72	21.66	15.21	18.07	19.74	20.91	21.83	15.48	18.28	19.91	21.07	21.96
.20	18.11	21.55	23.56	24.98	26.08	18.50	21.86	23.82	25.21	26.28	18.82	22.11	24.03	25.39	26.44
.24	21.26	25.19	27.47	29.09	30.35	21.71	25.54	27.77	29.36	30.59	22.07	25.82	28.01	29.57	30.77
.28	24.35	28.73	31.29	33.10	34.50	24.85	29.13	31.63	33.40	34.77	25.25	29.45	31.90	33.64	34.99
.32	27.39	32.21	35.02	37.01	38.56	27.94	32.65	35.40	37.35	38.86	28.38	32.99	35.70	37.61	39.10

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 1

N	4					6					8				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.18	2.04	3.08	3.82	4.39	0.24	2.14	3.18	3.90	4.46	0.30	2.22	3.24	3.96	4.52
.08	0.68	4.23	6.03	7.29	8.26	0.84	4.39	6.17	7.41	8.36	0.97	4.51	6.27	7.49	8.44
.12	1.47	6.47	8.93	10.64	11.96	1.73	6.68	9.10	10.78	12.07	1.94	6.84	9.22	10.88	12.16
.16	2.55	8.76	11.79	13.91	15.54	2.90	9.00	11.98	14.06	15.66	3.17	9.18	12.12	14.17	15.75
.20	3.90	11.07	14.64	17.13	19.05	4.32	11.34	14.84	17.29	19.17	4.65	11.54	14.99	17.40	19.26
.24	5.53	13.42	17.46	20.30	22.49	5.99	13.70	17.67	20.46	22.61	6.34	13.91	17.83	20.58	22.70
.28	7.43	15.98	20.27	23.43	25.88	7.90	16.08	20.49	23.60	26.00	8.25	16.29	20.64	23.71	26.09
.32	9.59	18.16	23.06	26.54	29.23	10.04	18.46	23.28	26.70	29.34	10.36	18.48	23.44	26.81	29.42

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 1

N	10					15					20				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.35	2.28	3.29	4.01	4.56	0.47	2.39	3.39	4.09	4.63	0.58	2.48	3.46	4.15	4.69
.08	1.09	4.61	6.35	7.56	8.49	1.35	4.79	6.49	7.68	8.60	1.57	4.92	6.60	7.77	8.67
.12	2.13	6.96	9.32	10.96	12.22	2.50	7.18	9.49	11.10	12.34	2.81	7.35	9.62	11.21	12.43
.16	3.41	9.32	12.23	14.26	15.82	3.88	9.58	12.43	14.42	15.95	4.25	9.77	12.57	14.53	16.04
.20	4.91	11.69	15.10	17.49	19.33	5.44	11.98	15.32	17.66	19.46	5.85	12.18	15.47	17.77	19.55
.24	6.63	14.07	17.95	20.67	22.77	7.18	14.37	18.17	20.84	22.89	7.60	14.59	18.33	20.96	22.99
.28	8.53	16.46	20.77	23.80	26.15	9.08	16.77	20.99	23.97	26.27	9.48	16.99	21.15	24.09	26.35
.32	10.62	18.85	23.56	26.90	29.48	11.12	19.17	23.79	27.06	29.59	11.48	19.39	23.95	27.17	29.67

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 1

N	30					40					50				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.78	2.60	3.57	4.24	4.77	0.97	2.69	3.64	4.31	4.82	1.14	2.77	3.70	4.36	4.87
.08	1.95	5.11	6.75	7.90	8.78	2.26	5.25	6.86	7.99	8.86	2.54	5.36	6.94	8.06	8.92
.12	3.31	7.59	9.80	11.35	12.55	3.72	7.76	9.93	11.46	12.64	4.07	7.89	10.04	11.54	12.70
.16	4.83	10.04	12.77	14.69	16.17	5.30	10.24	12.92	14.81	16.26	5.69	10.39	13.04	14.90	16.33
.20	6.48	12.48	15.69	17.94	19.68	6.97	12.69	15.84	18.06	19.77	7.37	12.86	15.97	18.15	19.85
.24	8.23	14.90	18.55	21.12	23.11	8.71	15.13	18.72	21.25	23.20	9.11	15.31	18.84	21.34	23.27
.28	10.08	17.32	21.38	24.25	26.47	10.53	17.55	21.55	24.37	26.56	10.89	17.73	21.67	24.46	26.63
.32	12.01	19.72	24.18	27.33	29.78	12.40	19.96	24.34	27.45	29.86	12.71	20.14	24.47	27.54	29.92

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

N	4					6					8				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.15	1.93	2.99	3.76	4.35	0.20	2.03	3.09	3.84	4.42	0.25	2.12	3.16	3.90	4.48
.08	0.41	3.70	5.62	6.98	8.04	0.52	3.80	5.89	7.15	8.17	0.62	4.00	5.73	7.23	8.26
.12	0.74	5.50	8.20	10.11	11.56	0.91	5.56	8.37	10.23	11.70	1.05	5.73	8.51	10.36	11.81
.16	1.14	7.09	10.47	12.99	14.90	1.36	7.34	10.71	13.30	15.12	1.54	7.52	10.89	13.34	15.22
.20	1.59	8.74	12.90	15.89	18.21	1.85	9.12	13.18	16.04	18.41	2.06	9.31	13.35	16.21	18.53
.24	2.08	10.59	15.21	18.65	21.45	2.38	10.87	15.60	18.91	21.59	2.62	10.97	15.78	19.09	21.78
.28	2.61	12.18	17.63	21.41	24.50	2.95	12.53	17.87	21.70	24.84	3.21	12.85	18.20	21.92	24.91
.32	3.18	13.82	19.92	24.20	27.62	3.54	14.25	20.33	24.46	27.95	3.83	14.70	20.51	24.78	28.13

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

N	10					15					20				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.29	2.17	3.21	3.95	4.52	0.40	2.30	3.32	4.04	4.60	0.50	2.38	3.39	4.13	4.66
.08	0.70	4.10	5.83	7.30	8.32	0.90	4.32	6.15	7.44	8.44	1.06	4.40	6.25	7.53	8.53
.12	1.18	5.86	8.60	10.46	11.89	1.44	6.12	8.76	10.61	12.05	1.66	6.29	8.88	10.73	12.16
.16	1.69	7.69	11.22	13.50	15.32	2.01	7.91	11.28	13.63	15.53	2.28	8.18	11.46	13.80	15.64
.20	2.24	9.48	13.48	16.34	18.65	2.61	9.84	13.77	16.54	18.86	2.91	9.98	13.97	16.77	18.97
.24	2.82	11.30	15.89	19.23	21.89	3.23	11.59	16.21	19.48	22.16	3.56	11.83	16.47	19.68	22.31
.28	3.43	12.98	18.31	21.10	24.99	3.87	13.40	18.68	22.33	25.32	4.22	13.64	18.84	22.53	25.53
.32	4.06	14.03	20.68	24.84	28.30	4.52	15.00	20.92	25.14	28.46	4.88	15.36	21.26	25.31	28.68

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 4

N	30					40					50				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.68	2.50	3.50	4.21	4.74	0.84	2.58	3.56	4.26	4.80	0.99	2.66	3.62	4.31	4.84
.08	1.36	4.62	6.39	7.68	8.66	1.61	4.81	6.51	7.78	8.75	1.84	4.86	6.61	7.85	8.82
.12	2.04	6.60	9.15	10.94	12.32	2.35	6.75	9.26	11.04	12.43	2.63	6.92	9.40	11.14	12.52
.16	2.72	8.50	11.70	14.10	15.81	3.07	8.74	11.90	14.17	15.95	3.38	8.91	12.05	14.30	16.05
.20	3.40	10.38	14.25	17.13	19.20	3.79	10.60	14.43	17.19	19.35	4.12	10.79	14.63	17.33	19.46
.24	4.08	12.24	16.73	19.12	22.50	4.49	12.40	16.91	20.15	22.67	4.84	12.63	17.12	20.29	22.78
.28	4.76	13.92	19.16	22.91	25.72	5.18	14.26	19.35	23.10	25.89	5.54	14.42	19.55	23.19	26.03
.32	5.44	15.84	21.52	25.92	28.92	5.87	16.00	21.76	25.93	29.07	6.23	16.38	21.91	26.03	29.21

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

N	4					6					8				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.13	1.88	2.93	3.67	4.25	0.18	1.99	3.03	3.77	4.34	0.23	2.07	3.10	3.83	4.41
.08	0.32	3.56	5.49	6.86	7.92	0.42	3.74	5.65	7.01	8.06	0.52	3.87	5.77	7.12	8.16
.12	0.54	5.18	7.92	9.88	11.44	0.69	5.41	8.14	10.07	11.57	0.83	5.59	8.30	10.21	11.69
.16	0.78	6.75	10.29	12.80	14.75	0.98	7.04	10.54	13.03	14.95	1.16	7.26	10.73	13.19	15.10
.20	1.04	8.29	12.59	15.65	18.03	1.29	8.63	12.89	15.91	18.25	1.50	8.88	13.10	16.09	18.41
.24	1.31	9.81	14.85	18.44	21.23	1.61	10.19	15.19	18.73	21.47	1.86	10.48	15.42	18.93	21.64
.28	1.60	11.31	17.08	21.19	24.38	1.94	11.73	17.44	21.49	24.64	2.23	12.05	17.71	21.71	24.82
.32	1.89	12.79	19.28	23.90	27.49	2.28	13.26	19.67	24.22	27.75	2.60	13.60	19.95	24.45	27.94

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

N	10					15					20				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.28	2.13	3.16	3.89	4.46	0.38	2.25	3.27	3.99	4.55	0.48	2.34	3.35	4.07	4.62
.08	0.60	3.98	5.87	7.20	8.23	0.80	4.18	6.04	7.36	8.38	0.97	4.32	6.17	7.47	8.48
.12	0.95	5.73	8.42	10.32	11.79	1.22	6.00	8.64	10.52	11.97	1.46	6.19	8.81	10.66	12.10
.16	1.32	7.43	10.88	13.32	15.21	1.66	7.75	11.15	13.55	15.42	1.96	7.99	11.35	13.72	15.56
.20	1.70	9.08	13.27	16.23	18.53	2.11	9.46	13.58	16.50	18.76	2.46	9.73	13.81	16.69	18.92
.24	2.08	10.70	15.61	19.09	21.78	2.56	11.13	15.96	19.38	22.02	2.95	11.44	16.21	19.58	22.20
.28	2.48	12.30	17.91	21.88	24.96	3.01	12.77	18.29	22.20	25.22	3.46	13.11	18.56	22.42	25.41
.32	2.88	13.87	20.17	24.63	28.09	3.47	4.38	20.58	24.97	28.37	3.96	14.75	20.88	25.21	28.56

UNTIED SYSTEM - INTERSTATION STORAGE CAPACITY OF 8

N	30					40					50				
V \ M	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
.04	0.66	2.47	3.47	4.17	4.72	0.83	2.54	3.55	4.25	4.79	0.99	2.65	3.62	4.31	4.85
.08	1.28	4.54	6.35	7.63	8.63	1.55	4.70	6.49	7.15	8.73	1.81	4.83	6.59	7.85	8.82
.12	1.88	6.48	9.05	10.87	12.28	2.24	6.69	9.22	11.02	12.41	2.57	6.86	9.36	11.14	12.51
.16	2.47	8.33	11.63	13.97	15.77	2.91	8.59	11.84	14.14	15.93	3.30	8.79	12.00	14.28	16.04
.20	3.05	10.13	14.13	16.96	19.16	3.56	10.43	14.37	17.16	19.32	4.01	10.66	14.55	17.31	19.45
.24	3.63	11.89	16.57	19.88	22.45	4.20	12.22	20.19	20.10	22.63	4.70	12.48	17.03	20.26	22.77
.28	4.20	13.61	18.95	22.74	25.67	4.83	13.97	19.24	22.97	25.86	5.37	14.26	19.46	23.15	26.01
.32	4.77	15.30	21.30	25.55	28.84	5.44	15.69	21.60	25.79	29.04	6.03	16.01	21.84	25.98	29.19

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