UNIVERSITY OF NOTTINGHAM
DEPARTMENT OF CIVIL ENGINEERING

SITE LAYOUT AND CONSTRUCTION PLANNING

by

David Charles Morgan, B.Sc.

Thesis submitted to the University of
Nottingham for the degree of
Doctor of Philosophy

October 1986

ACKNOWLEDGEMENTS

This work has been undertaken in the Civil Engineering Department at Nottingham University. I would like to thank all its members, especially Professor P.S. Pell for making the facilities available.

Special thanks are due to my supervisors, Mr. G. Cullingford and Dr. M.J. Mawdesley for constant guidance and advice; my research colleagues, Pete, Saad, Nora, Bill, Gerry, and John; and finally to Sue and John for their help in preparing this thesis.

The work in industry was carried out by Mr. D.J. Brown of High-Point Services Group plc and Mr C.J. Adams of Mowlem (Civil Engineering) Limited. Their input has been much appreciated.

Last, but not least, thanks are due to Julie for much support and encouragement throughout the course the research.

ABSTRACT

The work described in this thesis is concerned with site layout and construction planning.

The current usage of site layout information in construction planning techniques is investigated, and the layout development methods used in other fields such as Architecture and Production engineering are also reviewed. The limitations, applicability and potential of these models is discussed.

The layout of a construction site affects the manner in which construction plans are formed. This research is an attempt to isolate the site layout factors which are taken into account in the planning stages of a project. The layout of a construction site may be utilised in the formation of construction plans in two ways. Firstly, the large scale layout of the structures may influence the order in which the structures are built. Secondly, the small scale layout of the work within each individual structure will determine the order in which that work will be carried out. A model has been developed which uses the two types of site layout information for the structure and activity sequencing in the production of construction plans on a micro-computer. The practicality and performance of this model has been tested by comparison of the plans produced wih those produced with other planning methods and those produced in industry.

The feasiblity of the integration of this model with Computer-aided design packages has been discussed with a view to producing construction plans automatically from the contract drawings.

CONTENTS

LIST OF PLATES

CHAPTER 1

INTRODUCTION

Planning techniques have had widespread use in the construction industry since the introduction of network planning in the mid-fifties. In their original form, network techniques included very simple relationships between various activities or work packages, which collectively made up the project as a whole. The form of these relationships were "activity B may only be started after the completion of activity A".

Since their introduction, much work has been carried out in developing planning methods that are more realistic models of the project. Some of these models have been extensions to the original networking techniques, whilst others have been completely new models. Examples of the introduction of "realism" into planning methods include:

a) Full precedence method. This model is an extension to normal networking techniques, that has expanded the possible types of relationships between the activities to allow both start and end constraints. This is particularly useful in modelling situations where activities may overlap one another.

b) PERT. This model is a networking technique that has introduced uncertainty into individual activity durations to allow an average project duration and associated variabilities to be calculated.

c) Line of Balance. This method was developed to handle linear or repetitive projects. This type of project are difficult to satisfactorily model using networking techniques.

d) Method of Potentials (Roy's method). This method introduced another type of relationship between the activities in networks. The relationship is of the "must" type, and may be described as "concrete pouring must occur within x hours of concrete mixing".

e) Resource scheduling. Resource scheduling is not a specific method, but rather a technique that is used throughout construction planning. It is generally used to introduce resource limitations to networking methods.

All these methods, have to some degree, have found uses in the construction industry.

Site layout is one feature of construction projects that has received little attention in the development of new planning methods.

1.1 Site Layout in construction planning

One of the main goals of planning in the construction industry is to reduce the cost of construction. Construction costs can be broadly split into two categories:

a) Non-billed costs
b) Billed costs

Billed costs are those costs which are generally accounted for in the Bill of Quantities, and are those that the contractor would incur regardless of the work method adopted. They include:

a) Cost of materials
b) Cost of resources
c) Billed work
d) Billed temporary work
e) Insurance

Non-billed costs are those which arise as a result of the contractor's work method and are very largely dependent on site layout and the resources used. The tender for the contract will generally make a sensible allowance for these types of cost. They include:

a) Transfer of materials on site
b) Wastage and theft of materials
c) Non-billed temporary work
d) Supervision
e) Movement of resources around site

In tendering for a contract, a contractor will generally not directly include site layout information in the tender, because standard rates are often used which make "blanket" allowances for it. However, if the estimator has a plan or work method which takes account of the site layout at the tendering stage, then more accurate tenders may be produced. This is very important in terms of corporate security.

During the construction of the project, a plan which has included site layout will generally allow more efficient utilisation of men and plant, as inefficiencies in resource movement may be eliminated in the early planning stages.

In order to incorporate site layout into a planning method it is useful to sub-divide the site layout into two categories:

a) Permanent works layout
b) Temporary works layout

This division is carried out because their incorporation into a planning method may take very different forms.

1.2 Permanent works layout

The completed site layout for any contract will be the same whatever work-method the contractor chooses to use. However, at any intermediate stage during the construction of the project, the partial permanent works layout will change with each structure that is started or finished. This means that during the course of the construction the permanent works layout does depend on the work-method adopted by the contractor.

If the project contains structures that are "useful" the contractor may elect to carry out their construction early in the contract. For example, a contractor would normally partially complete permanent roads to allow good access, and small structures, such as garages and sheds, for use as dry, safe and secure material stores and workshops. The early construction of this type of structure eliminates the need for the provision of temporary structures for these facilities and functions, whose cost is bourne by the contractor.

In order to achieve this cost reduction in temporary works, the contractor has to modify the work-method to allow the early usage of this type of structure.

The relative positioning of the structures on site may also influence the order in which the contractor decides to carry out the work. In certain projects, the order of the construction of the structures is carried out in such a way as to minimise resource movement and material handling. This situation is mainly exhibited in linear projects, such as roads, although all projects will have some resource movement implications considered in the formation of the plan.

On a more localised scale, the relative positioning of items of work to one another may influence the order in which this work is carried out. A simple example is that of a trenching operation where the trench excavation has to be carried out before any of the pipe laying activities may occur. The "micro" site layout may therefore be utilised to define the order of work within the individual structures, whilst the "macro" may influence the construction order of the structures themselves.

1.3 Temporary works layout

Temporary work is normally un-billed work carried out by the contractor in order to provide all the facilities that are necessary for the construction of the project. Generally it includes temporary haul roads, material stores, workshops, batching plants, and temporary site offices, and many of the other facilities.

The extent of the temporary work and the positioning of it's various features are decided by the contractor, and is often a complex problem. The problems occur because the need for resources, materials and access varies at every stage of the construction, and any decision concerning placement of temporary works has to take account of future working positions.

1.4 Research Objectives

The aims of this research are itemised below:

a) To investigate the current usage of site layout information in construction planning.

b) To develop a method that attempts to realistically model the construction site. This method will consequently utilise not only "micro" and "macro" site layout information, but also many other features such as efficient resource usage in the formation of construction plans.

c) To investigate the feasibility of integrating this planning model to Computer Aided Design (CAD) packages with a view to producing plans automatically.

CHAPTER 2

PREVIOUS WORK

2.1 Site layout in Construction

Discussions on the layout of construction sites has received scant attention by many authors of books and papers in construction planning. Of those that have considered site layout, most have been concerned with the positioning of temporary works. Calvert (1), Broughton (2) and Edmeades (3), identified the following site layout considerations:

a) Access and traffic

Access requirements vary with each job and stage of construction. The positioning of access routes depends on many factors, but should generally be placed in such a way as to avoid service lines, areas to be excavated or permanently paved, or in areas where they may need to be repositioned. Continuity of flow through the site is another important consideration, and may be achieved by having short, one-way routes which should be treated as clearways by people and plant on the site.

b) Material storage and handling

When planning the position of material stores the aim should be to minimise double handling and unnecessary movement. This may be achieved to some extent by planning them in conjunction with the access routes and providing loading and unloading facilities as necessary. Material stores should also be placed in positions which avoid services or positions where they will have to be repositioned, and if possible, close to the areas which require the materials. Wastage and losses due to poor storage and theft are also factors which may affect the positioning of material stores.

c) Administration buildings and Site facilities

Administration buildings generally require a good view of the site, easy access to the site, and freedom from noise. Other facilities, such as canteens, drying and changing rooms, toilets and workshops should be placed in positions which cause as little disruption to the project as possible.

The three points above illustrate some ways in which the site layout affects the organisation of a construction site. Almost without exception they include some travelling influence, whether of people, plant or materials.

Causey (4) isolated seven factors which affect the progress on construction sites:

a) The design of the project and the incidence of design changes
b) The supply of materials to the site
c) Site planning and efficiency
d) The efficiency of the work force
e) The wage system
f) Difficulties with sub-contractors
g) The relationship between the contractor and the client.

Causey (4) concluded that only 32% of a workforce's time was usefully employed. Site surveys (Appendix A), carried out during this research, illustrate that approximately 47% of the time of the labour force was usefully employed, whilst 17% was spent in travelling around the site. These statistics indicate that significant savings in time and money may be realised if a work-method incorporates site layout in it's formulation.

2.2 Previous work in Layout Development

Past work in layout development has been almost entirely carried out by Architects and Production Engineers, in the design of buildings and production lines respectively. In developing their models they have been able to rely on relatively unchanging patterns of movement, if the building (or production line) is used for what it was originally designed. Construction sites have very dynamic patterns of movement with different structures requiring different materials and plant at different times.

Whitehead and Eldars (6) said that inefficiencies in building layouts were difficult to identify, although in a study of a hospital, they estimated that up to a third of the total salary cost of the staff was taken up in travel, and as this was a running cost, there could be significant savings over time, if building designs which allowed more efficient flow of people were adopted. Agraa and Whitehead (7) in their study of the flow of people in a school building suggested that rooms in buildings should be placed in such a way as to minimise the total cost of the flow. In a later paper (8), they stated that nuisance considerations should also be taken into account in the design of buildings.

The criterion usually used for layout development is the minimization of the cost of flow of people or materials in the building or plant. Buildings and process plants generally have relatively unchanging patterns of movement, and layout development methods have relied on the use of existing movement information in their algorithms. If an architect wants to design a school, for example, information will be collected from existing schools, scaled to suit the size of the new school, and used as the basis of the design information. An architect, therefore, would assume that there are similar flow patterns between similar types of buildings. In process plant design, existing information that is applicable to the process in question may not be available, as process plants are often "one-off" projects, however in this case, movement information will normally be available from a knowledge of the process itself.

There are basically two types of method that have been used on computers to help the design engineer produce outlines for layouts, these are:

a) Construction Type.

b) Improvement Type.

2.2.1 Construction type Methods of Layout Development

This method adopts a heuristic approach to the development of layouts, and places each department (or facility) around a nucleus of previously placed departments (hence Construction type). The order of placement of the departments is usually defined by the cost of flow of people or materials around the layout. LOKAT (8) and CORELAP (9,10) are programs developed using this type of model.

Whitehead et al (5,6,7,11) used this type of model in their studies carried out on existing buildings (a hospital operating theatre and a school) to produce layouts from existing information. In this model, the flow in the building is studied, and the total number of trips between each department, for each type of staff found. These trips are then scaled by factors which standardise the trips according to the cost of each. For example, if a trip by a hospital porter is taken as a standard trip, then if a porters wage is a tenth of that of a surgeon, then each of a surgeons trips represents 10 standard trips. A flow matrix representing the number of standardised trips between each department, is formed from this information, and used as the basis for the development of the layout.

The first department to be chosen for placement is the one which has the highest number of standardised trips to and from it, and this is placed in the centre of the plan. The next department to be placed is the one which has the greatest flow from the last department placed (or in other methods, all the placed departments). This department is then placed on the plan in such a way as to minimise the cost of flow, either with just the last placed department or with all the previously located departments. This procedure is repeated for all other departments until the layout is developed.

The Whitehead method has the advantage that the most important departments are positioned first, and all subsequent departments placed are less significant. The end layout may not be the best, however, as this depends to a large extent on the initial department choice.

Sekhon (12) suggested that layout development was an N stage decision process (for N departments), and that the problem was one of choosing the optimum order of placement out of a possible N! orders. His method is similar to Whitehead's except that he finds the best path for each of the N possible initial departments, and then finds the best from these. The selection policies he uses are similar to Whitehead's. Sekhon showed in his paper that by considering all the possible initial starting departments, better results are obtained.

2.2.2 Improvement type Methods of Layout Development

This type of model improves existing layouts subject to similar criteria to those used in the Construction type Methods. Armour et al (13,14,15) primarily used this method in his CRAFT (Computerised Relative Allocation of Facilities Technique) program, which modifies existing layouts by exchanging pairs of departments (Pair-wise exchange, PWE) if a lower cost is obtained in doing so. For CRAFT the cost criterion is the minimisation of the material handling flows, although any suitable criterion could be used.

O'Brien and Abdel Barr (16) used a similar model in which at each iteration stage, 3 pairs were exchanged instead of just one. They found that there was no significant difference in the type of layout produced, although there was significant computer time saving.

2.2.3 Intuitive Methods of Layout Development

This type of model tries to produce layouts using subjective information. Muther (17), amongst others, has developed models using this approach.

This type of model are largely based on "closeness" ratings. A closeness rating is a value associated to a pair of departments indicating the worth, as perceived by the designer, of placing them close to one another, or otherwise. A high rating indicates that it is absolutely necessary for the two departments to be together, and a low rating indicates that it is undesirable to have two departments close to one another. This information can then be used as the basis of the formation of a layout.

2.2.4 Recent developments in Layout Development

Much of the recent work in layout development has been aimed at integrating the qualitative methods (as in section 2.2.3) with the quantative methods (as in sections 2.2.1 and 2.2.2). The two different types of approach each have their advantages and disadvantages, and the recent work has been aimed at forming more suitable layout solutions by combining the two. Rosenblatt (18), Dutta and Sahu (19) and Fortenberry and Cox (20) have developed models that have used both quantative and qualitative information in their formulation.

Further recent work have developed graph-theory solutions to the Layout development problems. Hammouche and Webster (21) have developed a graph theory model based on research experience and suggestions of Moore, Carrie, and Seppanen. Comparisons of their program, GASOL with other existing programs such as CORELAP and CRAFT, have shown that graph-theory may produce "better" layouts with only moderately increased computational time.

2.2.5 Layout development in Construction

The existing layout development models all have one common characteristic, in that the patterns of movement of people and materials remains relatively unchanging. In construction the movement of plant, people and materials changes throughout the duration of the contract. For this reason, the static approach to layout development used in existing models is not applicable to the development of temporary works layouts on construction sites.

CHAPTER 3

PLANNING METHODS IN CONSTRUCTION

3.1 Introduction

There are two planning methods which are mainly used in the Construction industry. These are:

a) Critical Path analysis

b) Line of Balance

These methods are discussed in sections 3.2 and 3.3 respectively.

3.2 Critical Path Method

The interest in network planning was first generated in the mid 1950's with various research teams producing models for network analysis.

The first development in network analysis was produced by the Central Electricity Generating Board in Great Britain, which used a technique of identifying a "longest irreducible sequence of events" (22,23) for a project. This technique was later called the "major sequence" technique, and stated that any delays in the major sequence would lengthen the project duration.

The U.S. Navy, at a similar time, was developing the Program Evaluation and Review Technique (PERT) (22,24,25), which expressed project progress in terms of milestones or events.

Further work was being carried out, also at a similar time, by the E.I. du Pont de Nemours company which developed a technique called the "Critical Path Method" (CPM) to control a very large project (22,24,25).

The basic principles and limitations of network analysis is the topic of many publications (22,23,24,25,26,27,28,29), and will not be discussed further.

It is useful to distinguish two distinct (although often unrecognised) approaches in critical path analysis.

a) Non-resource constrained
b) Resource constrained

3.2.1 Non-resource constrained critical path analysis

In critical path analysis, the development of the network defines the inter-relationships between a set of activities or jobs which makes up the project. The inter-relationships, or logic, is defined by the necessity of completing one activity before another. A logic link may exist, for example, between steel fixing and concrete with the steel fixing preceding the concrete pouring. This type of link is defined by the physical nature of the activities or structure. Logic links may also occur in networks which are included to allow for resource constraints that may exist on the construction site. A typical example is where precasting jobs are carried out in series to allow for batching plant limitations.

In non-resource constrained critical path analysis, the latter of these logic links does not exist, so the network in this type of critical path analysis is totally independent of resources. The reasoning behind this is that often resources constraints can be more flexibly handled by a resource scheduler. The advantage of this flexibility is that the plan is more adaptable to changein the resources or the construction process. The main disadvantage of this type of planning, however, is that the network and "critical path" are completely unrealistic. Consider a housing project to build four identical houses. Simplistically, the network would be as shown in figure (3.2.1.1) with a critical path equal to the construction time of one house. A resource scheduler would then be applied to produce more satisfactory plans, by limiting the number of resources on the site.

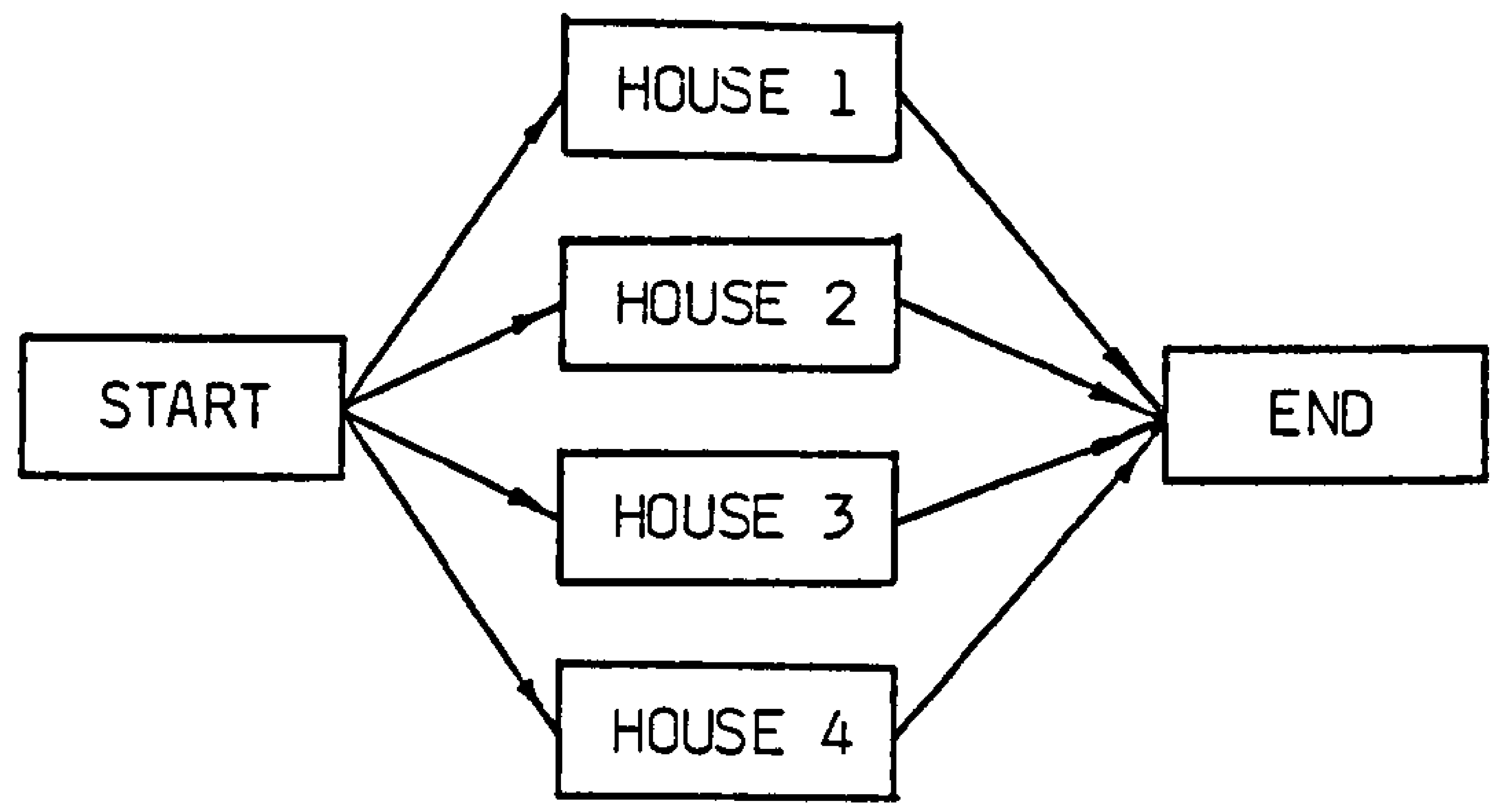


Figure (3.2.1.1) Simplified House Project Network

3.2.2 Resource constrained critical path analysis

Often contractors will produce critical path networks which include resource constraints. Typically this occurs when the contractor:

a) does not use (or want to use) a resource scheduler

b) wishes to have realistic, readable networks for use as a plan

c) needs to produce a realistic network for the client as stipulated in the conditions of contract. (e.g. Clause 14 of I.C.E Conditions of Contract).

The main disadvantage of planning in this fashion is that the plans are very inflexible to changes in resource availability, although realistic, readable plans are produced relatively quickly.

3.2.3 Site Layout and Critical path analysis

The incorporation of site layout in critical path analysis has been limited, with involvement left to the planners experience. A planner may study the layout of the construction site, and intuitively choose work methods which are suited to the particular site. The proposed work method can then be included in the network. For example, access to a certain area of the site may not be available until the partial completion of a permanent road that forms part of the contract. This provides a logic link from the road construction to the activities in this particular area of the site.

Sophisticated resource schedulers, may handle certain site layout features. Resource generation by activities, allows many independent activities to provide the necessary resource for a particular succeeding activity. In the road example above, the resource generated by the partial completion of the road is access. If access may be generated from either end of the road, then the access is provided on the completion of any one of the sections. Difficulty arises when many activities compete for the generated access, for example, there are cases where access may be wholly allocated to one activity, such as large earthworks, and also cases where many activities may use the access at the same time. Traditionally, this type of problem has been handled by allowing a resource to be allocated in percentage terms to the necessary activities. So, for example an excavation operation may require 90% of an access routes capacity, whereas other activites, such as steel fixing may require only very small percentages.

Work space, another site layout factor, may be modelled as a normal resource with activities competing for work space in the same way as they would for say, a labourer. The only major difference is that the number of labourers on site at any time may be increased if necessary. This is not so with work space.

Modelling of site layout factors using resource schedulers is clumsy because of the large numbers of "resources" that are required.

3.3 Line of Balance

The line of balance technique was originally developed by the U.S. Navy Department in 1942 for the planning and control of repetitive projects. Repetitive projects or linear projects are those which consist of a set of sub-projects which contain the same type of work in each. A traditional example is that of the construction of a housing estate where each house represents a sub-project. Repetitive projects are normally unsuitable for planning with - normal networking methods because of the large number of activities they may contain. For example, if the housing estate is made up of one hundred houses and there are twenty different activities for each house, then the whole project consists of two thousand activities in total. This may not seem excessive, but when considered in the context of the number of different trades that may have to be controlled (perhaps only ten) then this is a large number of activities.

The line of balance method basically consists of inclined bar lines representing each trade or resource on a time-progress chart, showing the expected extent of completion for each trade at any time, as shown in figure (3.3.1)(a). The progress axis on the line of balance chart may basically take two forms. With the housing project, the progression of work is measured in terms of discrete house units, whereas with road construction, the progression is measured in terms of a continuous chainage. Associated with each bar line on the chart is a buffer which reflects the time taken for each trade to complete the work on one particular unit and any interruption effects that may occur between consecutive trades.

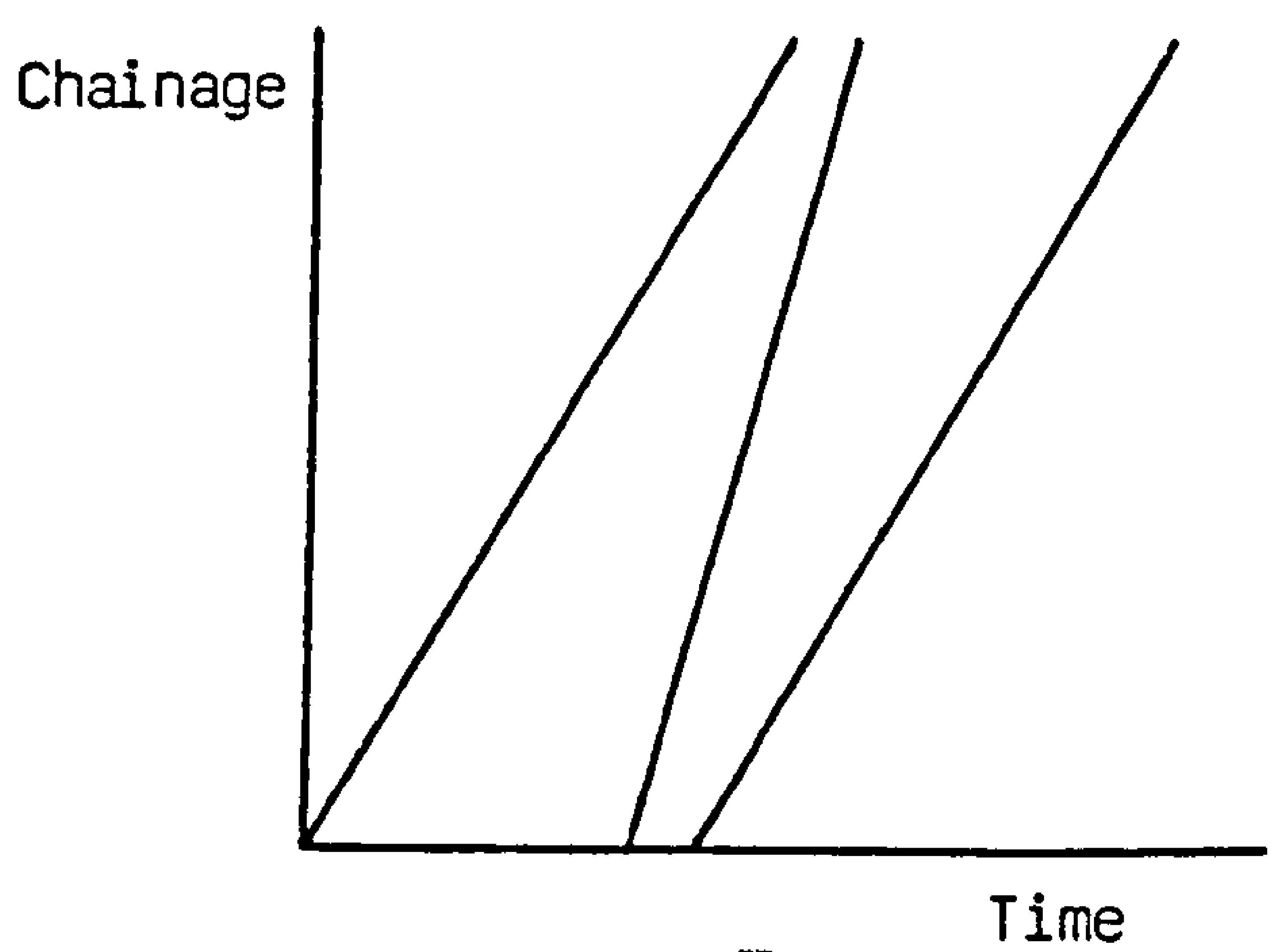


Figure (3.3.1)(a) Simple line of balance chart

Figure (3.3.1)(a) shows how the buffers affect the spacing, and start and completion of each bar line. The rate of work of the trades may be manipulated (either faster or slower) to achieve efficient construction with limited interference between trades, as illustrated in figure (3.3.1)(b).

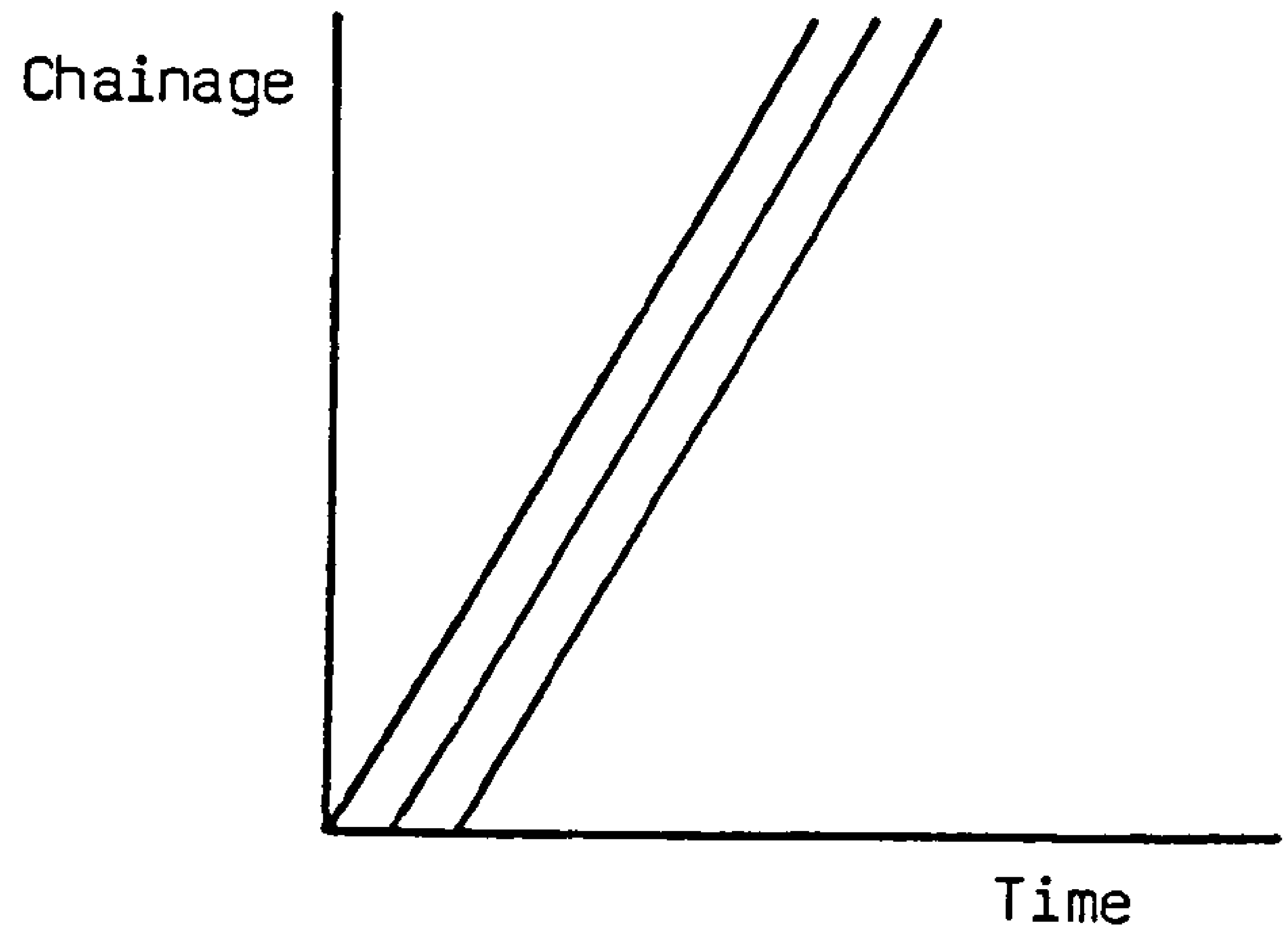


Figure (3.3.1)(b) Balanced production rates

Lumsden (30) and the National Building Agency (31) give detailed accounts of the principles of the line of balance technique and it's application to house building.

Lumsden (30) discusses resource optimisation in terms of "natural rhythms". A rhythm is defined by the number of units produced by one team in one time unit. There are three ways that natural rhythms may be achieved. The first is carried out by modifying the numbers of each team of resources to achieve a balanced production rate between the teams. For example, if the number of teams is doubled, then the production rate increases twofold.

The second option is to modify the teams make-up to try to lower the rhythm. Resource teams with low rhythms are most satisfactory, as it is easier to balance them.

The third method of resource optimation may be used when successive activities in the project utilize the same or similar resources of trades. These activities may be grouped together as one to reduce the natural rhythm of the combined resource.

By the modification of the rates of progress of the activities, a line of balance chart with almost parallel bars may be produced, as illustrated in figure (3.3.1)(b).

The involvement of site layout factors in the line of balance method has been more widespread than that in network analysis. In housing estate building, for example, the order in which the houses are constructed may be representative of the order in which they occur on the street. This has the advantage that there is a continuous progression of resources and materials geographically through the site.

In other types of construction geography plays a more important role. In road construction, for example, the order of work is dictated entirely by the geography of the road. Johnston (32) describes a line of balance technique applied to highway construction.

Johnston (32) identified some important extensions to the line of balance method. The first was the need for variable production rate for the resource teams. Whereas previous models used constant production rates for the activities and resources, Johnston recognised that for certain activities, such as earthworks, the quantity of work and the type of material vary along the chainage. This meant that with uniform resource teams, the progression rate along the road would alter significantly, as illustrated in figure (3.3.2)(a).

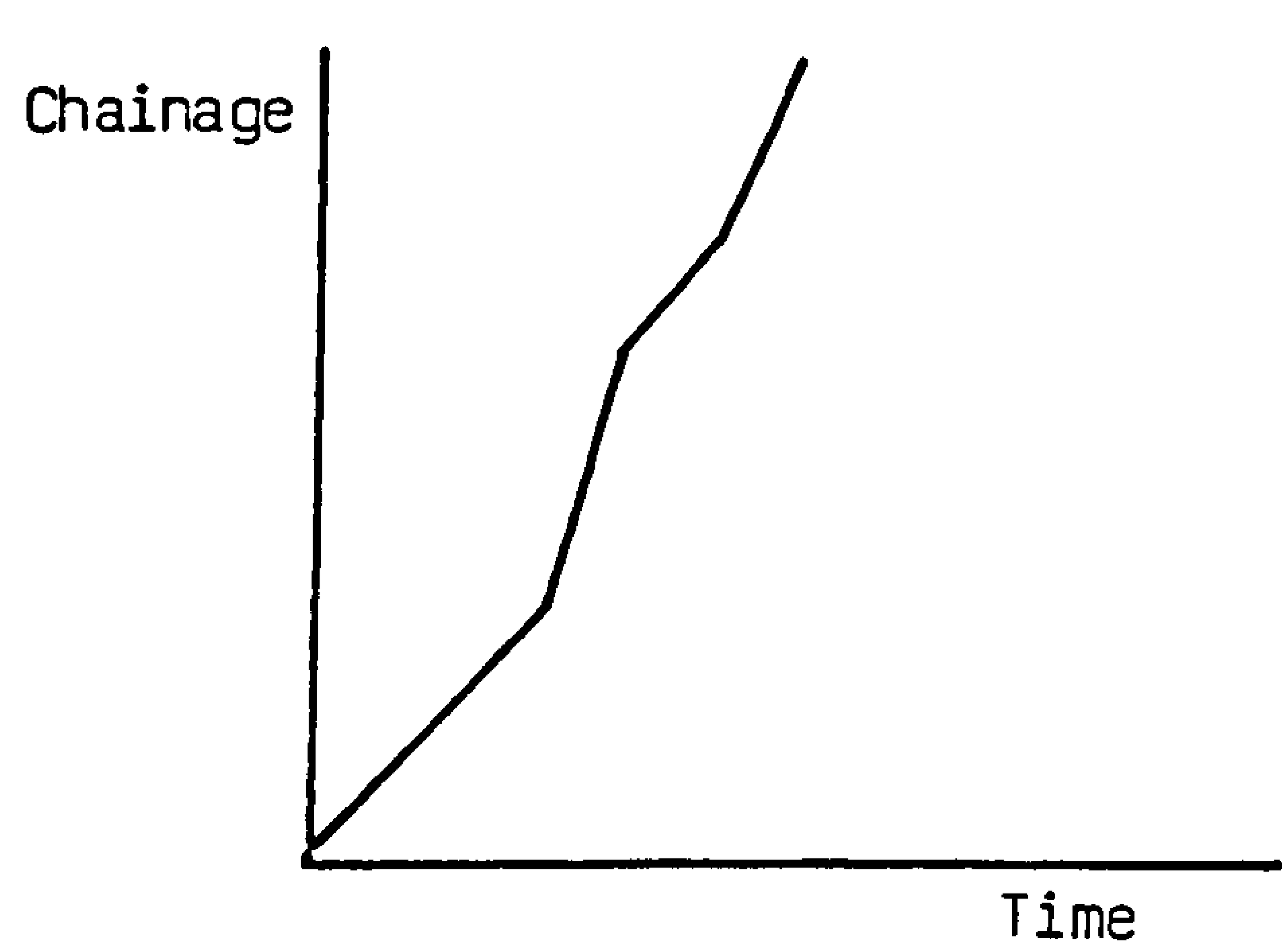


Figure (3.3.2)(a) Variable progress

The second extension is related to the first. Where the quantity of work varies along the length of the road, it is not sufficient to apply a simple time buffer from the start of the preceding activity to the start of the succeeding activity (as described earlier). In this situation it is necessary to show the start and finish time of any activity on the line of balance chart. This is shown in figure (3.3.2)(b).

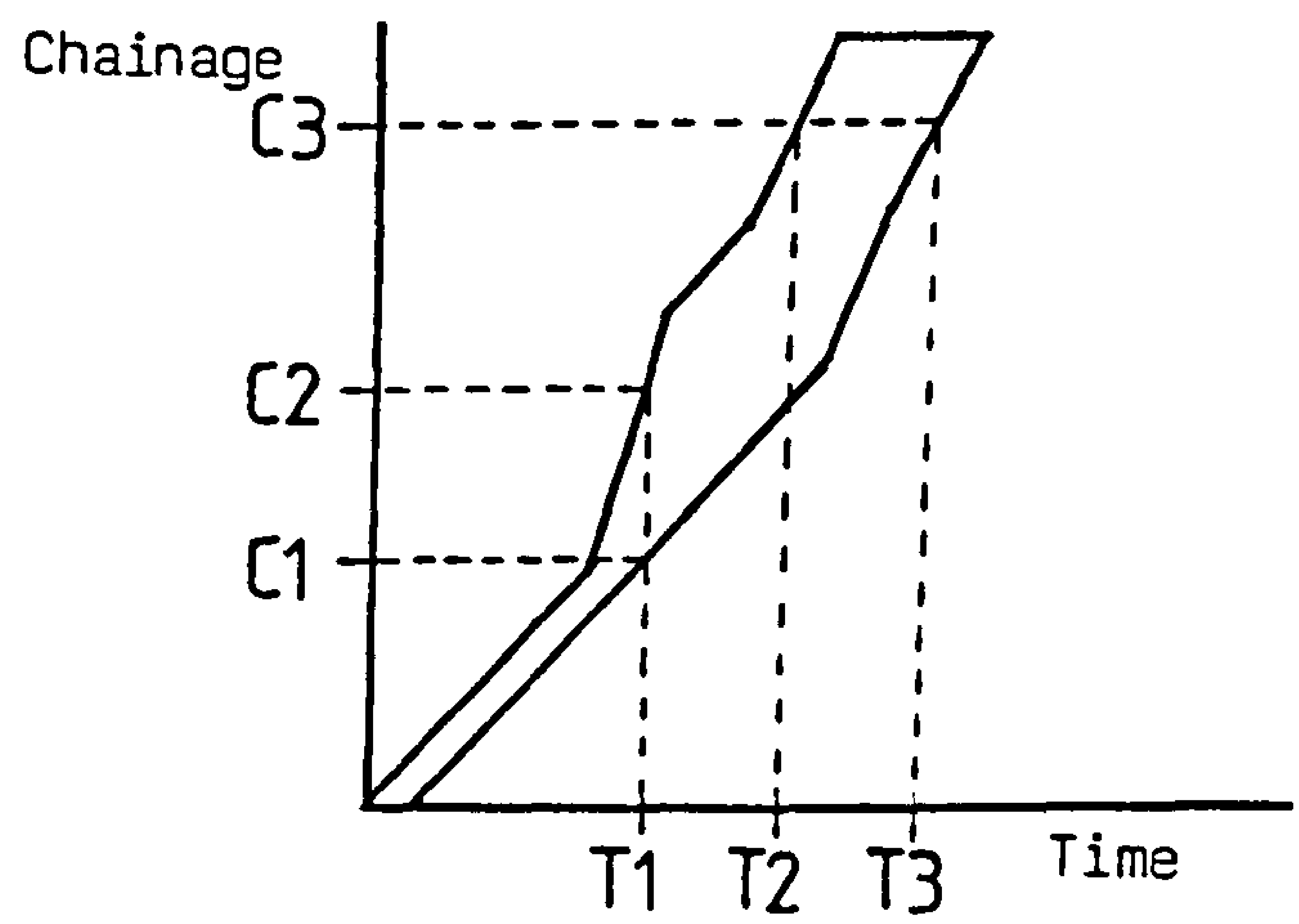


Figure (3.3.2)(b) Start and Finish time bars

Figure (3.3.2)(b) shows that at time T1 excavation occurs between chainages C1 and C2, and that similarly that at chainage C3 excavation occurs between times T2 and T3. This type of bar makes it much more difficult to balance resources due to it's irregularity, it is, however, a truer reflection of the situation on site.

The third extension to the line of balance method discussed by Johnston, was the inclusion of non-linear activities on the line of balance time-progress chart. In highway construction this may be the construction of a culvert or bridge which generally occur at one chainage, and directly affects the construction of the road.

Finally, Johnston included a "must" link between the different activities. An example in road construction is the rolling of macadam, which must occur very soon after it is laid. This link in reality may be of little use as laying and rolling are usually carried out as one operation.

O'Brien (33) wrote of a line of balance style of planning technique, called the Vertical Production Method (V.P.M.), applied to high-rise construction. This is another example of where the geography of the structure dictates the order of construction of the "units". In this case, the units are the high-rise storeys.

V.P.M. divides high-rise construction into two distinct parts. The foundations and site work form a set of non-linear activities, whilst the high-rise storeys form linear activities. O'Brien advocates the planning of these two parts independently, the first using a network approach, and the second a line of balance style of planning. The network planning for the site works provides a "key junction point" at which time the linear planning of the storeys may commence.

Leaving both plans completely separate as O'Brien suggests may be satisfactory if a high proportion of the work is carried out by sub-contractors. If, however, the construction is carried out by the contractor then some control and interaction of the resources on both plans is necessary for the efficient construction of the contract. This perhaps is the major failing of the V.P.M.

Birrell (34) broadly divides construction planning into two types:

a) Macro planning
b) Micro planning

Macro planning is the planning carried out by the site agent or the contractor's head office which produces schedules of work and site resource levels. Micro planning is the type carried out by a general foreman on a daily or weekly basis. The foreman's task is to allocate the available resources to the areas that are ready for work. Birrell argued that if some of the principles used in this short term planning were used in the long term macro planning then better plans would be produced.

He considered the major considerations in a (sub)contractors mind were:

a) Maximum usage of the learning curve
b) Minimizing stopping and starting of resources
c) Reducing hire/fire of resources

d) Minimising the cost of the control system

e) Planning as many work squads as possible adjacent to one another.

Birrell suggests that the easiest way to achieve these aims is to consider the work squad (or team) as a continuous flow around the site. The teams move around the site carrying out the same type of work at each work location. If the resource flows are organised so that the resources pass through the areas in the same sequence, then many of the aims above will be achieved.

The subdivision of the project is carried out in such a way as to have the same quantity of work in each location for each team. This subdivision may be feasible for highly repetitive projects, but for more general projects this task seems to be totally infeasible, as the work content for each resource team will vary greatly across the site.

The starting order of the different trades in the flows around the site will depend on the physical nature of the project, with some trades following others by necessity, for example plasterers must follow bricklayers, whilst others, for example plumbers and electricians have no direct involvement with one another. The concepts of absolute and preferential logic (see section 5.3) illustrates this distinction in the types of logic. The sequencing of the work areas in the resource flows is not discussed by Birrell, although presumably it is formed with geographical and resource continuity considerations in mind.

The model is basically a line of balance style of planning method with the resource teams represented by slanted lines on a work area/time chart.

Birrell's model is important in two respects. Firstly it recognises that work areas do not necessarily need to be repetitive units, and that line of balance style planning may be applicable to non-linear sites as long as there is sufficient work for each resource team to carry out in each work area. The second is realisation that continuity of flow of resources around a non-linear site may be included as part of a planning method.

Trimble (35) followed up the ideas presented by Birrell and produced a computer program called ROS (Resource Orientated Scheduling) to carry out this type of resource scheduling. In using this program, Trimble identified those activities in the project that would benefit from application of this scheduling method, and produced a "sub" plan for those activities i.e. he produced resource requirements and a duration for those activities taken as a whole. With this information, he then combined this group of activities, with the remaining activities in a commercially available network package. This arrangement of the two types of planning methods overcomes the problem of the subdivision of the site into suitably sized work areas (as discussed above), although it takes no account of the interaction of resources that may occur between the linear and non-linear activities of each method.

The line of balance style of planning has become accepted practice in some sections of the construction industry with it's simple effective usage of resource information in its formulation. In certain cases the site geography is also integral in the method. Further extensions to the line of balance method have been developed during this research and these are discussed in the next chapter.

CHAPTER 4

EXTENSIONS TO LINE OF BALANCE

4.1 Introduction

The previous chapter discussed the current usage of models that exist for planning in construction management. The line of balance method and associated methods have shown some promise of achieving the incorporation of site layout features in plans for linear projects. The main shortcoming of the line of balance method with regard to this aim is perhaps the simplicity of the model and it's lack of applicability to non-linear projects.

This chapter discusses work carried out during this research that has expanded the line of balance method to allow the integration of site layout factors for linear projects.

4.2 Network representation of Line of balance

The line of balance method in it's original form is too simple for use with many construction applications. Scriver (36) devised an extension to the line of balance method whereby a network representation of a linear project was produced. This network was similar to a job-on-node critical path network with several more relationships defined. The relationships used in this network representation were:

a) Time-after relationship (Time lag)

This relationship is similar to a normal network connection and is illustrated in figure (4.2.1)(a). It may be expressed as "job B must succeed job A by at least x time units, at any coincident position".

b) Distance-after relationship (Distance lag)

This relationship is similar to the one above, but in this instance the relationship is governed by the progress difference between the activities. It may be expressed as "job B must succeed job A by at least x progress units, at any particular time". Normally the progress units will be a distance measure. Figure (4.2.1)(b) illustrates this relationship.

c) Time-between relationship (Time buffer)

This relationship is illustrated in figure (4.2.1)(c) and may be expressed as "at any coincident location, job A may not commence within x time units of job B, and similarly, job B may not commence within y time units of job A".

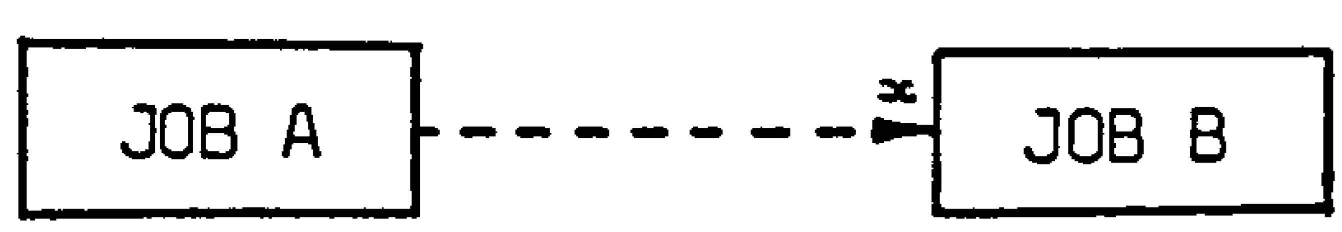
d) Distance-between relationship (Distance buffer)

This relationship is illustrated in figure (4.2.1)(d) and may be expressed as "at any coincident location, job A may not commence within x distance units of job B, and similarly, job B may not commence within y distance units of job A"

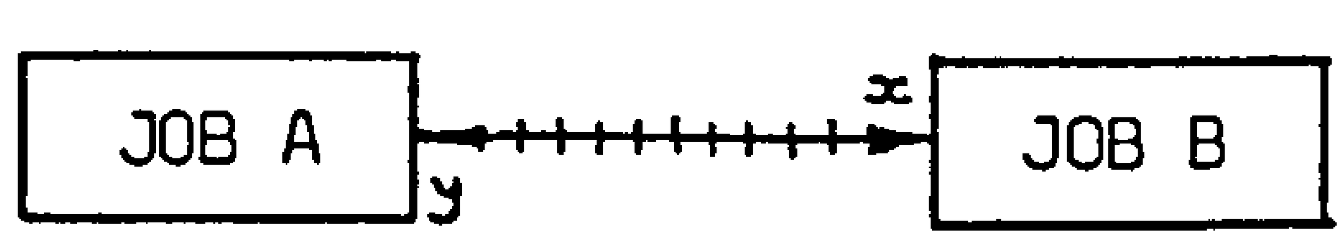
Figure (4.2.1) shows the network representation of the four types of relationships. Relationships (a) and (b) are uni-directional and imply a sequence of work, and may therefore be defined as lags, whilst relationships (c) and (d) are bi-directional and may be defined as buffers. Many of these relationships are applicable to both linear activities and to non-linear activities, and figure (4.2.2) gives a line of balance chart example for each application.

The network representation, is called "Fully Defined network" aids in the construction of a line of balance chart for the project. Scriver produces a fully defined network for an example road and bridge project, and then illustrates the steps used to produce a plan based on the line of balance chart.

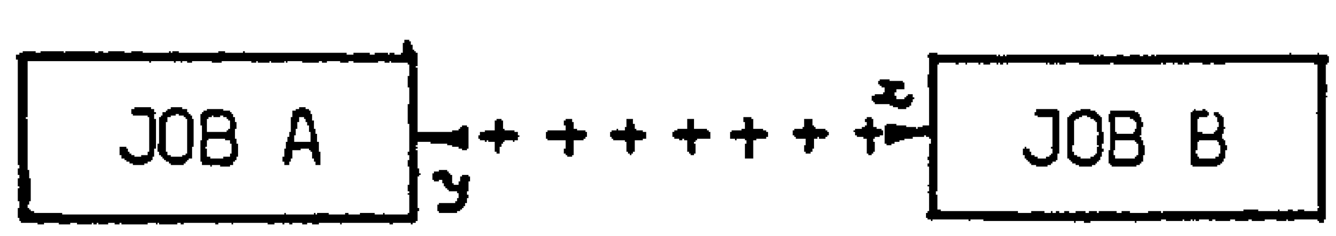
a) Time Lag



b) Distance Lag



c) Time Buffer



d) Distance Buffer

Figure (4.2.1) Relationships in the Network representation

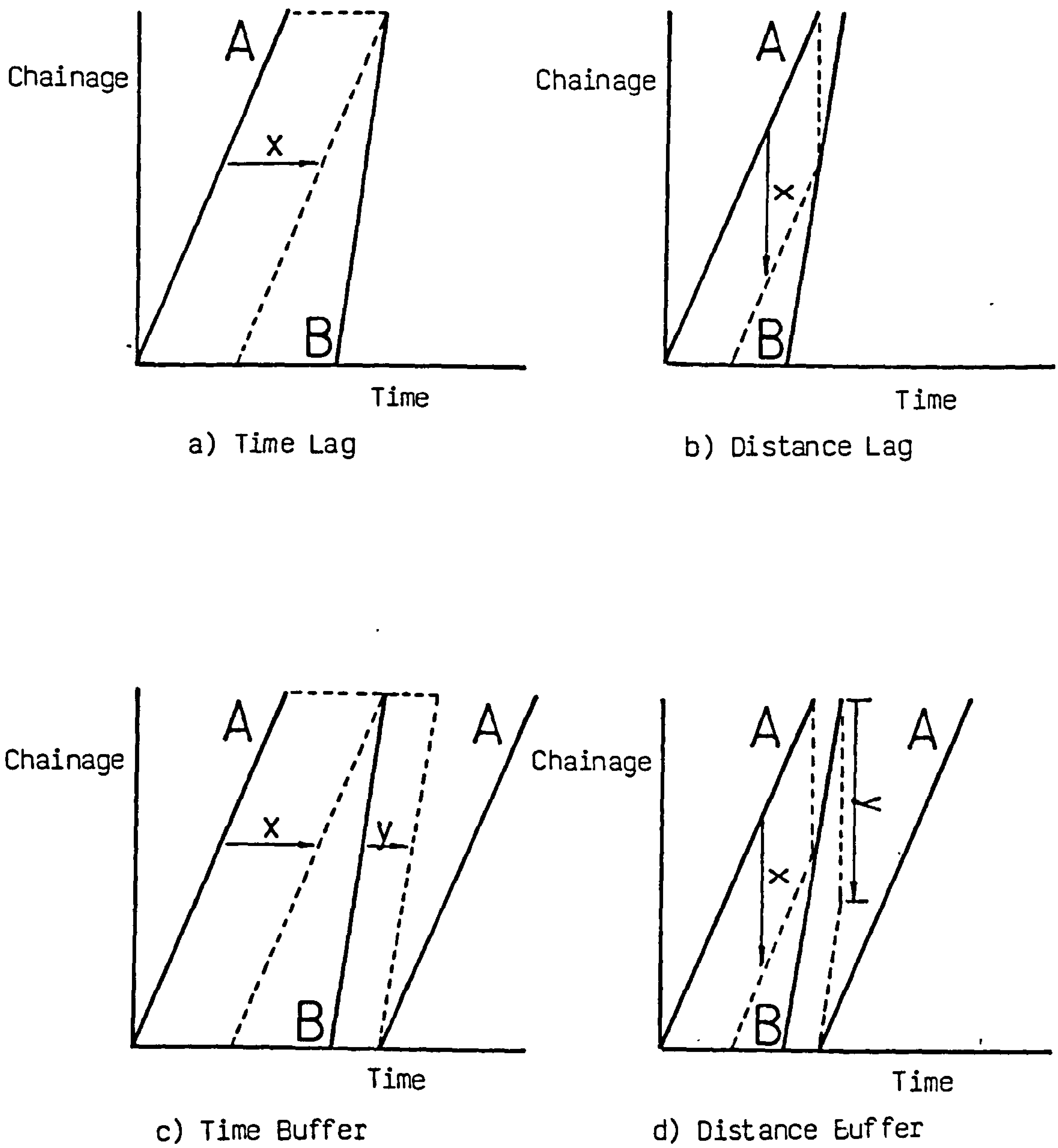


Figure (4.2.2) Relationships in the Network representation

Scriver's work is the first occurence of a planning method, based on the line of balance method, that has attempted to expand and model the relationships that occur between activities in a construction project. Work carried out during this research has followed on from Scriver's work and has extended the line of balance method yet further. The further extensions are described in the following sections.

4.2.1 Percentage complete relationships

The time and distance relationships (as discussed in section (4.2)) may be used to represent most situations that may arise in construction planning. There may be cases, however, where progress is measured in terms of the percentage of an activity completed instead of time and distance. Typically this may arise when the work content for a section is not linear with either time or distance. In a road project this may occur whilst excavating through a hill consisting of both rock and clay. If another area of the site requires a certain percentage of the volume of cut for fill, regardless of whether it is clay or rock, then this cannot be modelled purely by time and distance links. This is because the volume excavated is linear with neither time or distance.

Percentage complete links and buffers may often be modelled in terms of time or distance, but it is useful to include them for completeness.

4.2.2 Must link

The earliest reference to must links was made Roy (29), who developed a network planning method which incorporated them. A must link may be expressed as "job B must follow job A by x time units". They were initially discussed with reference to the line of balance method in Johnstons work on highway construction, which is described in section (3.2).

Johnston used the example of the laying and rolling of macadam, indicating that the rolling must almost immediately follow the laying of the macadam. A similar effect may be achieved simply by combining the laying and rolling operations into one. In reality however, there would usually be some delay between the laying and rolling operations to reduce interference between the two teams of plant. We may model this situation with a combination of a lag (time, distance or percent) and a must link (time, distance or percent) between the two operations, as illustrated (for distance) in figure (4.2.2.1).

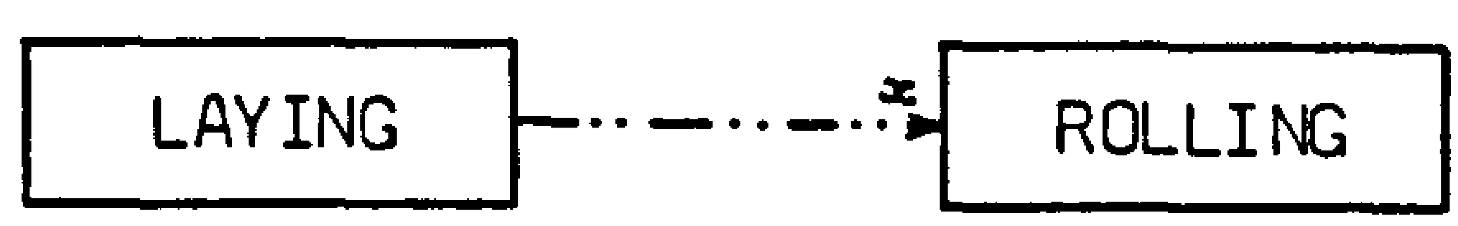


Figure (4.2.2.1) Must link for Macadam Laying

4.2.3 Interactive production rate

The interactive production rate is a complicated relationship, but one that is necessary to model situations that may arise in construction. This relationship may be expressed in qualitive terms as "if job B follows job A then the rate of work for job B will altered by a factor of x". Figure (4.2.3.1) illustrates a situation where this may arise for the drainage construction of a road project. In this case, the production rate of the drainage may be doubled if it follows the general excavation and grading of the road.

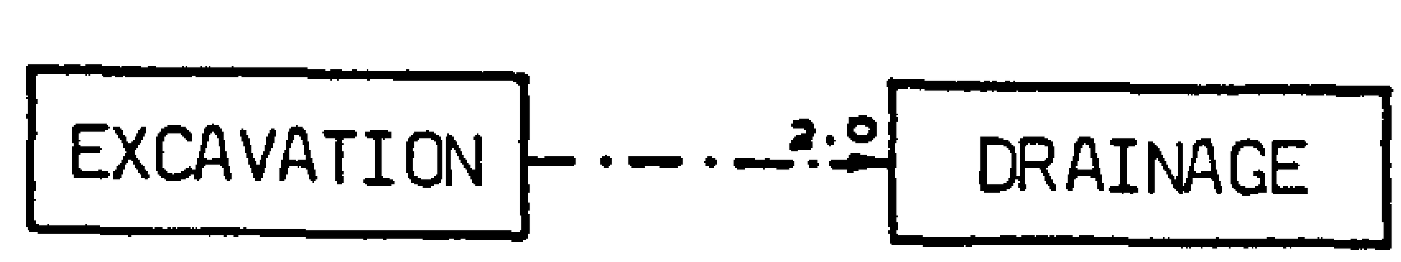


Figure (4.2.3.1) Interactive production rate for drainage

This type of relationship may also be used with time or distance based interactive production factors. For instance, deterioration of an excavated trench occurs in direct proportion to the time delay before the backfilling of the trench. If the laying of the pipe occurs a long time after the excavation of the trench then the laying operation will be affected by the deterioration of the trench. This is illustrated in figure (4.2.3.2), where dt represents the time difference between the operations.

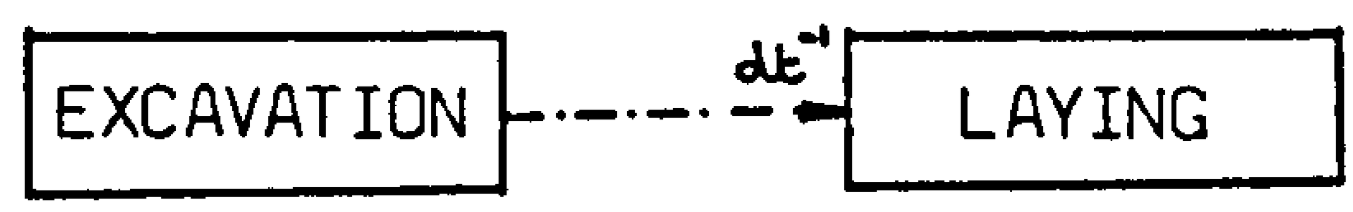


Figure (4.2.3.2) Interactive production rate for pipework

The example above illustrates the use of an interactive production rate link between two linear activities. If the relationship is used in conjunction with a non-linear activity then certain site layout factors, such as the positioning of a material store (or other similar facility), may be modelled. The provision of a material store will usually aid in the construction of any activity which requires the material used. The benefit of a material store, however, is inversely proportional to it's distance from the activity. If a material store holds the pipes used in a pipe laying operation, for example, then the production rate of the pipe laying team will slow down as the work face moves away from the material store. This is assuming, of course, that the make up of the pipe laying team remains the same. The positioning of the material store is therefore important in the production of efficient plans for the project. If the material stores are modelled using interactive production rates, then many plans may be produced with different material store positions. Each of these plans may then be evaluated in terms of the effect on project completion and resource continuity.

4.2.4 Minimum work distance, time or percentage

Figure (4.2.4.1) illustrates a situation where an end constraint precedes a start constraint. In this situation the project is delayed by having a fast operation occurring between two slower operations. This delay is caused by the continuity of the "sandwiched" team.

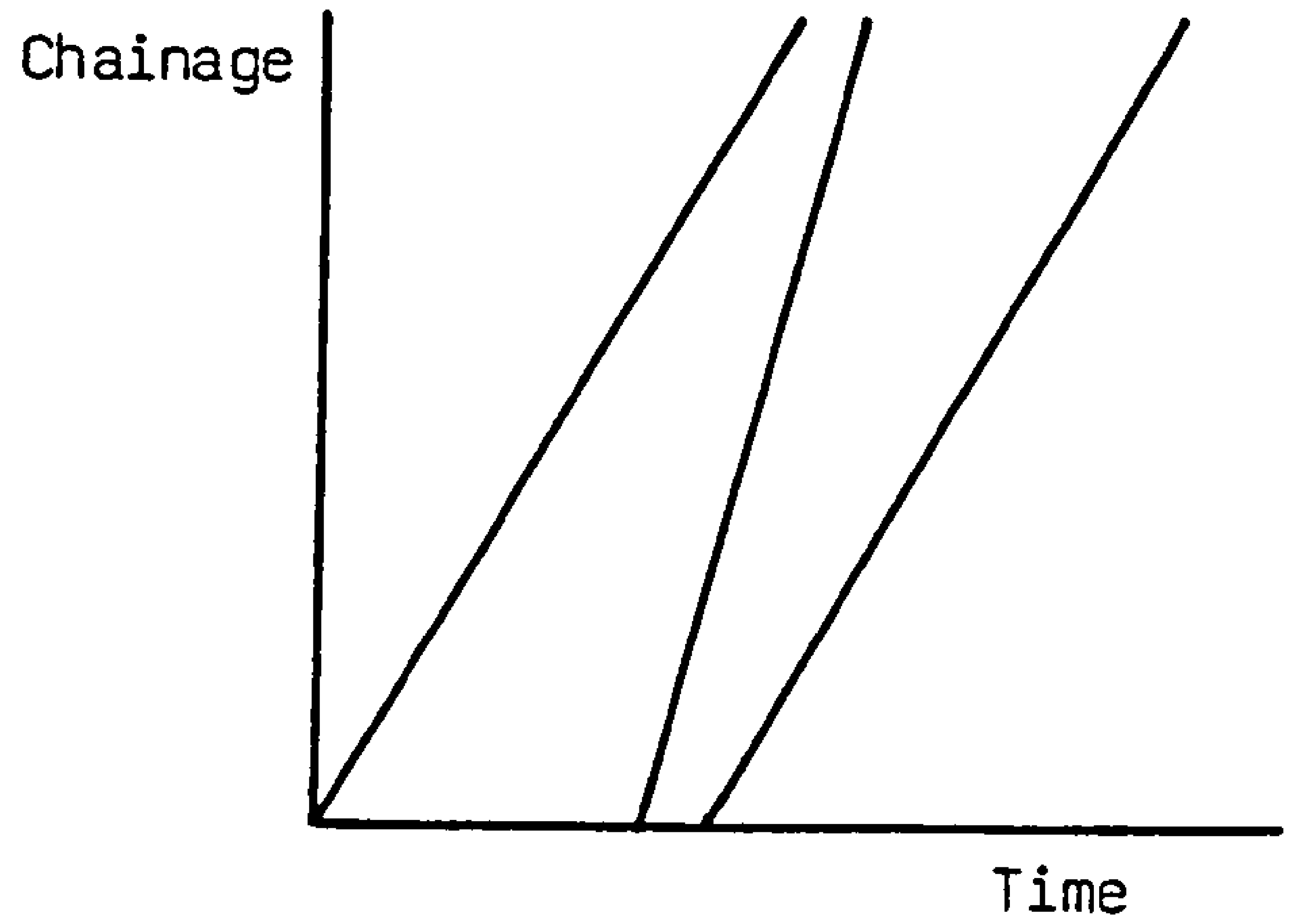


Figure (4.2.4.1) Inbalance in Production rates

In normal line of balance practice, a planner would try to reduce the production rate of the sandwiched team in order to achieve parity between the three operations, as shown in figure (4.2.4.2).

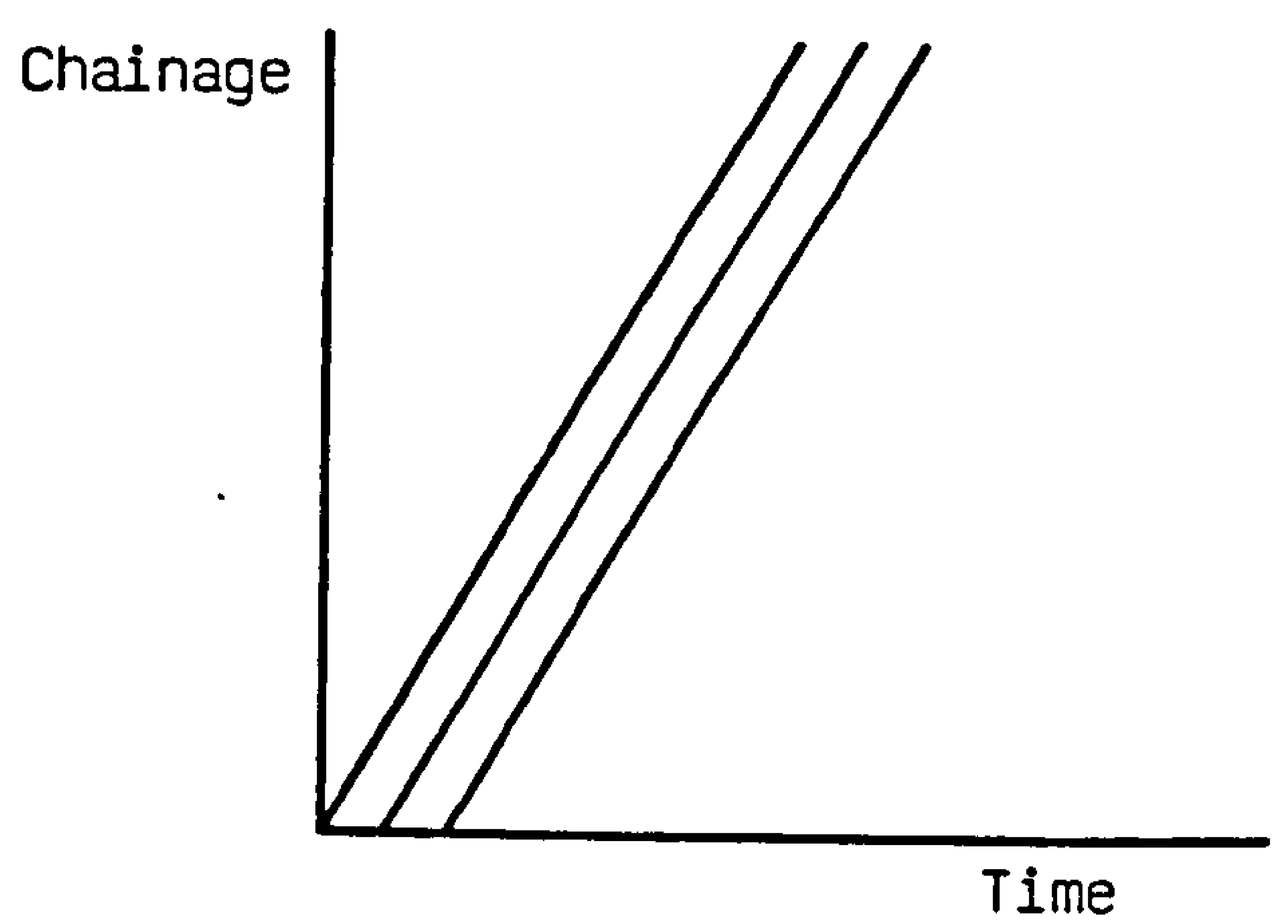


Figure (4.2.4.2) Parity in production rates

If however, the sandwiched team may not be slowed down, then it may be necessary to split it into smaller discontinuous sections, to produce a line of balance chart as illustrated in figure (4.2.4.3).

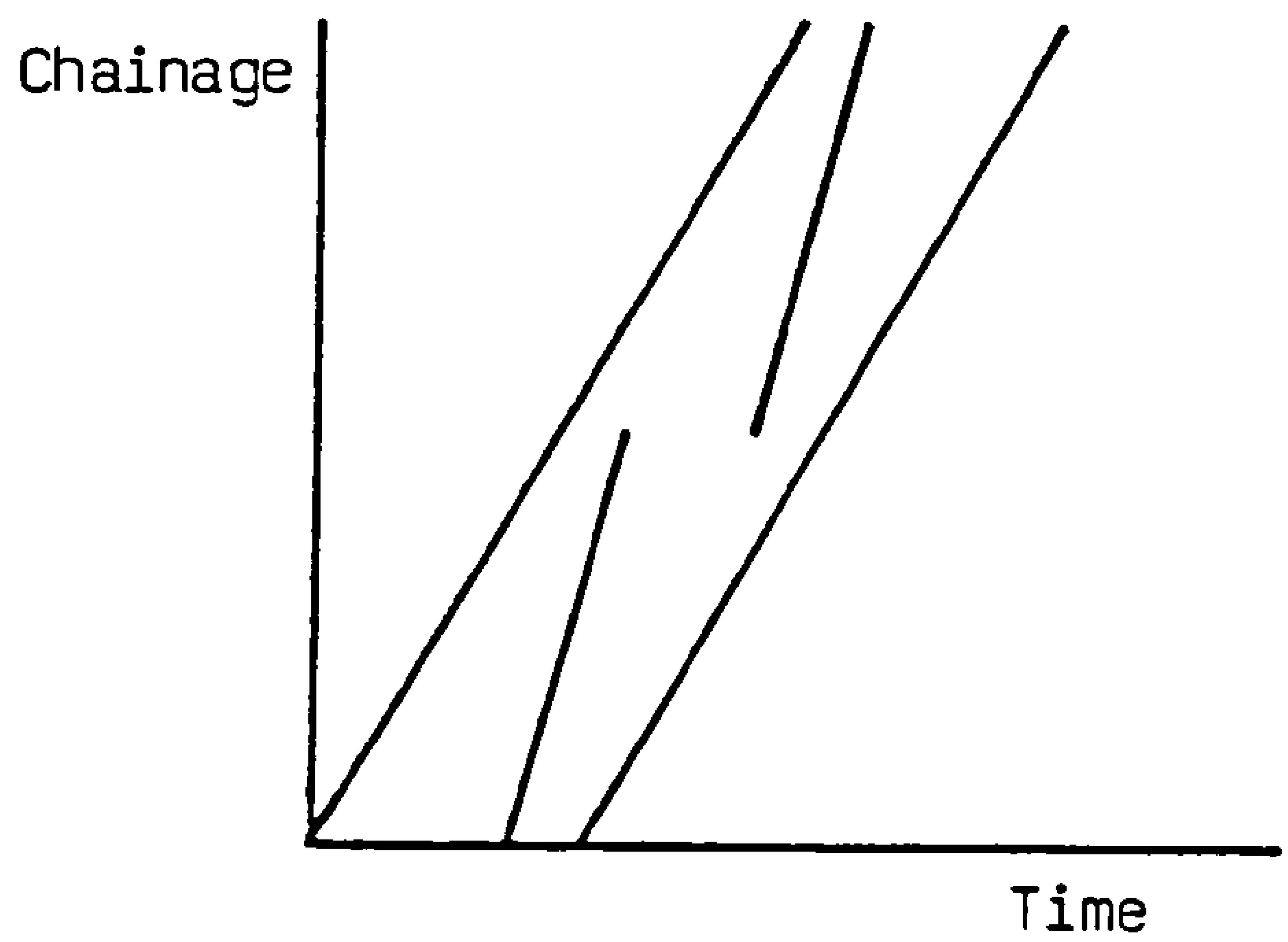


Figure (4.2.4.3) Split-down of the faster team

In order to do this each resource must be given a "minimum distance" (or time or percent) to define a sensible minimum work package for a team to produce in one continuous stretch. The penalty for allowing this split-down of the work is the extra time that a resource will stay on site. This may be offset to some extent by the saving in site overheads and liquidated damages due to over-run.

A further example of the split-down of work may be considered in the situation as illustrated in figure (4.2.4.4).

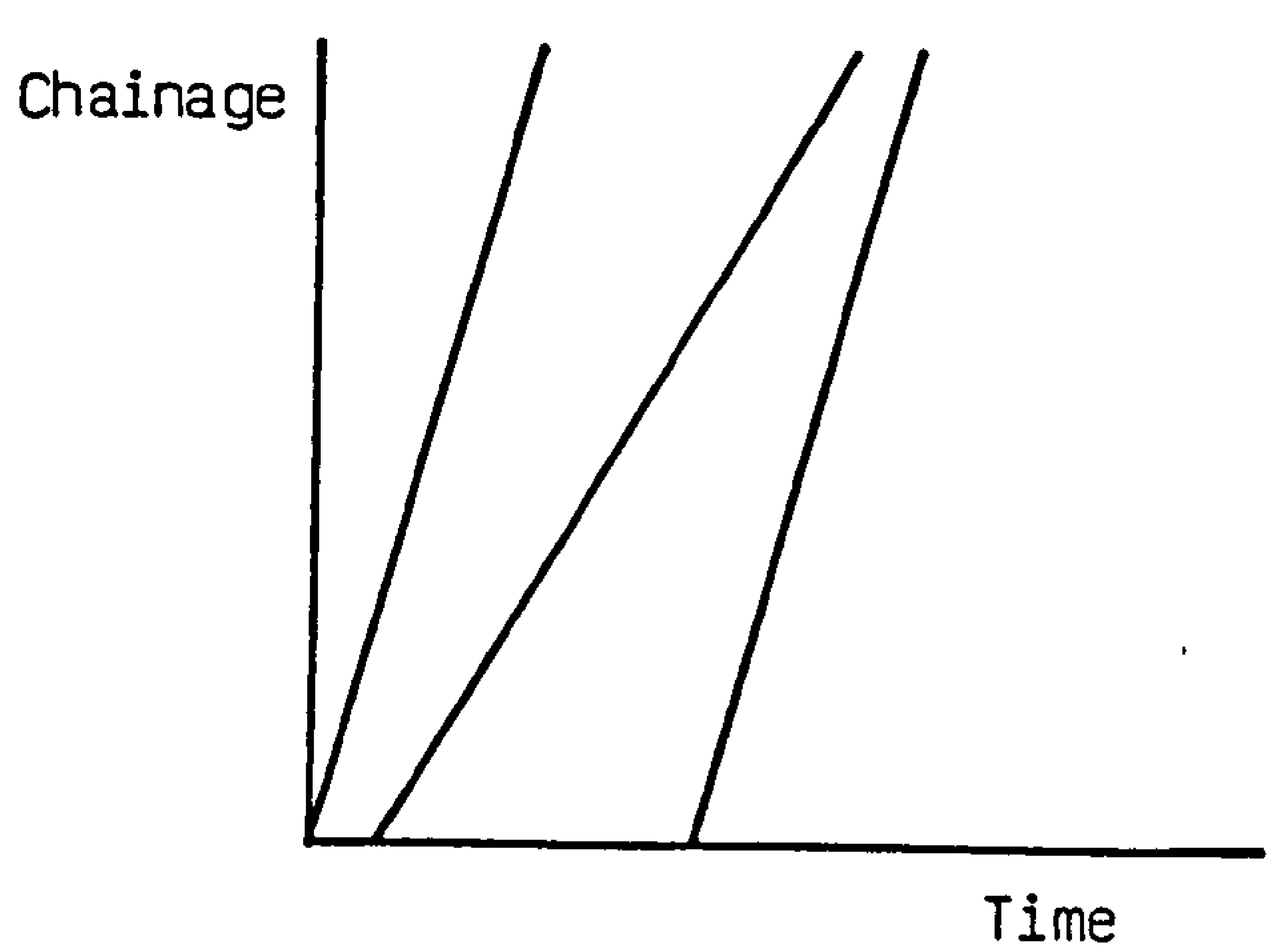


Figure (4.2.4.4) Inbalance in production rates

In this case the split-down may result in a chart as illustrated in figure (4.2.4.5). In order to achieve this plan many teams of the slower resource need to be employed. This situation is similar to Lumsden's method (30) of doubling or tripling team sizes to achieve faster outputs.

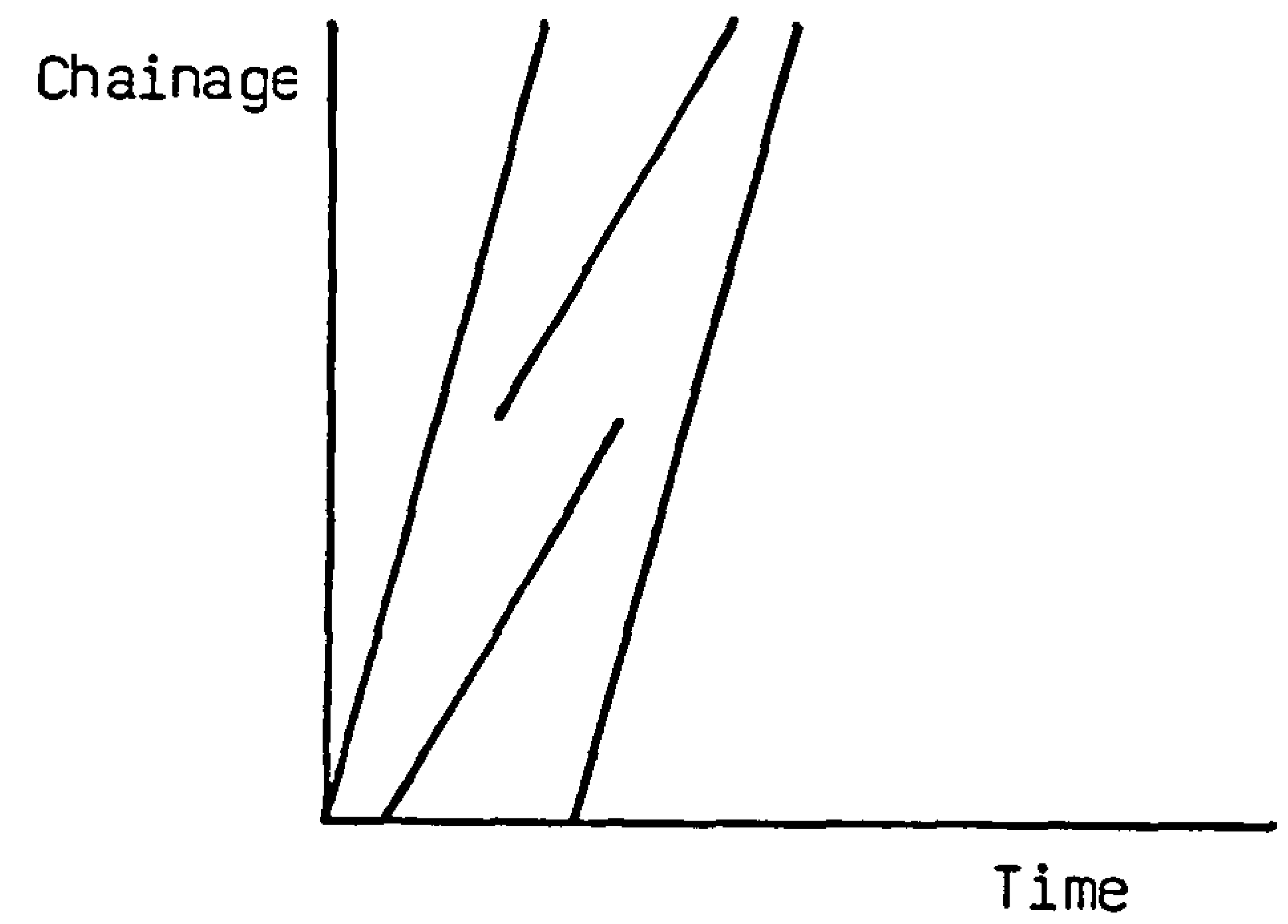


Figure (4.2.4.5) Overlapping of the slower team

4.2.5 Internal buffers

If situations like those illustrated in figure (4.2.4.5) occur, it may be necessary to define internal buffers to prevent interruption of work due to conflict between resource teams of the same type.

4.2.6 Access Diamonds

Access diamonds are symbols used in the network representation to indicate the position of possible access points. At these positions, access may be specified by the planner, before the formation of the plan. The plans may thus be produced with different combinations of access points on the construction site.

The iterative production of plans with different access points allows the planner to investigate the value of the provision and preparation of the access points by comparisons of the savings in contract duration, and resources employed. This is a futher case where site layout effects have been included in the extended line of balance method.

4.2.7 Either receivers

Normal networking links as shown in figure (4.2.7.1)) have the meaning "job C may commence on the completion of both jobs A and B".

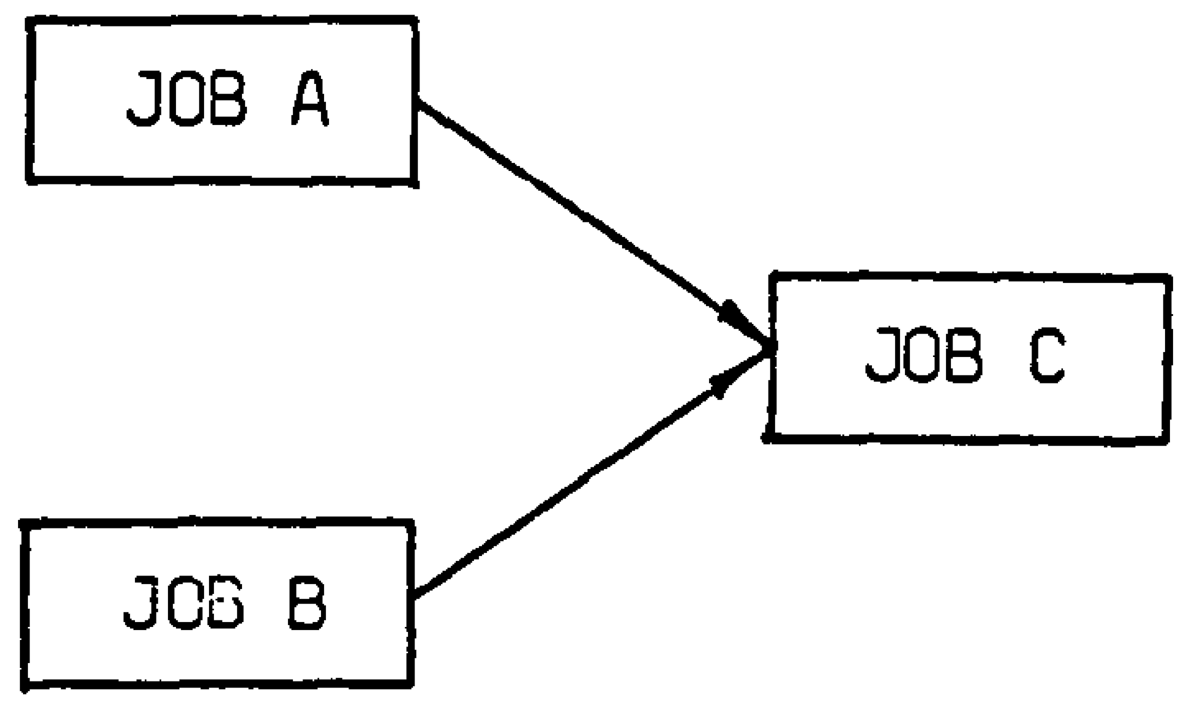


Figure (4.2.7.1) Normal network links

There may be some cases where an activity is free to commence on the completion of one of many preceding activities. This may occur when access is provided by one of the preceding activities. Figure (4.2.7.2) shows an "either receiver" and this has the meaning of "job C may commence on the completion of either job A or job B".

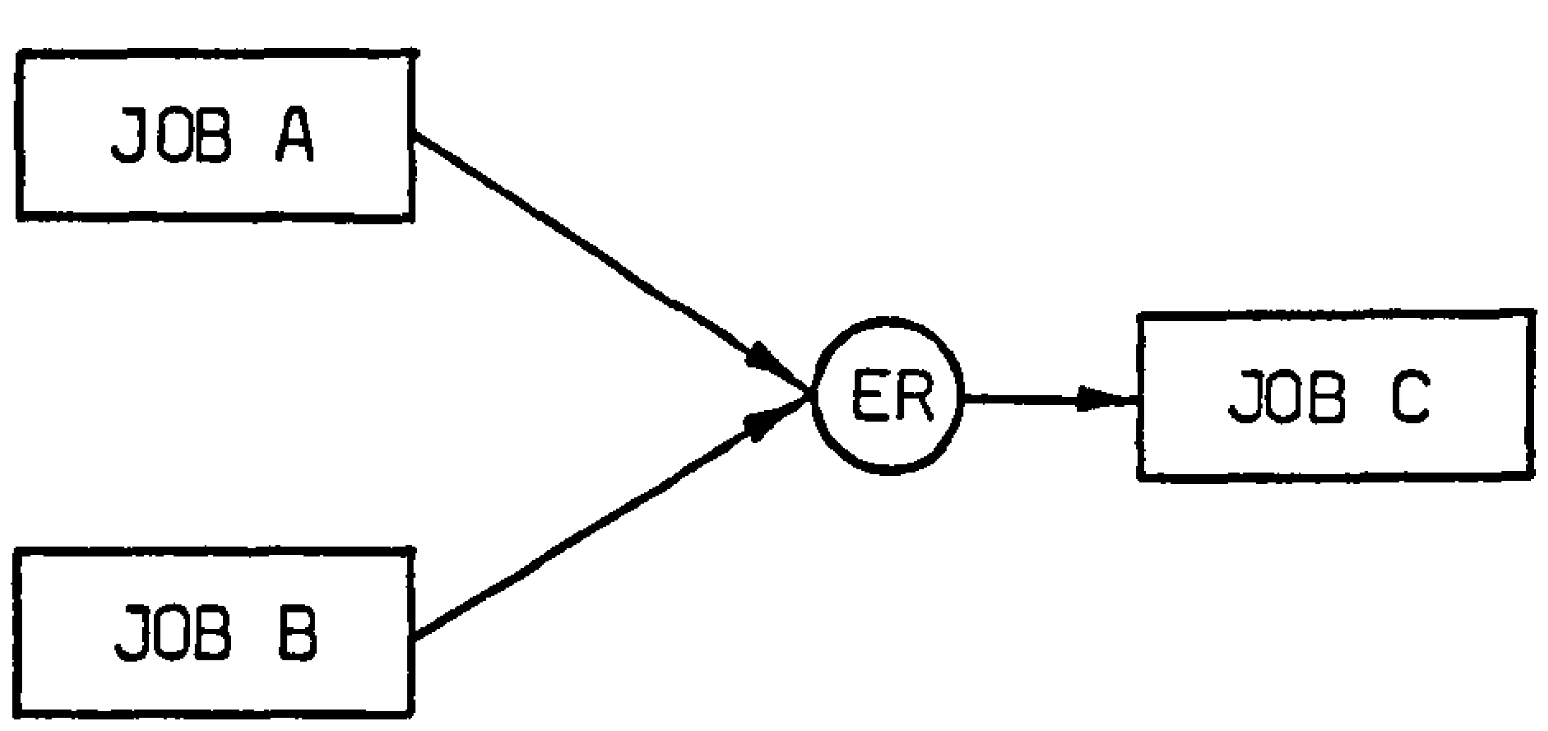


Figure (4.2.7.2) Either receiver

4.2.8 Linear and Non-linear activities

In order to distinguish between linear activities and non-linear activities the following notation illustrated in figure (4.2.8.1) has been adopted.

Figure (4.2.8.1) Linear and Non-linear notation

4.2.9 Simple example for a road project

The road project consists of a stretch of road 100 metres long, consisting of the following activities:

Activity	Rate (m/day)	Min. Distance (m)
Drainage	12	20
Earthworks	20	40
Sub-base	30	20
Road-base	25	33
Surface	35	25
Finishes	20	50

The activities will be constructed in the order in which they appear above, with the exception of the drainage which will be not constrained by any of the roadworks. Distance lags of 20m will exist between the roadwork activities. The network for the project is shown in figure (4.2.9.1).

Figures (4.2.9.2) and (4.2.9.3) show the line of balance charts for one resource team for each activity and two resource teams for each respectively.

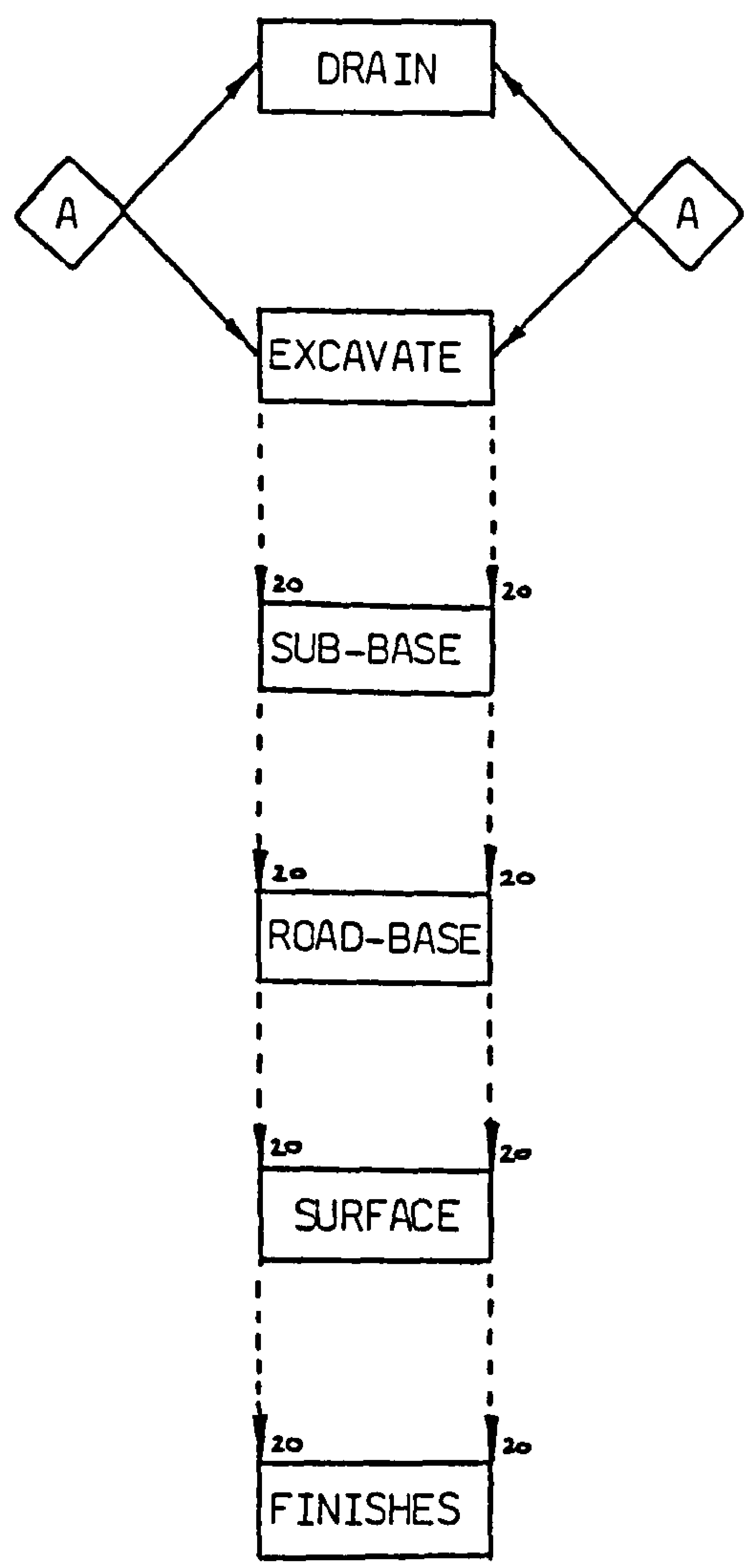


Figure (4.2.9.1) Network representation for the Road project

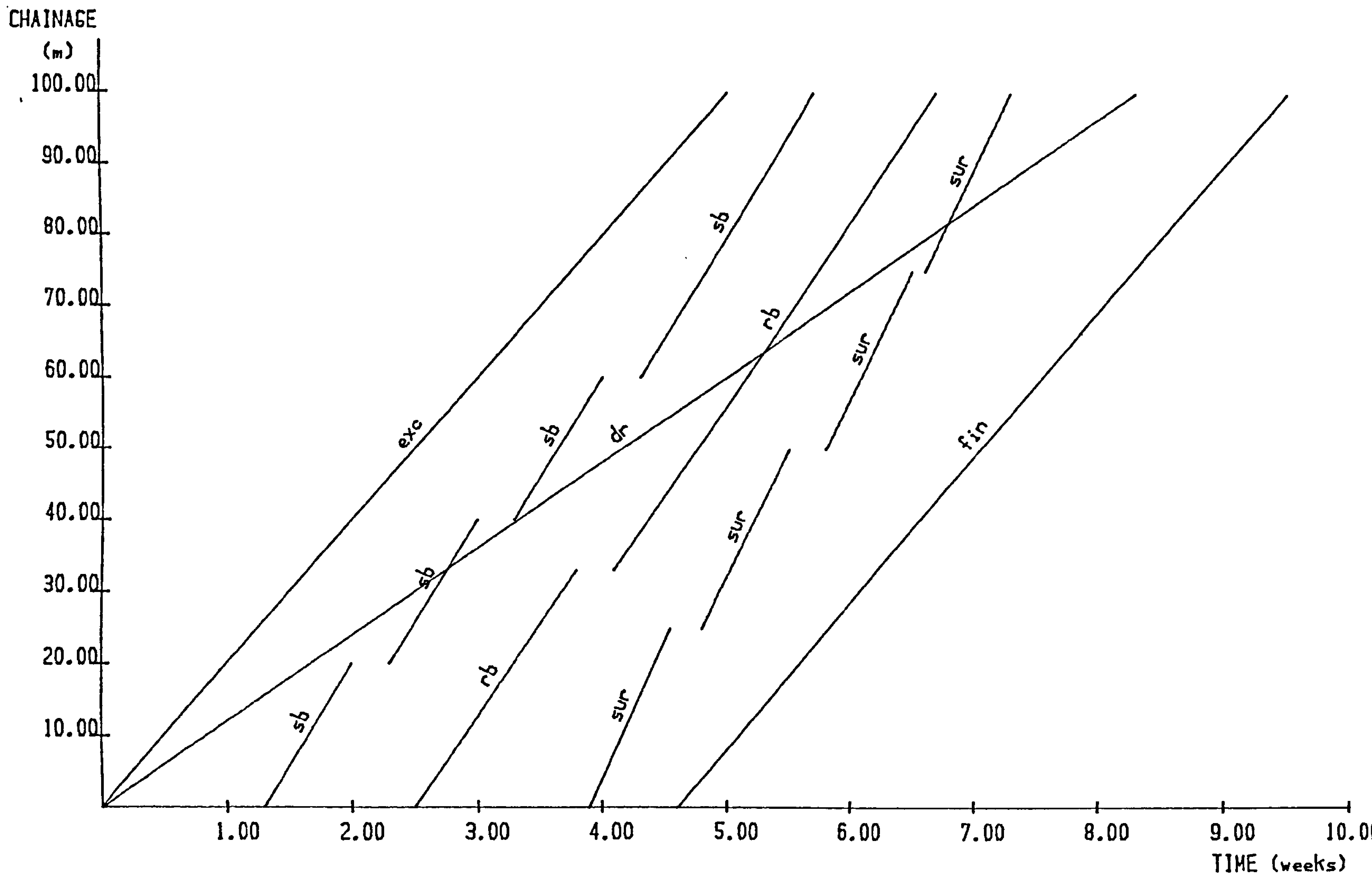


FIGURE NUMBER (4.2.9.2) Simple road project with access at chainage 0

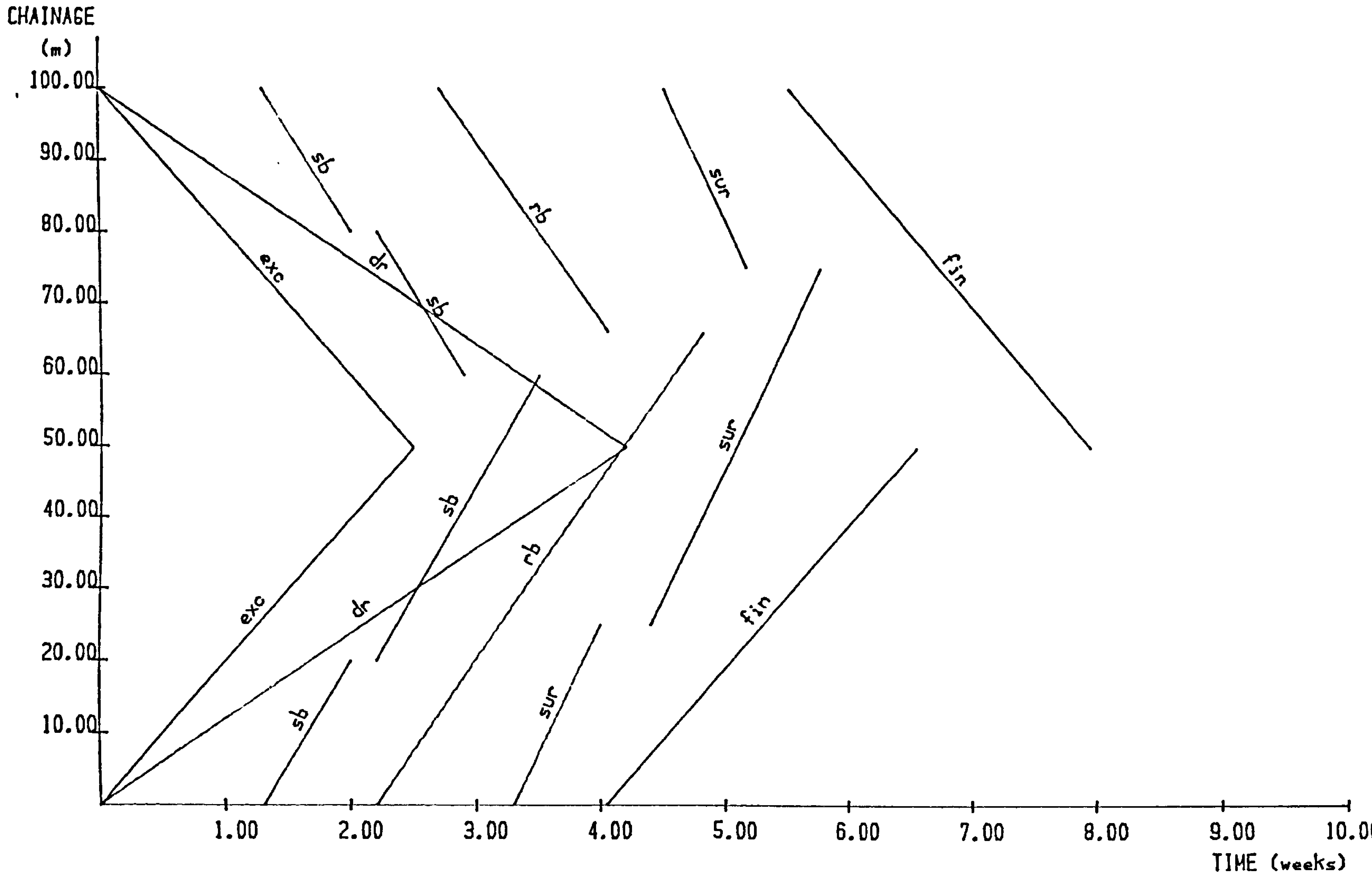


FIGURE NUMBER (4.2.9.3) Simple road project with access at chainages 0 and 700

4.3 Road and Culvert Example

This example is used to examine the usage of the extended line of balance method. The solutions are carried out by hand with intuitive decision making occuring throughout their production. Sections (4.4) and (4.5) illustrate two "automatic" methods of solution using the extended line of balance method, and these automatic methods will be evaluated against the hand-worked solutions.

The project consists of a stretch of road with possible access at 0, 200, 400 and 700 metre chainages. At chainage 200m the road crosses a culvert. See figure (4.3.1).

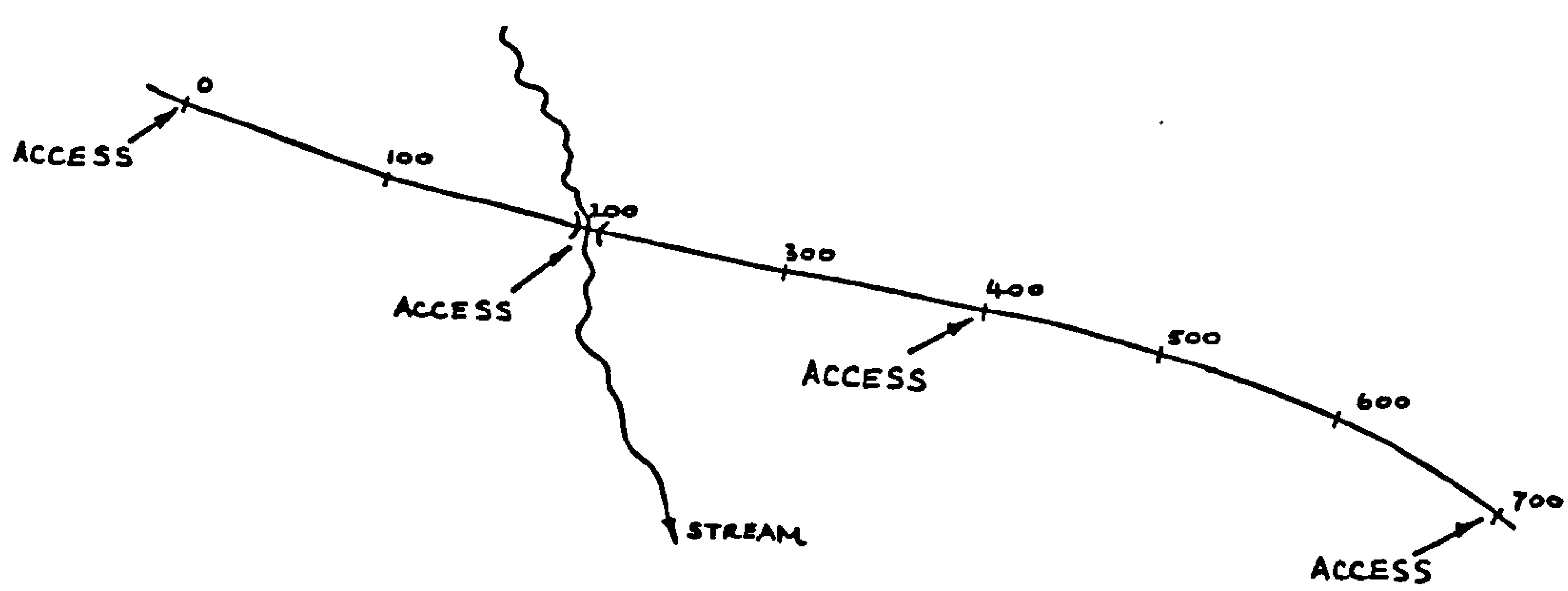


Figure (4.3.1) Sketch of the Road and culvert project

The information concerning the activities is shown below:

Activity	Rate (m/week)	Duration (weeks)	Min. Dist (m)	Dist. Buffer (m)
Earthworks	20	-	100	50
Sub-base	20	-	50	50
Road-base	20	-	50	50
Surface	30	-	100	50
Finishes	15	-	50	50
Drainage	7	-	100	50
Culvert	-	9	-	50

The plans are produced subject to the following constraints:

a) The roadworks are constructed in the order in which they appear above, with the exception of the drainage which will be subjected to no constraints.

b) The excavation of the road will provide the necessary access for any succeeding activity or the culvert.

c) The culvert construction must precede all roadworks except for excavation at chainage 200m.

The presence of many feasible access points requires the usage of the "access diamonds" as described in section (4.2.6). These occur at chainages 0, 200, 400 and 700m. In order to model this situation the project is split into three sections consisting of 0-200, 200-400 and 400-700 chainage ranges, with the access diamonds at the relevant chainages between them. These sections may then be planned in much the same manner as the earlier example described in section (4.2.9).

Figure (4.3.2) is the network representation of the road and culvert project. The plans produced from this network are illustrated in figures (4.3.3) to (4.3.6) inclusive, and represent some plans with different access points.

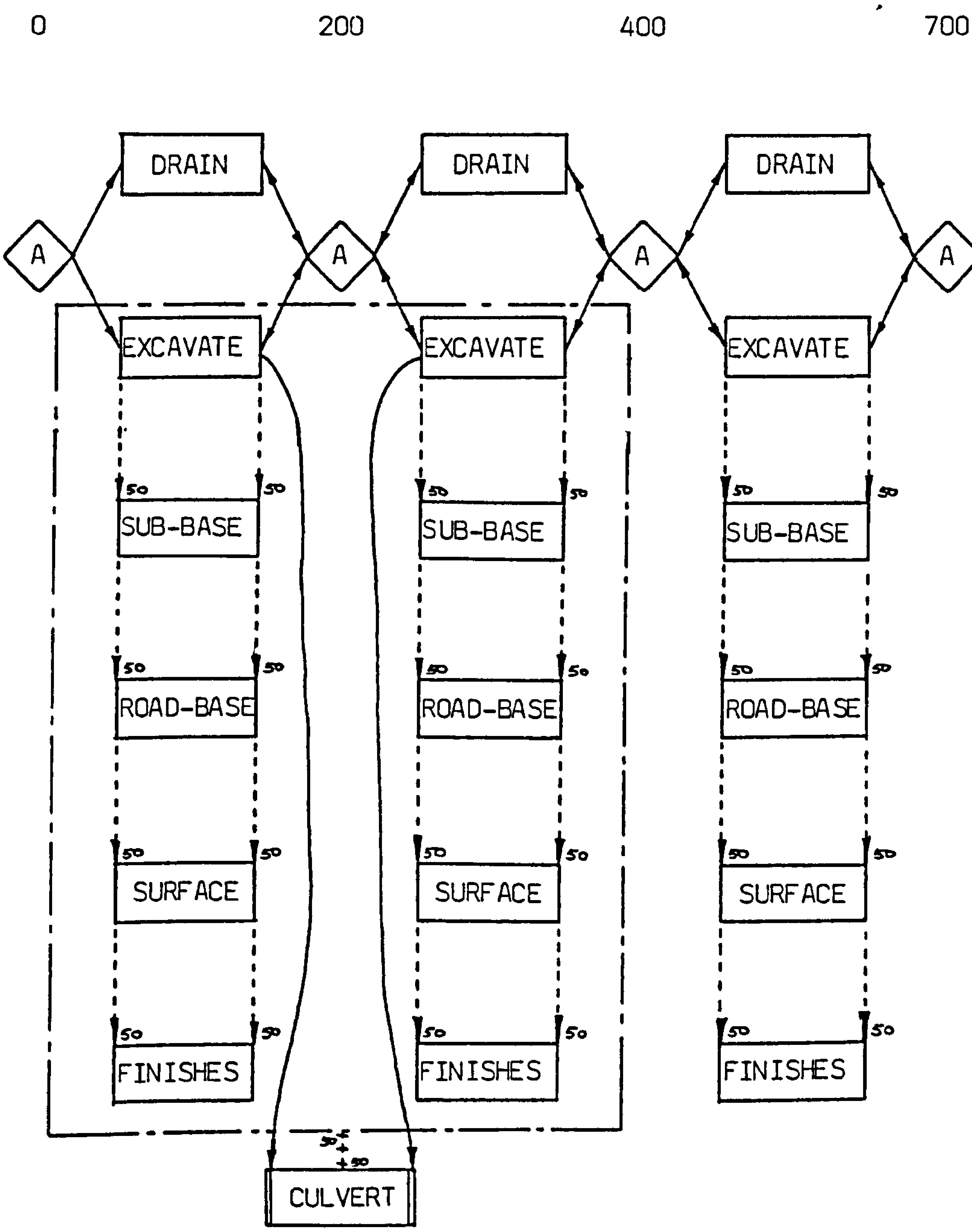


Figure (4.3.2) Network for the road and culvert project

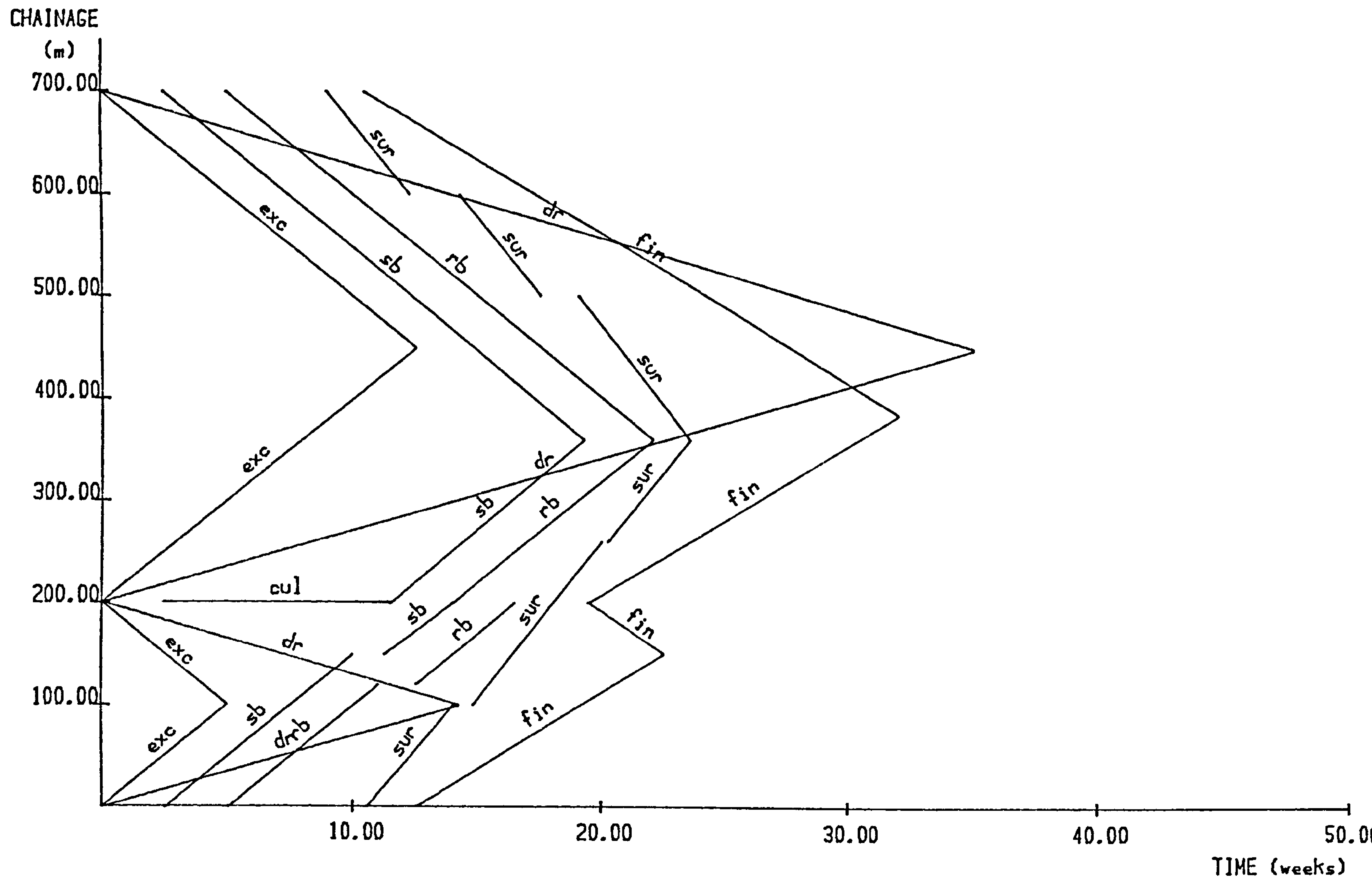


FIGURE NUMBER (4.3.3) Road and Culvert project with access at chainages 0, 200, 700

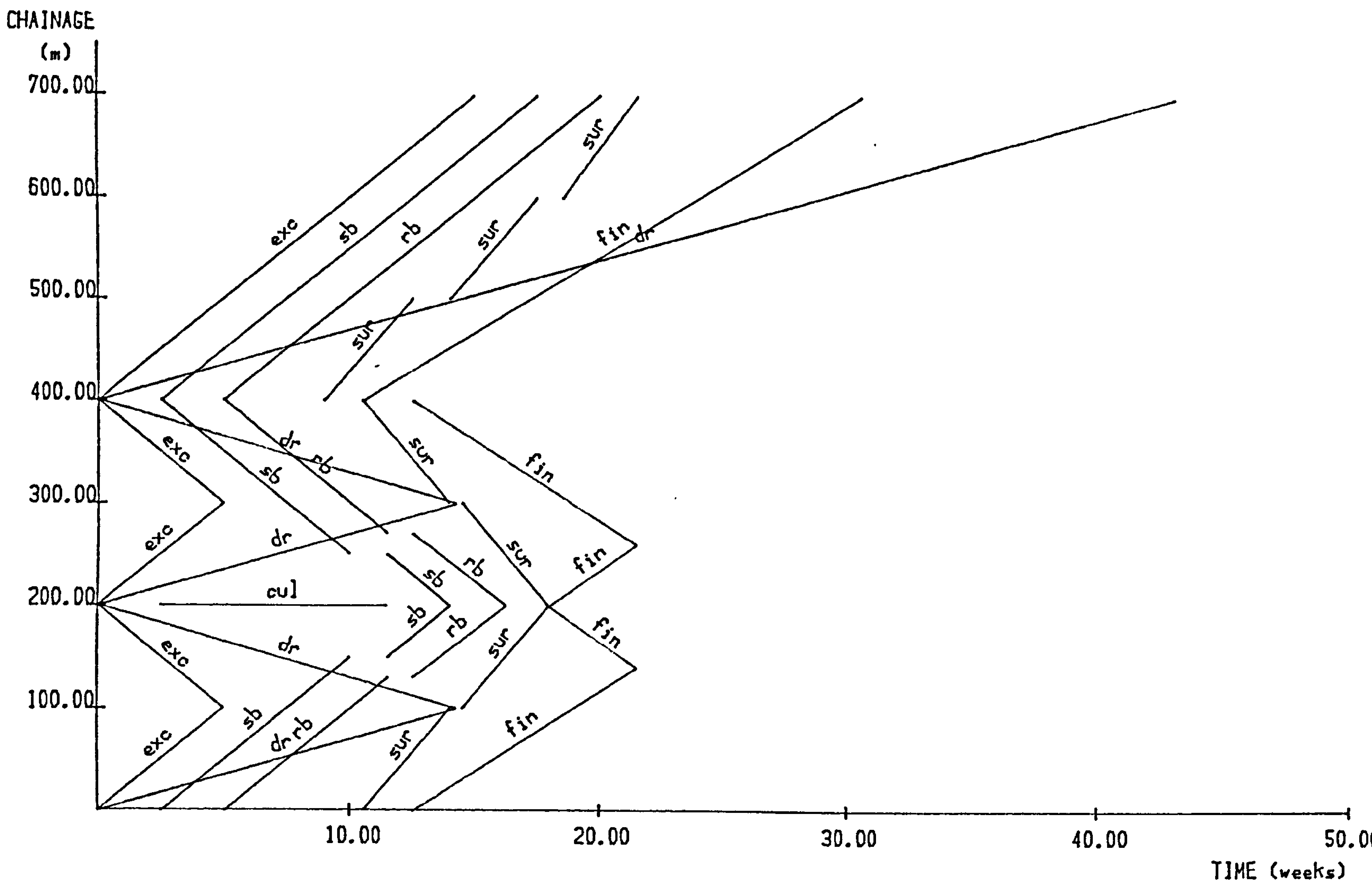


FIGURE NUMBER (4.3.4) Road and Culvert project with access at chainages 0, 200, 400

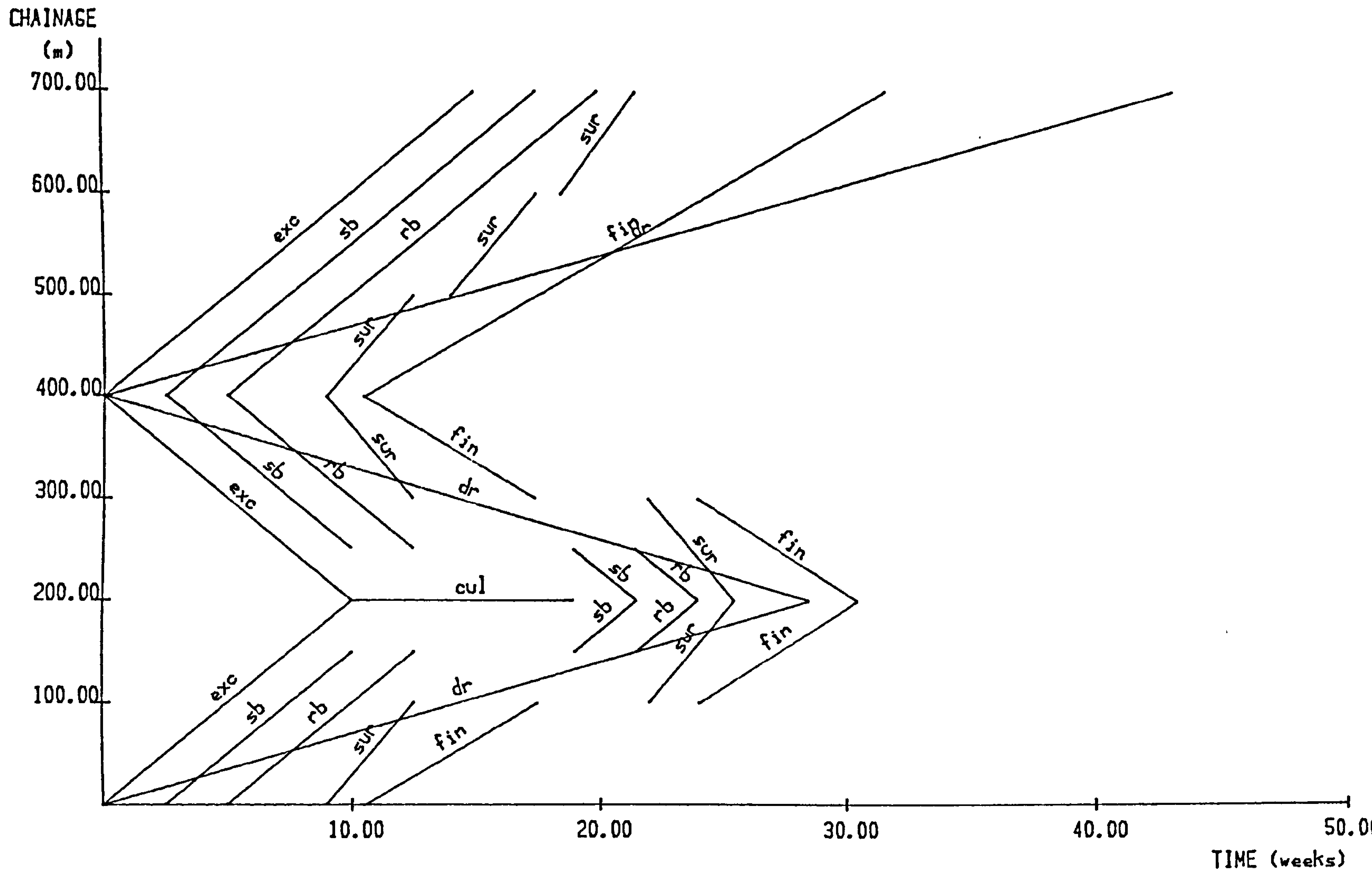


FIGURE NUMBER (4.3.5) Road and Culvert project with access at chainages 0, 400

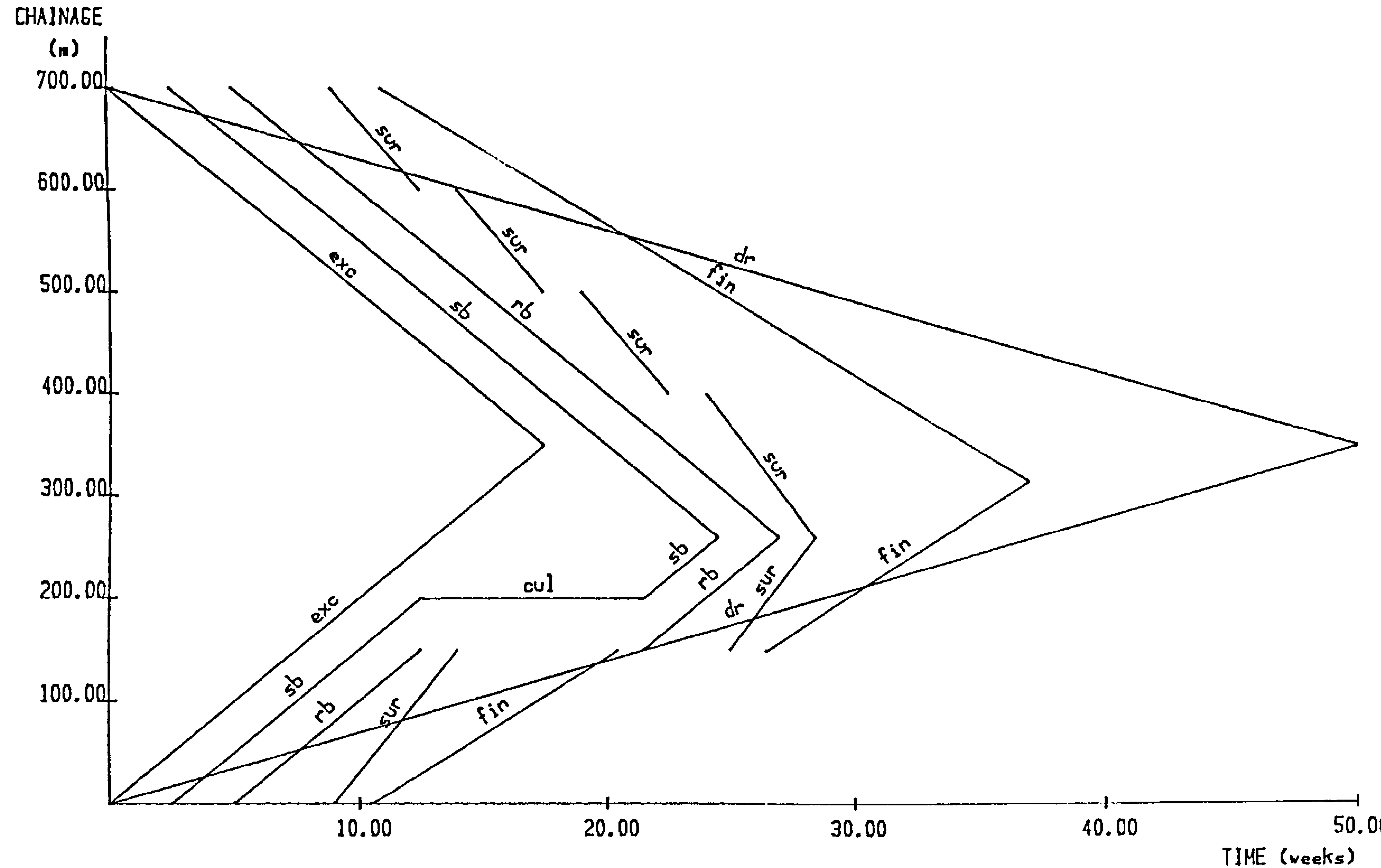


FIGURE NUMBER (4.3.6) Road and Culvert project with access at chainages 0, 700

4.4 Priority method of solution

The priority method is the first of two "automatic" methods of solution for the network representation of the extended line of balance method. The solution technique will be described with reference to the road and culvert example illustrated in section (4.3), and whose network is shown in figure (4.3.2).

A major problem in the production of the extended line of balance charts is the difficulty in deciding on the placement order of the bars on the chart. In the road and culvert example in section (4.3) the solutions were formed with intuitive decision making by the planner with regards to the placement order and relative importance of each operation. This intuitive decision making is usually based on the planner being able to "look ahead" and envisage possible states of the line of balance chart at a later stage of it's production. An analogy is that of a chess player who may project the probable positions of the chess pieces on the board five or ten moves hence. The player can then evaluate the merit of the first of these five or ten moves by the state of the board in the future.

The automatic methods will not be able to benefit from this style of "look ahead" decision making. The priority method is essentially heuristic and defines the placement order of the bars before the start of the production of the line of balance chart.

The order of placement of any bar in the priority method is found by considering the number of logical steps the bar is from any active access point. If the access diamonds at chainages 0 and 700 are active, and those at 200 and 400 are passive, then placement order is illustrated as in figure (4.4.1).

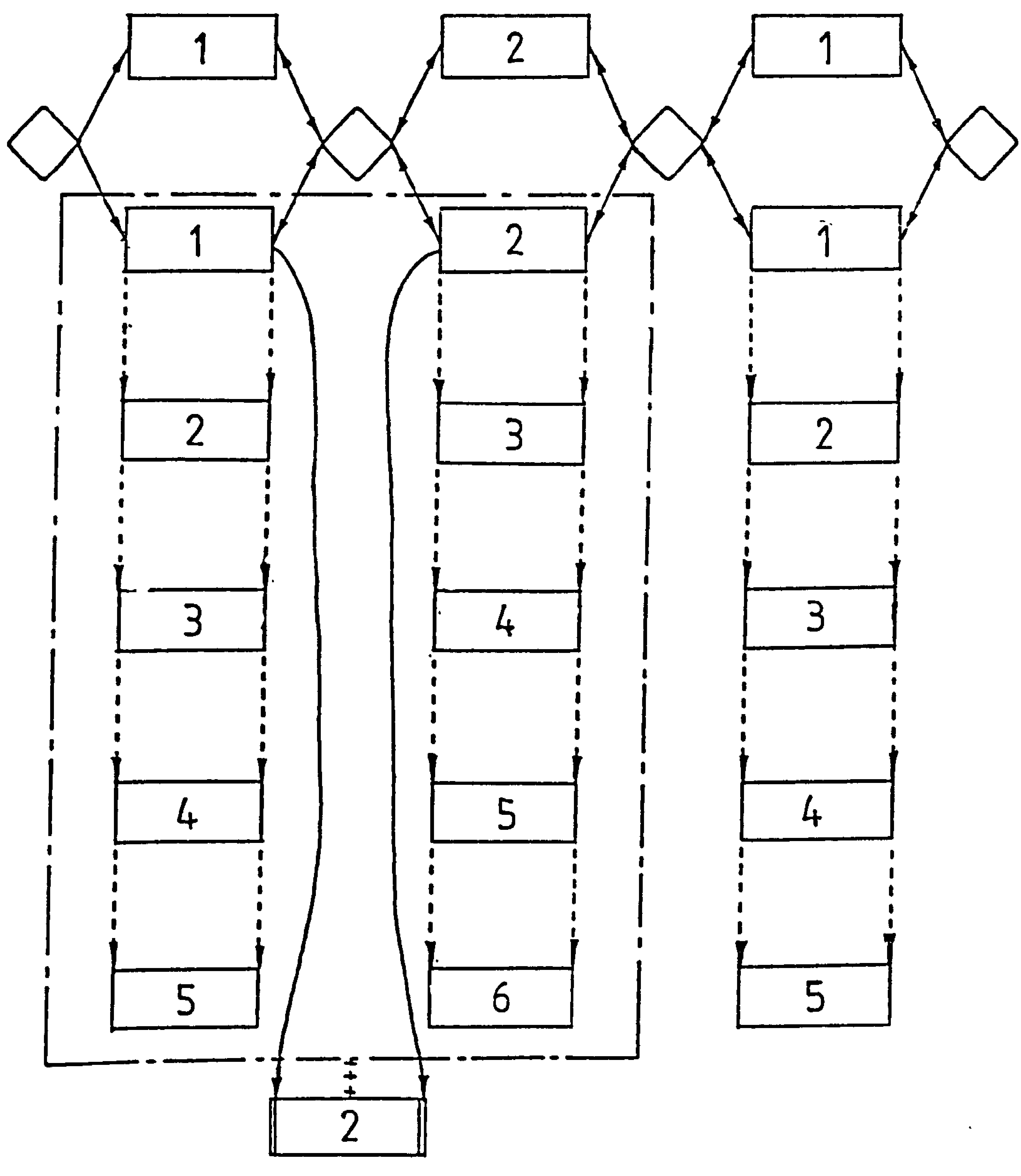


Figure (4.4.1) Placement order for the Priority method

The excavate section between chainages 200 to 400 has a placement order of 2 because it is removed from the nearest active access diamond by 2 steps. It follows then, that different access combinations will produce different plans by virtue of having different placement orders.

The advantage of this method is that the placement order of the bars will roughly reflect the order in which the operations will be carried out on site.

The construction of the line of balance chart is carried out by "drawing" the bars on the chart in the placement order defined above. Figure (4.4.2) at the end of this section shows the state of the chart after the placement of the order 1 activities.

The placement of the order 2 activities poses more of a problem. This set of activities consists of:

culvert (200)
excavate (200-400)
sub-base (0-200)
sub-base (400-700)
drainage (200-400)

When activities have the same placement order and are coincident in position and time then conflict will occur in trying to place the bars on the chart. It is therefore necessary to define a secondary placement order for the set of conflicting activities. This secondary placement order has to be defined by the user before the construction of the chart, and would normally reflect the order in which the activities would be carried out. For example, sub-base (0-200) and excavate (200-400) do not fall within the same chainage sections, although they are instanteously coincident at chainage 200. In this case, because excavate generally precedes sub-base, the excavate (200-400) will be placed before sub-base (0-200). The wisdom of this decision is illustrated when one considers that the sub-base (0-200) will be constrained by the previously placed excavate (0-200), and consequently conflict between excavate (200-400) and sub-base (0-200) may be totally avoided.

A secondary placement order for this project (excepting drainage which unconstrained) may be defined as:

excavate
culvert
sub-base
road-base
surface
finishes

The position of the culvert in the secondary placement order may be subject to argument, and is discussed later.

Figure (4.4.3) shows the state of the chart after the placement of the order 2 activities and figure (4.4.4) shows the final extended line of balance chart.

The only minor difference between figure (4.4.4) (priority method solution) and figure (4.3.6) (hand-worked solution) occurs as a consequence of the positioning of the surface (0-200) bar. In the priority method solution the bar is broken at chainage 100 to allow for the minimum distance criterion imposed on the surfaces of 100m. In the hand-worked solution, the planner was able to "look ahead" to see that the continuity of the surface bar from chainage 150 to 200 could be maintained for at least another 50m (to bring it up to the minimum distance of 100m) beyond chainage 200.

The major failing of the priority method, although not illustrated in the worked example, occurs when high priority non-linear activities have long durations. Consider the case in this example, if the culvert has a long duration. As this activity has a high order priority in comparison to most of the roadworks, the roadworks around chainages 150 to 250, would be severely delayed by the culvert construction. The hand worked solutions in this case would probably delay the start of the construction of the culvert until all roadworks within the vicinity of chainage 200 were completed. This would allow for continuous resource usage and consequently lower resource costs, with little delay to the project duration. The priority method does not have this flexibility. Any planning method, however, regardless of whether it is a critical path analysis or a line of balance method, does generally require slight modification to the constraints after the production of the initial plan, and the priority method is no exception.

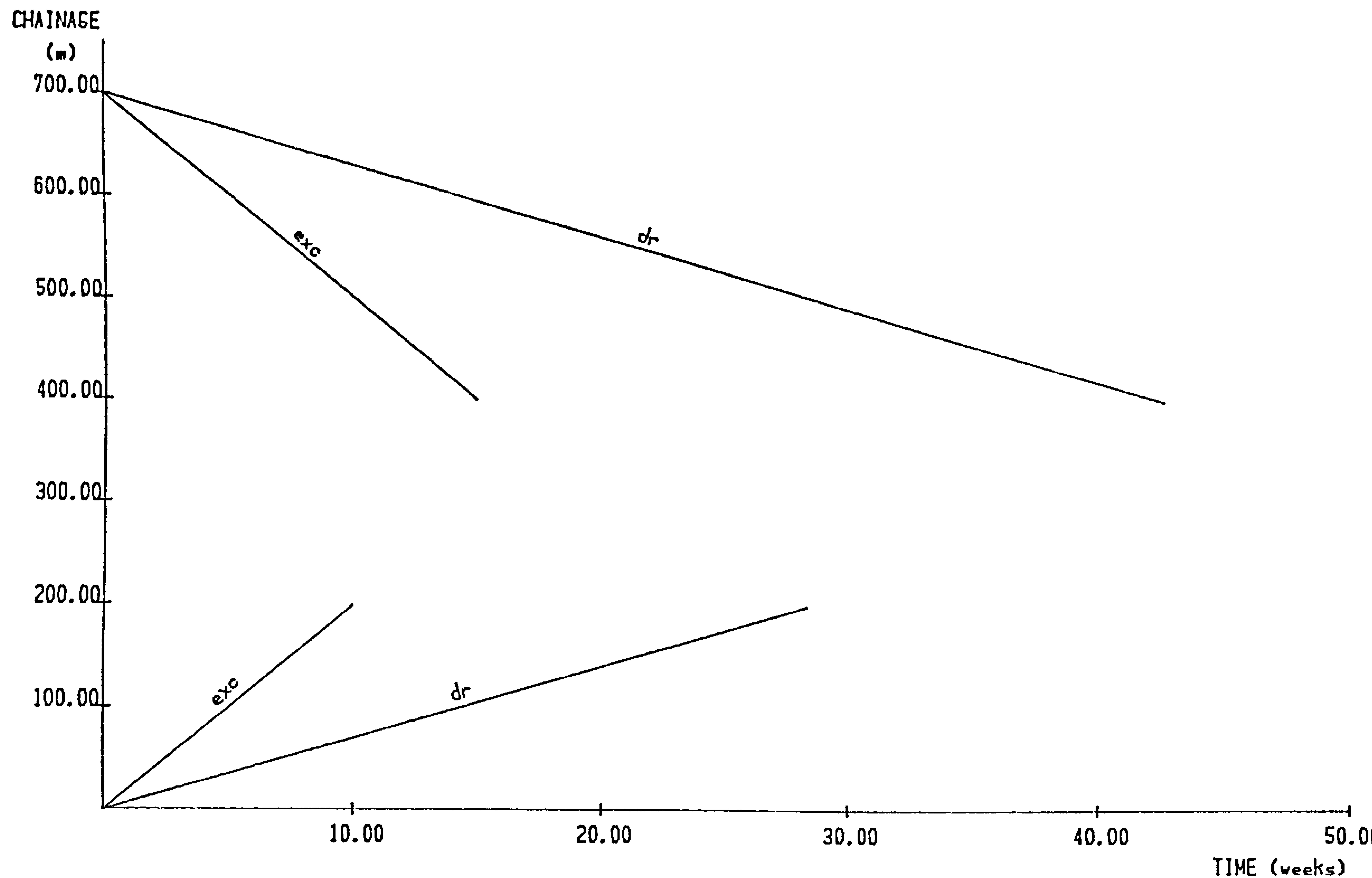


FIGURE NUMBER (4.4.2) Priority Method - Barchart after first order placement

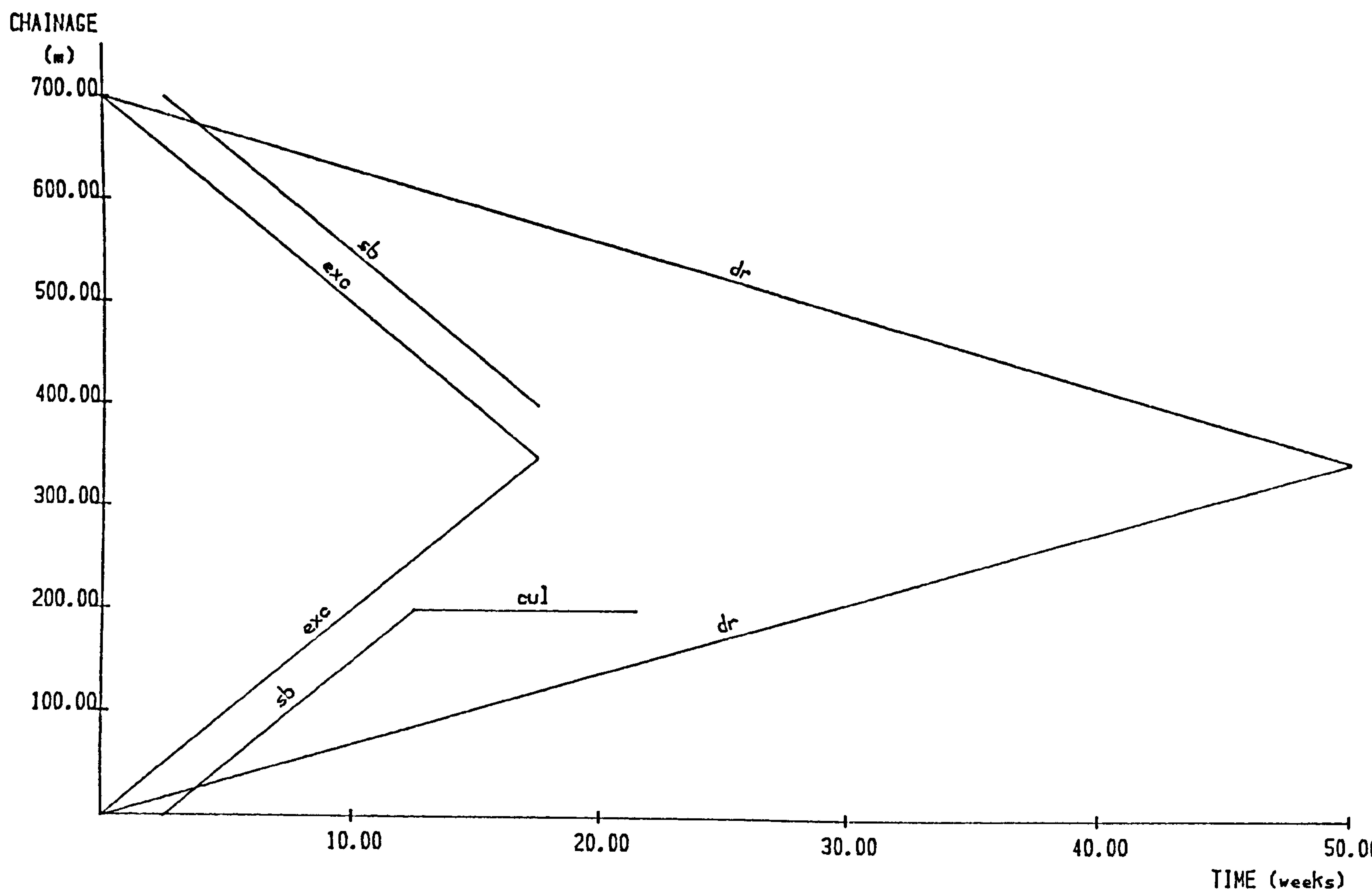


FIGURE NUMBER (4.4.3) Priority Method - Barchart after second order placement

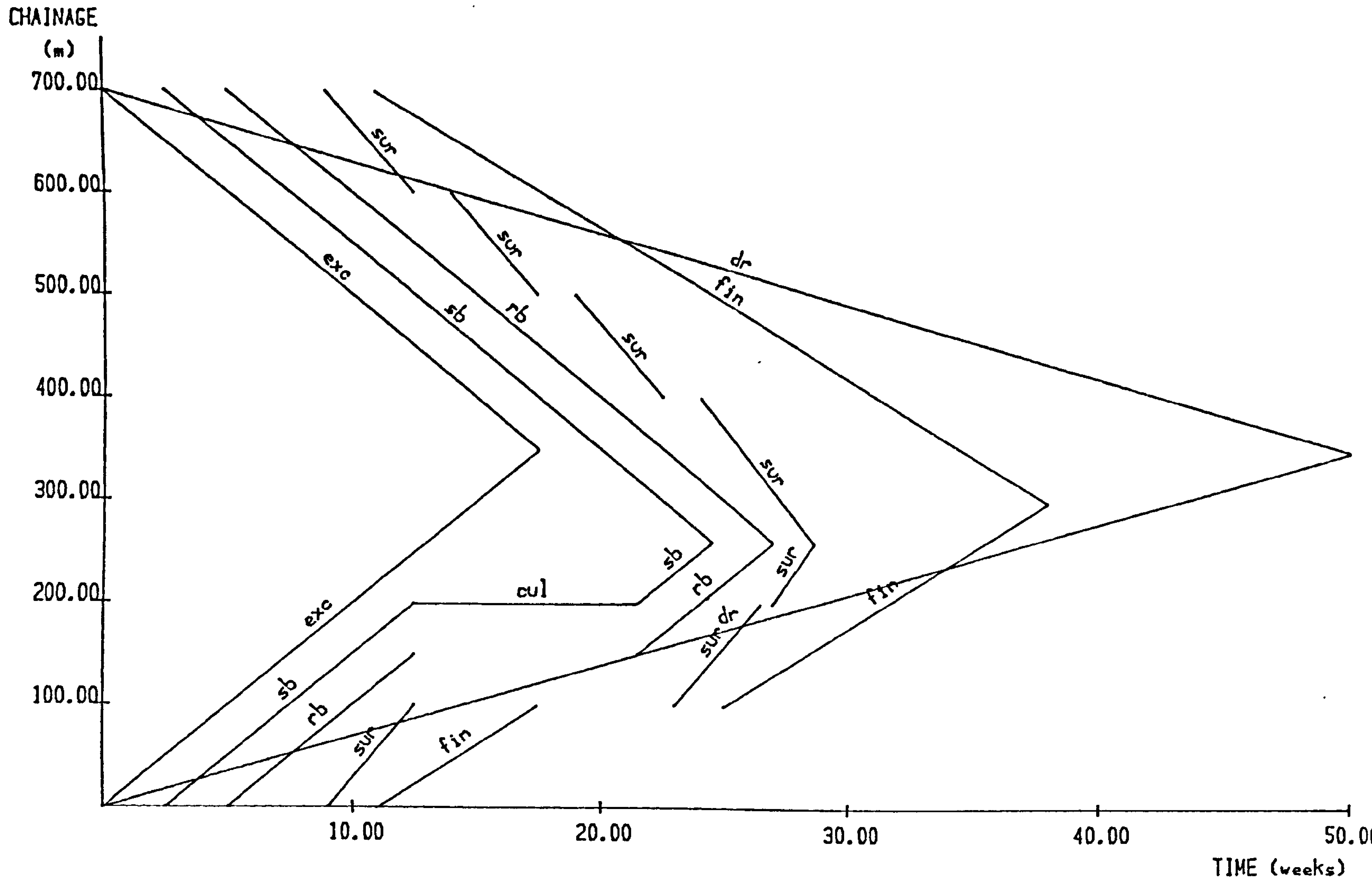


FIGURE NUMBER (4.4.4) Priority Method - Final barchart

4.5 Day-by-Day method of solution

The Day-by-Day approach to solution of the extended network representation was developed in any attempt to limit the conflict between activities at coincident positions. It was felt that the conflict was often generated by the blanket placement of large bars. For example, excavate (0-200) in figure (4.4.4) could feasibly be placed in smaller sections (of at least minimum size) in order to reduce any conflict that may have occured with other activities.

The general approach may be described as "do as little as possible, and only when necessary". The basic idea of the day-by-day method is to step through the project on a daily basis to find bars that can be either started or extended. If a bar may be started, then a minimum distance section must be drawn immediately to comply with minimum distance constraints. This will tend to have a knock on effect to the bars that have already been partially drawn, with extensions to these bars being necessary in order to check any distance or time constraints between the adjacent bars. An extension to a bar is only carried out when it is required by the commencement or continuation of a lower priority bar. If no bars may be started in the time frame being considered, then the existing bars are extended on a daily basis, starting with the lower priority activities and any associated knock-on's, until new bars may be started.

The method is described more fully with the aid of a worked example. The worked example is that of the road and culvert project with active access at chainages 0 and 700 (as in section (4.4). The first few stages of the drawing of the chart are given below.

a) Week 0

Activities started :	excavate (0-100)
	excavate (600-700)
	drainage (0-100)
	drainage (600-700)

These four bars represent the minimum work distances for the activities that may commence at week 0. The chart after this set of allocations is illustrated in figure (4.5.1), which may be found at the end of this section.

b) Week 2.5

At this time, the sub-base at chainages 0 and 700 may commence. The minimum distance for sub-base is 50m and this length may be drawn for sub-base (0-50) and sub-base (650-700).

c) Week 5

Road-base (0-50) and road-base(650-700) may be drawn. In order to check the end distance constraints at 50m and 650m, sub-base (50-100) and sub-base(600-650) are required. These two sub-base sections in turn require excavate (100-150) and excavate(550-600). This is the first example of the knock-on effect. Notice that because a minimum distance for the excavate has already been drawn, the continuation of the excavation may occur in stretches of less than the minimum distance. The chart at the end of this set of bar drawing is shown in figure (4.5.2).

d) Week 7.5

At week 7.5, surfacing of the road is free to start at chainage 0 and 700. As surfacing is a faster operation than the road- base operation, however, the distance lags between the operations will be end constraints at chainages 100 and 600. This consequently means that the surfacing may not be considered for placing before the road-base operations reach chainages 150 and 550, because there is a distance lag of 50m between these operations.

The continuation of the road-base, sub-base and excavation continues on a weekly basis until either the surfacing may commence, or other activities come up for consideration.

e) Week 10

Excavation has reached chainage 200. This means that the culvert construction may commence. The excavation between chainages 200 and 400 may also commence, and these two activities come into direct conflict. A decision has to be made concerning the order in which these should be drawn. This is a similar situation to that which arose in the priority method, with the subsequent formation of a secondary placement order, as discussed in section (4.4). In this example, the placement order will be:

culvert
excavate
sub-base
road-base
surface
finishes

with the culvert having a higher priority than the excavation. If the plan was formed with the same secondary placement order as that defined in section (4.4), the final chart produced would be the same as the one produced with the priority method, figure (4.4.6).

The process continues in a similar fashion until all the activities have been placed. The final plan produced is illustrated in figure (4.5.3).

The day-by-day method of producing plans for the network representation produces plans that are similar to those produced by the priority method. The "do as little as possible" policy adopted by the day-by-day method effectively breaks the projects into the smallest sections possible for placement. This suggests that the plan produced was as flexible as possible, given the constraints imposed on it. The fact that the two different methods arrived at similar solutions tend to lend credence to the methods themselves. The problems with the priority method and the day-by-day method in "looking ahead" are problems in the heuristic nature of the methods.

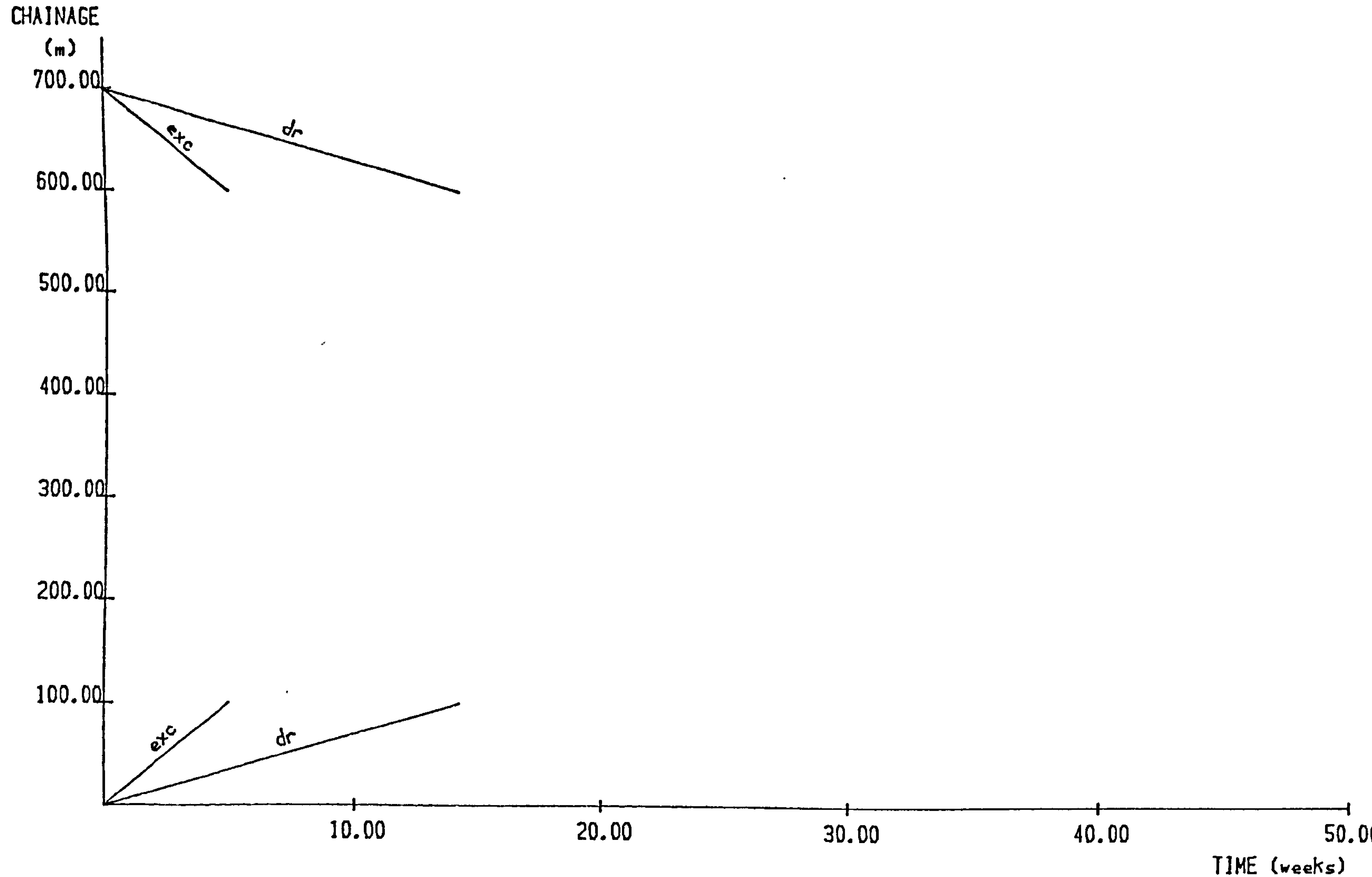


FIGURE NUMBER (4.5.1) Day-by-Day Method - Barchart after first order placement

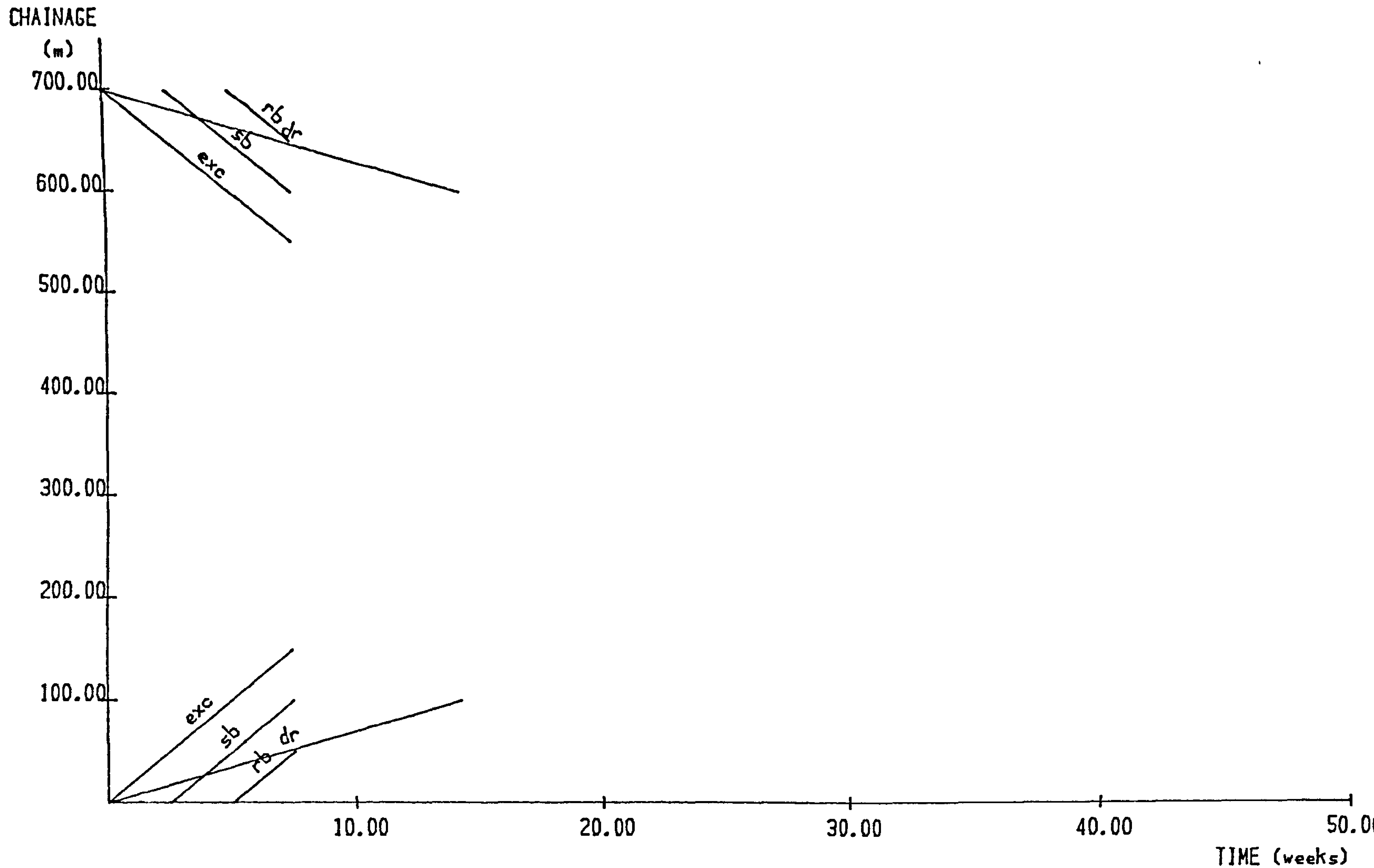


FIGURE NUMBER (4.5.2) Day-by-Day Method - Barchart after third order placement

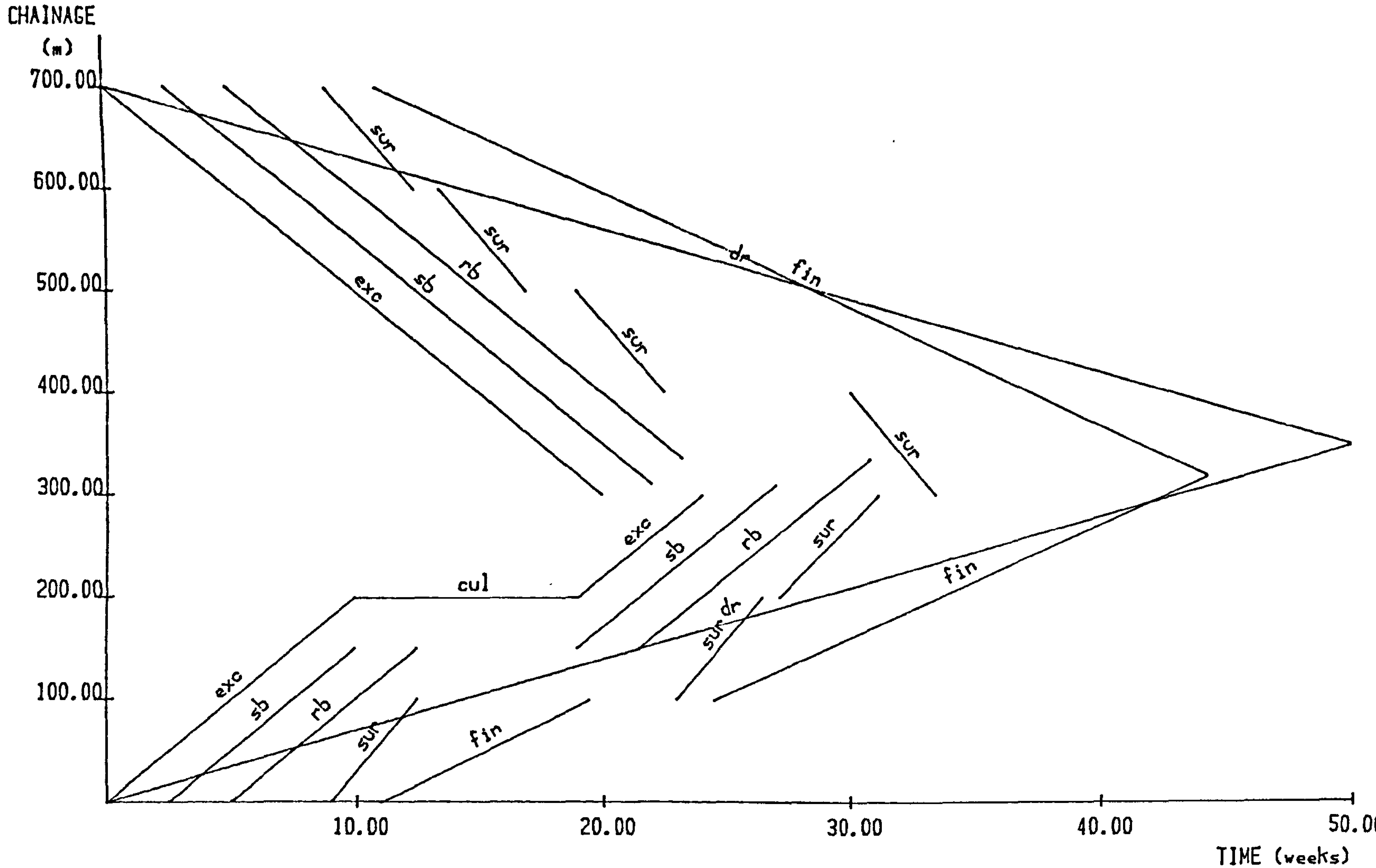


FIGURE NUMBER (4.5.3) Day-by-Day Method - Final Barchart

4.6 Conclusions to extended line of balance

The extended line of balance is capable of modelling many site layout features in the production of plans. The model allows different access points for the project to be considered, and a set of plans may be produced with different combinations of these access points. This set of plans may be evaluated to give one satisfactory plan and corresponding access pattern.

The second site layout feature modelled is the positioning of material stores, which was discussed in conjunction with the interactive production rate in section (4.2.3). Suitable material store positioning may be achieved by a similar iterative approach to the production of plans.

The major problem in line of balance style planning is that it is essentially a method for linear projects. Birrell (34) (see section (3.2)) tried to extend the application of the line of balance style planning to non-linear projects, but the constraints imposed by his method in essence rendered it difficult to apply to general construction projects.

The aim of this research was to produce a method that was capable of handling site layout features in all types of construction, regardless of whether it was linear or non-linear. For all their merits, the line of balance method, and it's various extensions are not capable of achieving this goal. The succeeding chapters present a method which is applicable to all styles of projects.

CHAPTER 5

THE MODEL

5.1 Introduction

Previous chapters have discussed the use of many planning models in the construction industry, of which network analysis and the Line of balance planning method are the most common. Network analysis generally does not incorporate site layout factors in it's formulation, although an experienced planner may include them in the production of networks. The Line of Balance method may allow some site layout factors to be modelled, however, it is essentially a linear project planning method, and consequently it's applicability is largely restricted to linear projects.

The aim of this research was to develop a planning method which modelled site layout features and was generally applicable to all types of construction site. Site layout information may be split into two types. The first of these is "macro" site layout which concerns the relative positioning of the structures and work areas across the whole site. This type of site information is useful in planning efficient resource movements around the site. The second type of site layout is "micro" site layout. This category concerns the relative positioning of work within very small areas. Often the sequencing of work packages within a small area is defined by it's positional relationship with other work packages, and the role of the "micro" site layout in this model is to define the sequencing of work.

The model developed follows on from the line of balance method, with resource teams "flowing" through the site. In the line of balance method, the direction of the progression of work is defined in terms of a single path, with the resources moving from one area in the path to another carrying out work. Subsequent resources follow one another in a defined order. The single path and predefined resource order allows linear projects to be planned very efficiently with no resource interference. In non-linear projects, however, these constraints make this model unusable, firstly because there is no predefined direction of work, and secondly because not every work type will occur in every area. In non-linear projects, a multi-directional progression of work must be modelled.

The allocation of the resources is controlled by means of a priority system, whereby certain areas on the site are considered more important than others. This has the effect of influencing the progression of work, although in a less rigid fashion than that used in the line of balance method. Priorities would typically model the site geography features such as access points and routes, highly valued structures, and also a dynamic resource priority which would endeavour to reduce unnecessary resource movement.

The site geography is modelled by means of a fine grid coordinate system with the work content of the project being allocated by position, to their corresponding grid squares. The plan is then produced by a resource scheduler, which allocates a resource to groups of grid squares at a time, producing feasibly sized work areas. The size of the allocation areas is dependent on the particular resource being used and the work type, and a resource model has been developed which incorporates work areas, work buffers and transfer speeds.

The theory of this model is developed in this and succeeding chapters. The remaining sections in this chapter deal with the following topics:

a) Formulation of the Site map.
b) Logic Formation.
c) The use of Knowledge in the Logic Formation.

5.2 Map formulation

The Site map forms an integral part of the model, and it's function is to store the information concerning the distribution of work thoughout the site.

The site is mapped by sectioning it into small areas by means of a grid coordinate system. The size and shape of the grid squares would depend on the type of construction, although a fine grid square dimension of 0.5m x 0.5m would satisfactorily model most situations. The small grid square dimension is advantageous for many different reasons.

Firstly, a fine grid system allows a greater accuracy of the information stored within the map, not only in terms of work content, but also in terms of structure definition and geographical positioning. This in turn will produce more realistic, and hopefully more accurate work schedules.

Secondly, the grid square should reflect the smallest possible working area of any resource on site. For example, a labourerwith a shovel may excavate a hole of one grid square (0.5m x 0.5m) in area, and a mechanical digger may excavate any multiple of similar sized grid squares. The converse is not true.

Finally, a small grid system allows the simple and realistic generation of interconnections between the different types of work in any particular area (see section 5.3). A disadvantage of having a small grid coordinate system is that large quantities of information are necessary. The acquisition and storage of this information is discussed in a later chapter (see chapter 10).

Certain types of more specialized construction may allow different shapes and sizes of grid to be used. A road project, for example, may have grid squares that reflect the width of the road. Similarly, a trenching operation may have grid square dimensions equal to the minimum pipe run. The application of this chainage style of coordinate system is limited to isolated linear structures, as they are unsatisfactory for modelling non-linear structures or a combination of non-linear and linear structures on one site. It is possible, however, to use the small, square coordinate system to model a wide range of possible types of construction, and for this reason, the rest of the model is described with reference to this more general system.

The allocation of work to the grid squares is carried out by breaking-down the construction of the structures into their elemental parts (jobs or activities). An elemental part of a structure may be defined as a quantity of work which is distinguished from other quantities of work by the use of different work methods or resources during it's construction. Consider a trenching operation, as illustrated in figure 5.2.1, as an example.

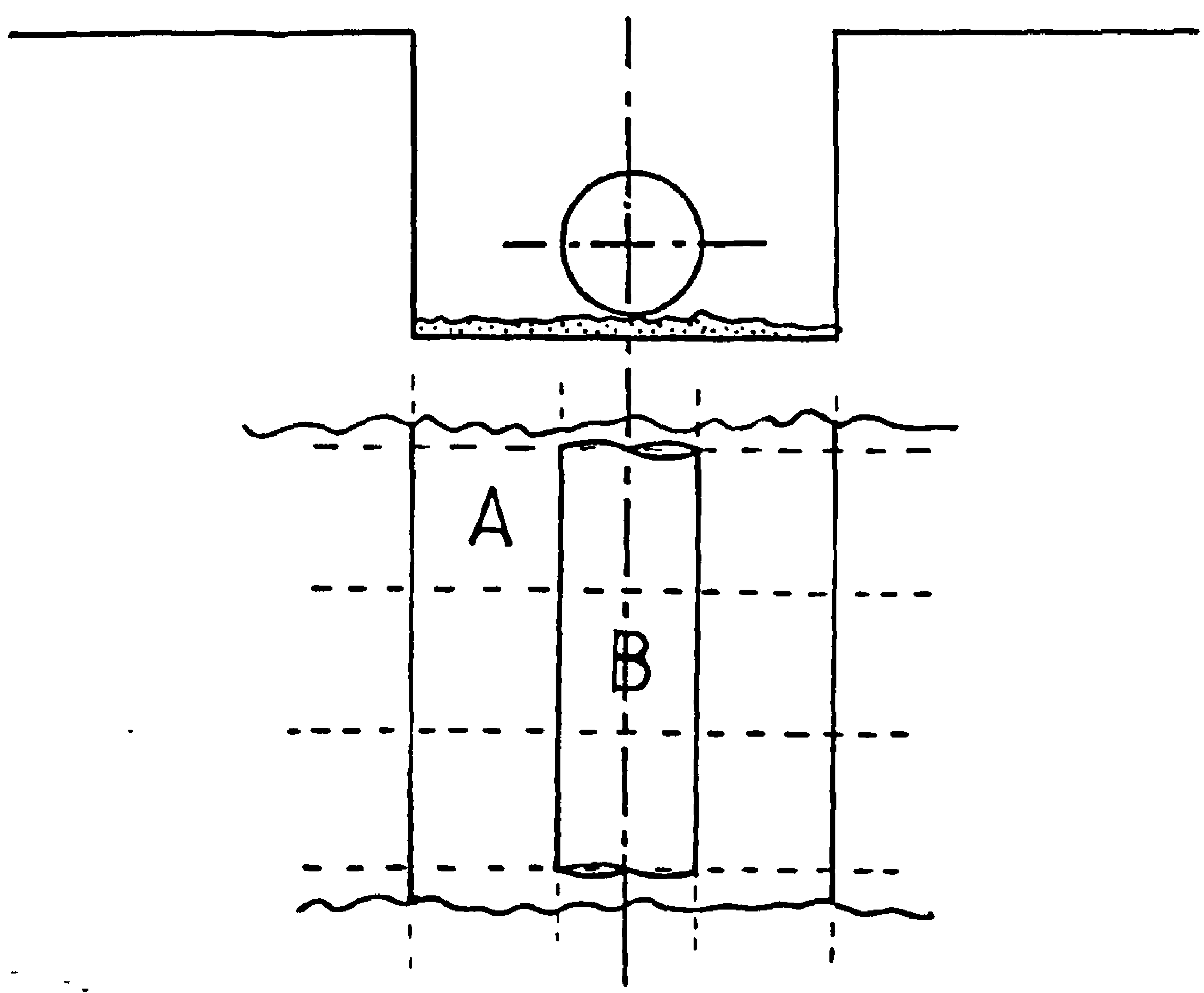


Figure (5.2.1) The Trenching Operation

The four activities involved in this operation are:

a) Excavate
b) Lay bedding material
c) Lay pipe
d) Backfill

The work in the grid squares A and B can be defined as:

A	B
Bedding	Bedding
Excavate	Excavate
Backfill	Backfill
	Lay Pipe

The sequence of construction within these grid squares is still undefined, and the formation of this sequence is the topic of the next section (5.3).

5.3 Logic Formation

Logic defines the sequence of construction of any activities in a project. Logic can be broadly split into two categories (after Birrell (34)):

a) Absolute logic
b) Preferential logic

Absolute logic may be thought of as the type of logic which is defined by the physical nature of the work. Examples of this type are numerous and range from "first storey precedes second storey" in high-rise construction to "steel reinforcement fixing precedes concrete pouring".

Preferential logic is that adopted by a planner to suit one particular method. They are largely resource, material or access based in nature, and typically allow for constraints such as batching plant limitations, crane usage and the construction of haul roads. This type of logic depends largely on the envisaged work method adopted by the planner, and in this respect is not very flexible to change or variations.

If an individual grid square is considered in isolation then the sequence of work within this square is defined entirely by the first category of logic, the absolute logic. Preferential type of logic may exist between adjacent grid squares, as resources will generally have operating areas that are larger than a single grid square in size. In order to accomodate such resources the grid squares have to be "bundled" to achieve feasible sized areas. The extent of this bundling depends largely on the resources employed during construction, and will be different for different resources. Preferential logic may therefore change significantly during the course of construction, and for this reason is handled by a resource scheduler which incorporates working and operating areas in it's resource model. This scheduler is discussed in chapter 7.

The absolute logic, is unchanging through the course of the construction and can be formed before the commencement of any schedule. Consider a grid square, taken in isolation, from the trenching operation discussed previously. Figure (5.3.1) shows, in job-on-node terms, the sequence of work in that grid square.

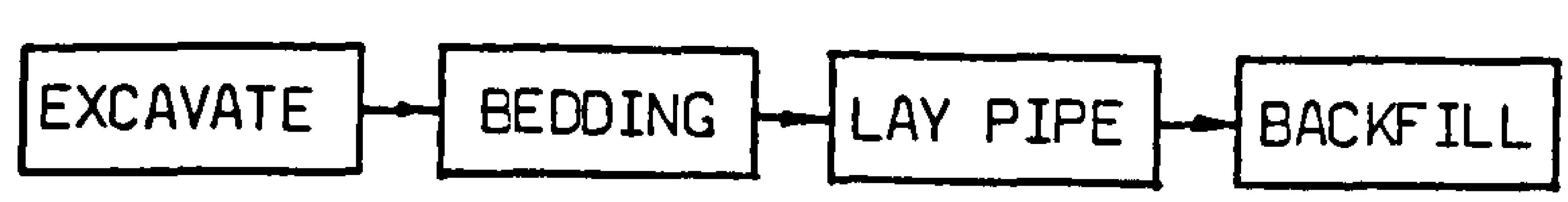


Figure (5.3.1) Sequence of work of the Trenching operation

If the height above a datum (level) is considered for each activity then the end level of a preceding activity is equal to the start level of the succeeding activity. This continuity in levels forms the basis of the formation of the simple grid square logic, and will be called the "Level method".

Generally, absolute logic exists only between activities in their own grid square, i.e. there are rarely any inter-grid square absolute logic links. Inter-grid square logic links tend to be of the preferential type as discussed in a previous paragraph. There is one type of situation, however, where absolute logic links do exist across grid boundaries. Consider the roof truss and column arrangement shown in figure (5.3.2).

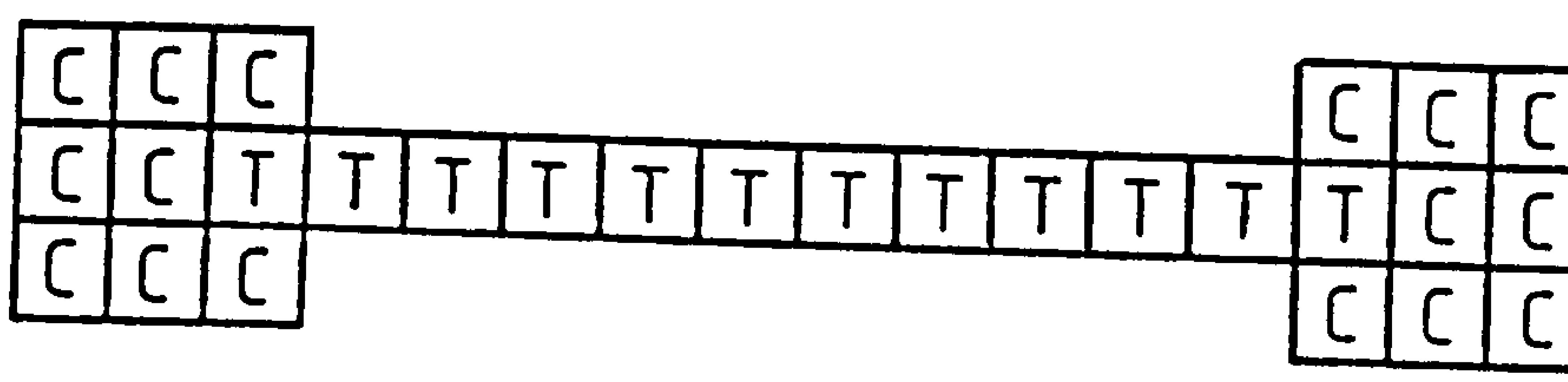


Figure (5.3.2) Roof truss and columns

In this situation, it is impossible to erect the roof truss before the two end columns are completed. As the constraint is defined purely by the structure itself, the logic that exists between the roof truss and the columns, is of the absolute type. Clearly this situation cannot be incorporated into the Level method, although some provision has to be made for it.

The roof truss problem arises because of the nature of the roof truss. Because the roof truss is pre-fabricated, it is of a fixed size, and consequently has rather similar size constraints to those that exist for the resources. If erection gang is restricted to working in areas that are equal to the size of the truss (i.e. 12 grid squares), then erection of the roof truss cannot be carried out until all the grid squares become available. The end grid squares are controlled by the Level method, however, and will not become available until the columns are completed. The roof truss situation can be recognised during the formation of the logic using the Level method by discontinuities in the start and end levels in a grid squares.

The level discontinuities may possibly cause further problems for the Level method, because as at any one time there may be the possibility of more than one active work face. So, for example, the concreting of the floor below the truss could feasibly be one working face, and the erection of the truss another. This means that the sequence produced for each grid square may not be single pathed, but may be dual or multiple pathed. This model has been developed with only the single path sequencing being considered, and if multiple paths do occur, the sequencing of these will be handled by decision rules, as described later in section (5.4).

If the columns and beams are cast in insitu concrete, however, the beams can be constructed before the completion of the columns because the beams are supported by falsework. This falsework will supply the necessary level continuity between the lower beam (or floor) and the higher beam, to allow the formation of this logic by the Level method.

Inter-grid square logic links may be necessary in other situations where damage to completed work may occur due to other work in adjacent areas. This may occur in a road project where drainage and sub-base activities occur in adjacent grid squares. If the sub-base is carried out before the drainage, then damage may occur to the sub-base during the excavation of the trench for the drainage. This situation also cannot be simulated by this model.

The Level method is not capable of modelling every situation that may arise, even within solitary grid squares. Figure (5.3.3) shows, also in job-on-node form, the sequence that would typically be produced by the Level method for the trenching operation. The logic link from the backfill to the excavation is formed, in this case, because the end level of the backfill is equal to the start level of the excavation.

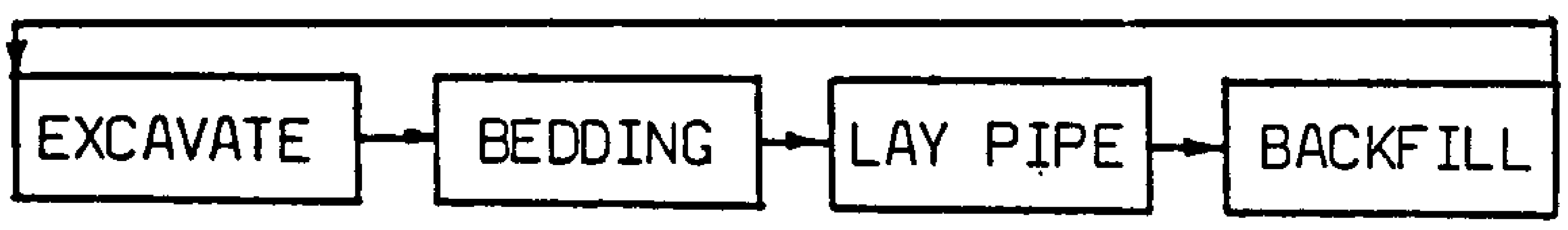


Figure (5.3.3) Logic loop formed by the Level method

Another situation that the Level method is not capable of modelling is highlighted in the construction of a floor slab. The activities involved in the floor slab are:

Excavate
Blinding concrete
Formwork
Steel fixing
Pour concrete
Strike formwork

and would typically require a sequence as illustrated in figure (5.3.4)(a), yet the Level method would yield a sequence as illustrated in figure (5.3.4)(b), because the formwork, steel and concrete activities are all coincident.

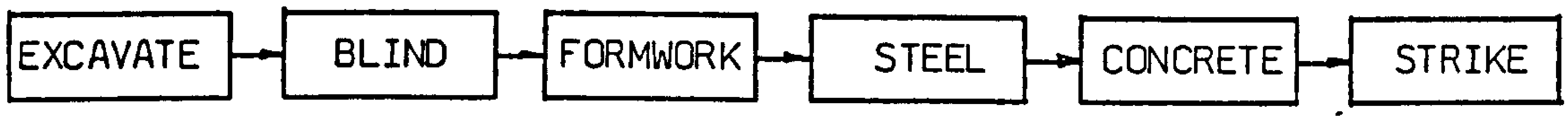


Figure (5.3.4)(a) Normal sequence for the Floor Slab

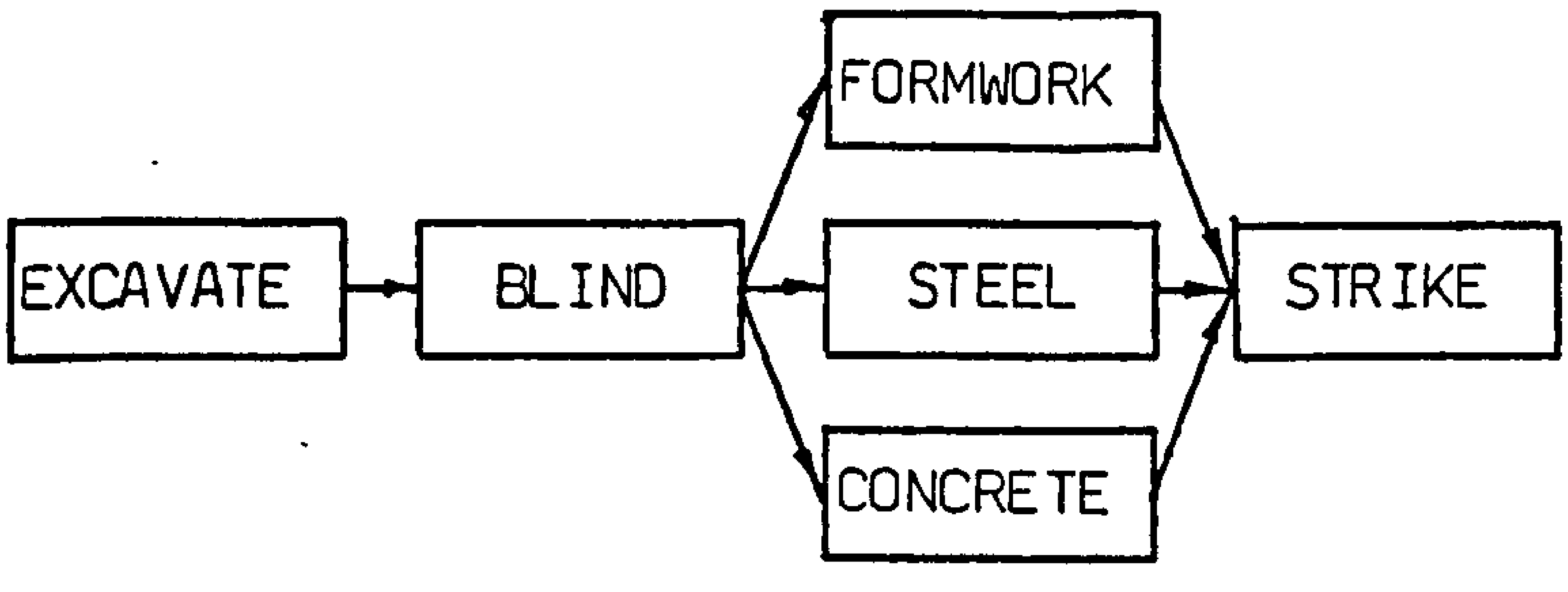


Figure (5.3.4)(b) Level method sequence for the Floor Slab

Finally, consider the situation where the pipe runs underneath the floor slab. In this instance, in grid squares where the pipe and slab operations are coincident, the pipe excavation and slab excavation form the same activity over the range of levels from the slab base and above. To avoid the duplication of work, the start level of the pipe excavation should be redefined to coincide with the end level of the slab excavation. The pipe backfill should also be modified in a similar way to give an end level equal to the base of the slab.

These three problems, and the multiple path sequencing problem indicate that there is a need to firstly recognise instances in which the Level method is either not suited to, or not capable of, handling; and secondly to form knowledge-based decision rules to solve them. The solution of these problems is discussed in the next section (5.4).

5.4 Knowledge in Logic Formation

Before including knowledge in the logic formation using the Level method, it is necessary to be able to recognise cases where it may be necessary.

There are effectively two situations where knowledge is required. The first of these is where two activities are coincident (i.e. have overlapping start and end levels) and are uni-directional (i.e. either both downwards acting, where the start levels are higher than the end levels, or both upwards acting, where the start levels are lower than the end levels). This is the situation that arose in the floor slab problem discussed in section (5.3), where the coincidence of all the concreting activities produced a sequence as illustrated in figure (5.3.4)(b). The same situation was responsible for the clash between the pipe excavate and the slab excavate, also discussed in section (5.3).

The second situation is encountered where there is a change in the direction of work, from one activity to another. This is the "U" bend situation which was responsible for the incorrect link from the backfill and excavate in the slab construction. It was, however, also responsible for correctly linking the excavate to the blinding concrete in the same example. This indicates, then, that the U bend situation does not always require a knowledge based rule to decide on the correct links. The logic loop problem may be overcome to a large extent if one of the activities is a start activity. A start activity may be identified if it's start level coincides with the site existing ground level (E.G.L) in it's grid square. This solution is not generally applicable, however, as it is feasible that neither of the activities is a start activity.

In these situations it is necessary to have some decision rule in order to produce satisfactory logic links. The decision rules are knowledge based, i.e. the model requires some experience of past decisions for similar circumstances. If the model comes across one of the situations where errors may possibly be made, then it searches it's knowledge base for a suitable solution to this problem. If a solution cannot be found, then it prompts the user for a solution, and stores this in the knowledge base, for future use.

The knowledge base is made up of two sub bases. The first is a general knowledge base which may be used for all construction contracts. This knowledge base holds more general information about the sequencing of work which is applicable to all types of construction. The second knowledge base is project specific and holds information particular to the project concerned. The project knowledge base will generally not be transportable from one project to another, although project knowledge bases for distinct types of construction, such as road building and pipe laying, may be applicable to similar types of project. This means that once a library of knowledge bases is compiled, very little further work is involved in their upkeep and use.

The knowledge takes the form of three types of decision rule:

a) Link
b) No Link
c) Change levels

5.4.1 Link Knowledge

This decision rule may be used to force a logic link between two activities. This may be necessary when the model is unable to determine the precedence to coincident activities. In the concreting situation that was discussed previously, we may define our concrete rules as:

formwork $\longrightarrow$ steel fixing
steel fixing $\longrightarrow$ concrete
concrete $\longrightarrow$ strike formwork

This would yield a modified sequence for the slab problem as illustrated previously in figure (5.3.4)(a).

5.4.2 No Link

This may be used to prevent a logic loop link being formed in the logic. This decision rule may be used to prevent the backfill to excavate link being generated in the pipe laying operation.

5.4.3 Change levels

This rule may be used to change the levels of two coincident, unidirectional activities, as in the pipe excavate and the slab excavate example. There are two possible ways in which the levels may be changed. Consider the general case of activities A and B, which are coincident, unidirectional activities as illustrated in figure (5.4.3.1)(a).

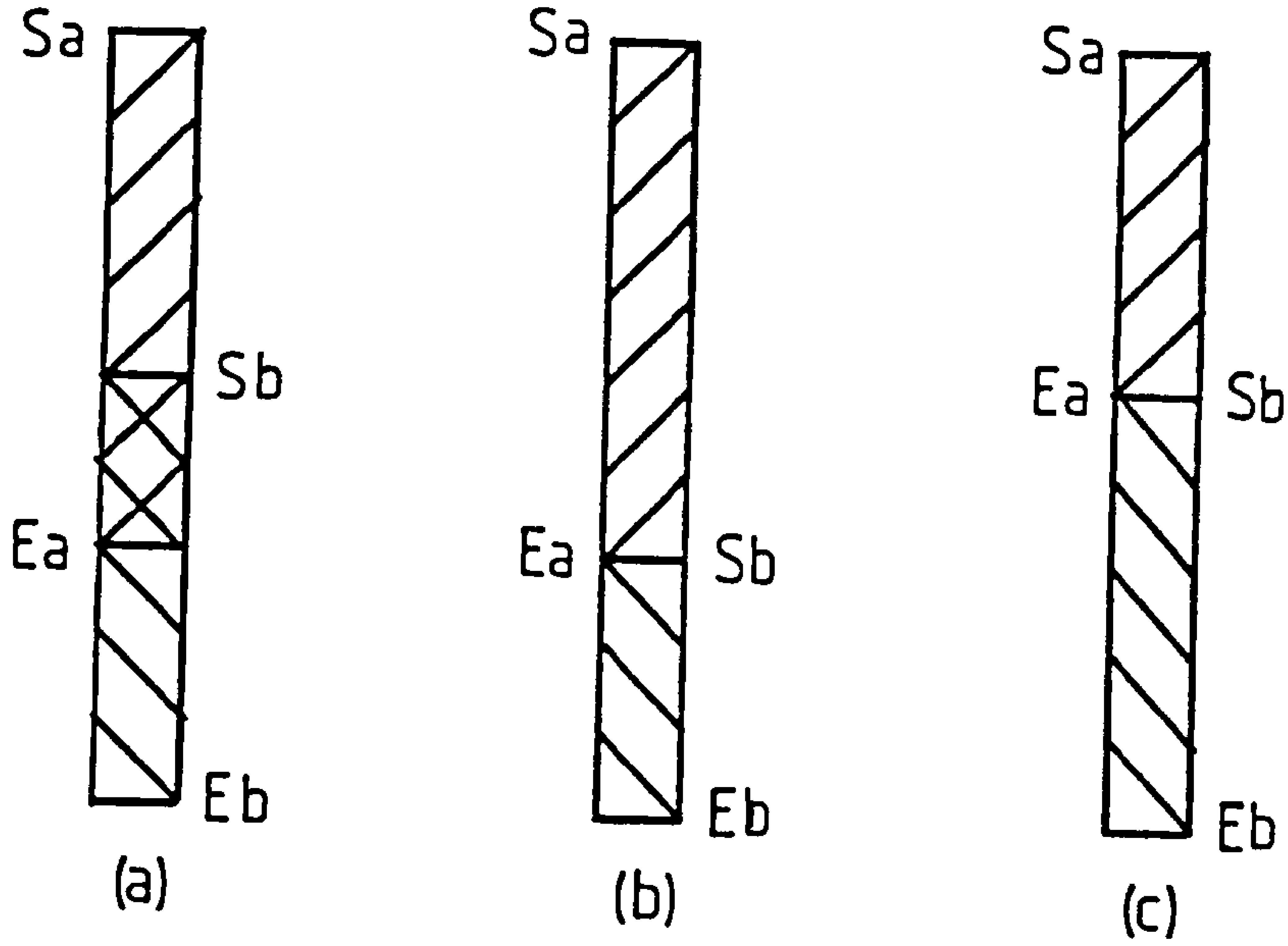


Figure (5.4.3.1) Level Changing

Figure (5.4.3.1) shows the two ways inwhich the levels may be changed. Figure (5.4.3.1)(b) shows a "fixed-end" level change, where the end levels of the two activities remains the same. In the situation, the start level which borders on the coincidence area, is changed to the end level which also borders on the coincidence area, i.e. in this case Sa becomes equal to Eb. Figure (5.4.3.1)(c) shows a "fixed-start" level change where the start levels remain the same, and the end level which borders on the coincidence area is changed, i.e. in this case Ea becomes equal to Sb.

This level changing not only has the effect of controlling the logic, but also of eliminating the duplication of work.

5.5 The End-product

The logic formation produces a small network for every grid square defining the sequence of work in that grid square, and is based solely on the positional arrangement of the work in that square. These small networks are not connected across grid boundaries, as all inter-grid square connections are material or resource dependent, and are more satisfactorily handled by a resource scheduler. The term network is perhaps misleading in describing the sequencing of the work in the grid squares, as there are no concurrent activities. The network for each grid square is a single path chain of work, and shall be called an array. Each work activity will be defined as an element of an array.

The site map can be represented as in figure (5.5.1) with each grid square containing an array of work elements. This diagram shows the information for the floor slab example ordered both in terms of it's position in x and y, and also the sequence in which the work will be carried out. Arranging the information in this manner allows the model to recognise when similar work elements are adjacent to one another, and available for work. This means that if the grid square dimensions are too small for a resource to fulfill it's size quota then adjacent grid squares can be "bundled" to give the required size. Figure (5.5.2) shows the situation when some of the excavation has been completed, and the consequential "exposure" of some blinding concrete.

The bundling of the adjacent grid squares is performed by the resource scheduler, and is discussed in chapter 7.

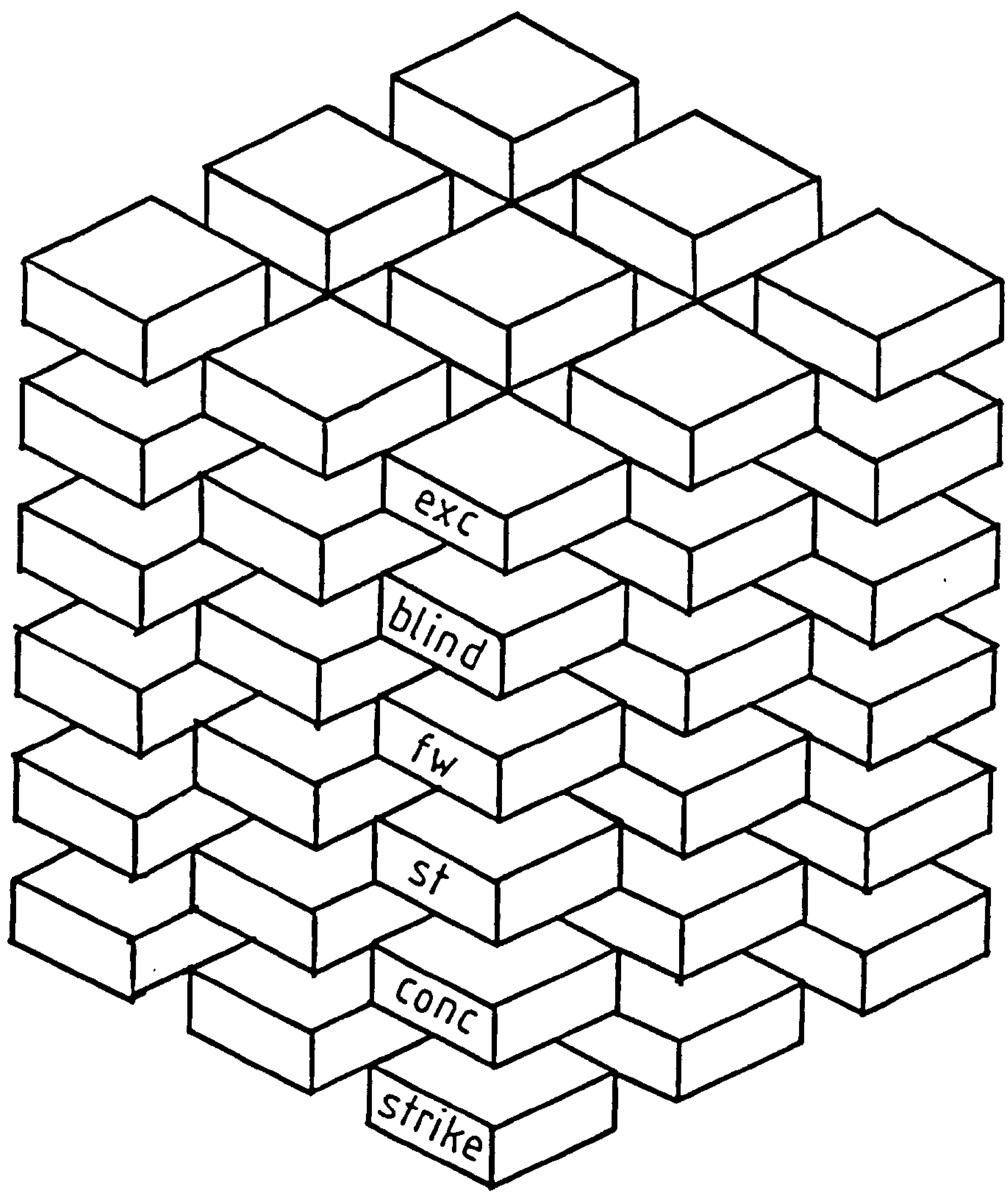


Figure (5.5.1) Pictorial illustration of the site map

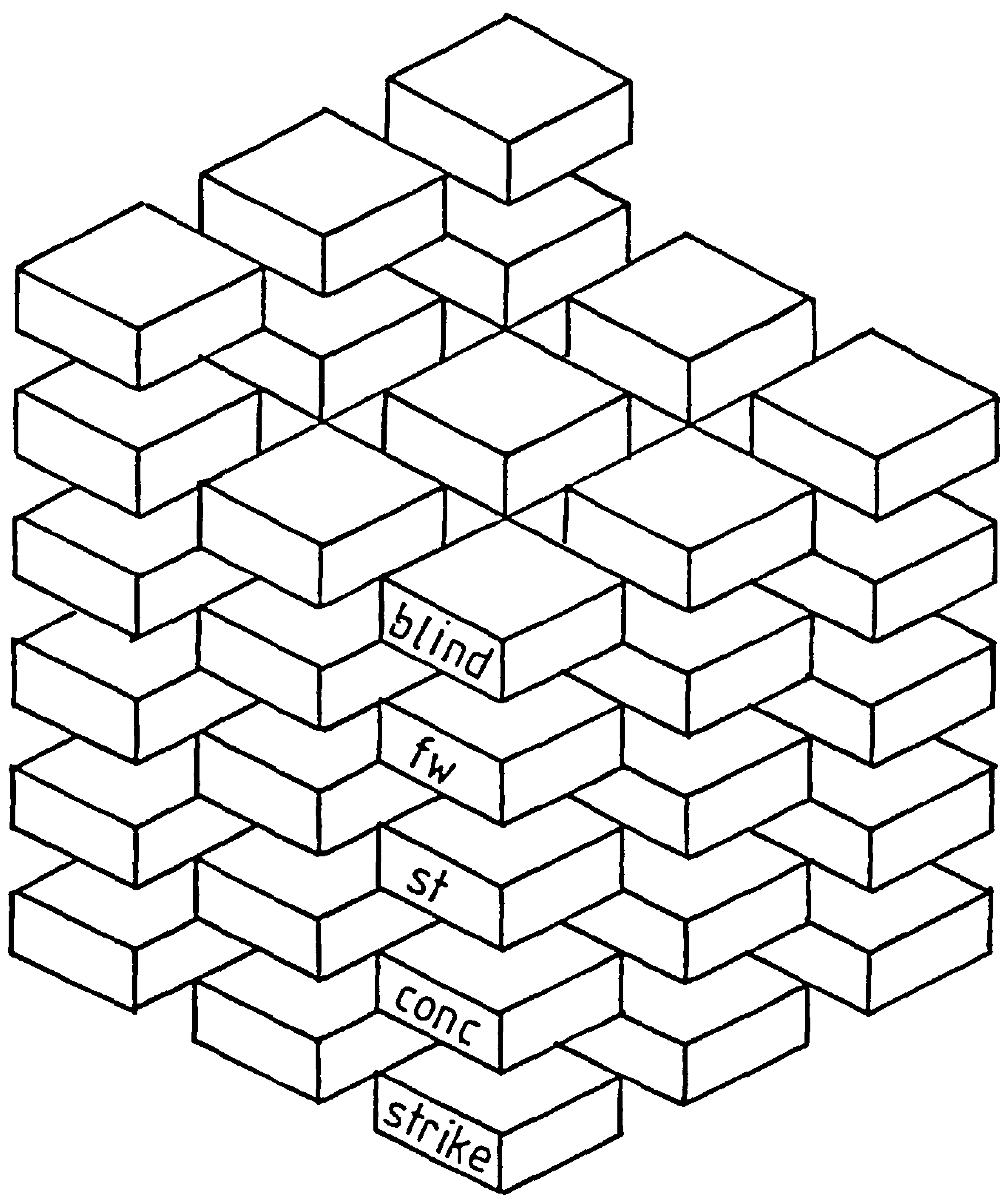


Figure (5.5.2) Exposure of some blinding concrete

CHAPTER 6

PRIORITIES

6.1 Introduction

The previous chapter discussed the formation and processing of the work information involved in the construction of a project, in a manner that was suitable for a resource scheduler to use. The scheduler has the task of allocating resources to work areas. In order to dictate the progression of the allocation, a system is needed that will model the site layout factors that have been discussed in previous chapters. The area priorities are a means of simulating these site related features.

An area priority is a number which is used to reflect the importance of any particular grid square on the site. They can be broadly sub-divided in 3 categories. These are:

a) Structure based priorities
b) Access and Site related priorities
c) Resource related priorities

The balance or existence of these sub-priorities will depend largely on the site itself, some lending themselves to highly access related priorities, others to resource or structure based priorities. The three priorites are all scaled so that their values are within the same limits so that a three-way ratio or priority balance may be used to reflect the different relative importance between the three. This balance will be discussed in more detail in a later secton.

6.2 Structure based priorities

This is a very simple priority which relates priorities to all the structures on site. This priority may be used to weight each grid square by the importance of the work that it contains, and will generally be used to influence the start times of different structures. An occasion where this may arise is where high value structures may be completed relatively early in the contract, allowing the high earnings received to fund the latter stages of the contract. The structure priority may also be used to allow the early release of high intensity work areas. For example, one may consider the excavation of the foundations of a high-rise building as essential early in the contract, because the completion of the excavation will allow an early start for the other resources in that structure. Conversely, the excavation of a trench for a pipe run will not release the same quantities of work, and consequently may be given a relatively low structure priority.

The first type of structure priority is money-orientated and may be calculated in two different ways. The first is to consider the likely cost of the construction within a grid square. This requires information concerning the cost of the resources and their rates of work, and the cost of materials. The "cost" of the work in that grid square can then be calculated by considering the time the resources will spend on that grid square and also the cost of any materials and their provision.

Perhaps an easier way of forming a money-orientated structure priority is to estimate the expected earnings in each grid square. This may be done by either using the estimators rates, or if the contract has been tendered for, the Bill of Quantities, and applying them to the quantities of work associated with each grid square.

The high intensity work areas may be mapped by considering the expected construction time for the work array associated with any grid square. This will also require a knowledge of the resources and their rates of work, and will similarly involve the calculation of the time any resource will spend on an element in that work array.

The calculation of the structure priorities, by whatever method, will generally result in a fairly consistent priority for each structure as shown in figure (6.2.1).

0	0	0	90	91	91	92	0	0	0	0
0	0	0	89	90	91	91	0	0	0	0
0	0	0	90	90	90	90	0	0	0	0
0	0	0	89	89	89	90	10	10	10	10
0	0	0	90	90	90	90	0	0	0	0
0	0	0	89	91	92	91	0	0	0	0
0	0	0	89	90	91	91	0	0	0	0
0	0	0	90	90	90	90	0	0	0	0

Figure (6.2.1) Structure priorities

6.3 Access and Site Layout priorities

This priority will be primarily used by the scheduler to reflect the effect that the site layout and access have on the construction process. The extent of this influence will vary considerably from one site to another. Sites which lend themselves to a line of balance style of planning will utilise the access priorities to a greater degree, whilst those which have less geographical influences will use them to a lesser degree.

The access priority for any grid square is formed from the inverse of it's distance from any access point, and then scaled to give the values within a suitable range.

The provision of access on a construction site will greatly affect the pattern of work, with different combinations access points on the same site giving very different work methods. Figure (6.3.1) for a road project illustrates the priority maps that are produced by giving different access to the same site. The arrows on these illustrations indicates the general direction of work that will be modelled with these priorities.

a)	1	9	17	25	35	45	55	65	75	84	92	100
	1	9	17	25	35	45	55	65	75	84	92	100
	B					C					D	A
b)	100	82	64	46	28	10	10	28	46	64	82	100
	100	82	64	46	28	10	10	28	46	64	82	100
c)	1	19	37	55	73	91	80	41	1	21	60	100
	1	19	37	55	73	91	80	41	1	21	60	100

Figure (6.3.1) Access priorities for a road

6.4 Resource priority

The resource priority is used to restrict the movement of the resources to areas that are close to where they last completed some work. The aim of this priority is to reduce unnecessary movement of resources. Figure (6.3.1)(b) may be used to illustrate this. Assume that the contractor on the road project has only one blacktop team. If no limit is put on their movement on site, then after completing some work at area A, then next highest priority occurs at B. The blacktop team will move to B and carry out the blacktop there. This process will occur repeatedly as the team gradually works towards the centre at C.

The formulation of the dynamic resource priority is similar to that of the access priority, with the priority of any gridsquare being the inverse of it's distance from the last position of the resource. This resource is dynamic because it will change for each different position of the resource in question, and consequently has to be recalculated for each resource allocation.

For the road problem the resource priority map after the completion of the blacktop at A, is illustrated in figure (6.4.1).

1	9	17	25	35	45	55	65	75	84	92	100
1	9	17	25	35	45	55	65	75	84	92	100

Figure (6.4.1) Resource priority after work at A

If this priority map is overlaid on the access priority map for the same project, then the resulting priority map is given by figure (6.4.2).

B					C					D	A
101	91	81	71	63	55	65	93	121	148	172	200
101	91	81	71	63	55	65	93	121	148	172	200

Figure (6.4.2) Resource and Access priorities overlaid

This combination of the two priority maps would have the affect of making the blacktop team move from position A to position D for the next allocation.

6.5 Priority Balance

To make use of all the different types of priority, the scheduler needs to recognise the relative importance of each type of priority for the particular site being considered. The importance of each of the priorities will vary from one site to another, and the priority balance may be used to reflect this.

At present, there are three types of priority map:

a) Structure based priorities
b) Access and Site related priorities
c) Resource related priorities

If a three-way ratio, reflecting the importance of each priority is associated with the three priority maps, then a fourth overall priority map may be formed, which reflects structure, access and resource factors. This overall priority map will change with each resource allocation, as the resource based priority map changes, but may be quickly reformed from it's root priority maps.

The advantage of having a three map arrangement is that different strategies in the plan may be investigated with relative ease, by altering the balance of the priorities.

CHAPTER 7

THE SCHEDULER

7.1 Introduction

The scheduler is a simulator of the construction site and it's resources. It attempts to gather together the small areas of work as discussed in chapter 5, to form work areas large enough for the resources to work on.

The scheduler is an "event-driven" scheduler, which means that the clock is only updated when the situation on the site changes. This usually occurs on the completion of some work, and allows the re-allocation of the resource that finished the work, and possibly the allocation of previously idle resources to the newly completed areas. Because the scheduler is event-driven, it means that the clock has to be a real-time clock, i.e. can deal with part-days of part-shifts.

The scheduler does not allow the splittability of work elements to be modelled. When a resource is allocated to a set of elements it remains working on those elements until the work is complete. The introduction of splittable work elements introduces some basic conceptual difficulties to the model. The difficulties arise when one considers how the time the resource spent on the set of work elements is sub-divided. In some cases it would be advantageous to sub-divide the work carried out equally between the set of work elements, hence reducing the work content in each element on a pro rata basis, and consequently leaving them unfinished. In other cases it would be advantageous to sub-divide the work to area so that some areas were totally completed, and others not started, and possibly have a "roll over" effect from areas to adjacent areas. The splittability of work elements was eventually ignored, with the resource allocation being controlled by specified minimum and optimum work areas for each resource. This effectively means that the area that a resource is allocated to is close to it's physical minimum. This is discussed in a later secton (7.2.4).

The information that the scheduler requires is of three types:

a) Positioning and sequencing of work
b) Priorities
c) Resource information

The former two were discussed in chapters 5 and 6 respectively, and provide information concerning the availability of particular types of work and the relative importance of any area on the site. The latter is discussed in the next section, with the scheduler being discussed in the last section of this chapter.

7.2 Resource characteristics and information

The following characteristics are thought to be important in the resource model:

a) Cost
b) Mobilisation Time
c) Rate of work
d) Work room
e) Operating room
f) Time lag.

A resource in this model will usually comprise a team of resources that are specialized at carrying out a set of specific work types. Each team may feasibly have many types of work which it may carry out, and hence will have a set of points (c) though to (f) for each type of work. So, for example, a labourer may generally be able to turn his hand to bricklaying, steel fixing and carpentry as well as more general labouring, although perhaps without as much ability as a tradesman in that skill. Consequently, the rate of work for a labourer performing steel fixing will be lower than that of a steelfixer. The resource characteristics are discussed in more detail below.

7.2.1 Cost

The cost of each resource will simply be the cost to keep that resource on site working for one day or shift. For labour this cost will generally be his daily wage, but for plant must include running costs, such as fuel and the operators wage, and also some allowance for wear and tear, depreciation (or hire charges), maintenence, and mobilisation costs. This information is generally available in a construction company.

The use of cost element in the scheduler is mainly as a performance indicator to assess the value of different combinations of resources and access models.

7.2.2 Mobilisation time

Each time a resource is allocated to an area of the site, there will generally be a time lapse between the the completion of the last section of work and the start of the new. This may be thought of as a mobilisation time, which is due to the movement of the resource to other areas of the site. This is distance dependent and may be formulated by considering the speed of the movement and distance travelled, hence:

Mobilisation time = Speed / Distance.

7.2.3 Rate of Work

The rate of work may be thought of in two ways. Firstly, there is the volumetric rate of work where the output of a team of resources is measured in cubic metres per day. The output of an excavating team may be measured in such a way. Secondly, there is an area rate of work where the resources output is measured in square metres per day. The output of a blacktop which is measured in metres squared of blacktop laid per day, is an example of this type. The quantities of each type of work is available from the site maps discussed in chapter 5.

The output of a team may also depend on the distance travelled by certain elements of the team. For example, a muckshift team will have output that is measured in cubic metre kilometre per day. This output however, is relatively unchanging for different positions on the site, and for this reason is not used.

Each resource or team will have different work rates for each of it's different types of work.

7.2.4 Work room

To facilitate the grouping of the work elements in different work arrays, as mentioned in section (7.1), the model needs to have some indication of the quantity of work, in terms of grid squares, that the resources require in order to operate. This size can be thought of as the physical dimensional constraints of the resource. For example, a scaper may only excavate wide expanses of excavation, whereas a mechanical digger is only limited by the size of it's bucket. There are three size limitations that may be considered in this context. These are:

a) Optimal work room
b) Minimum work room
c) Maximum work room

7.2.4.1 Optimal work room

This is the work space required by the team or resource for efficient production of work. The optimal value controls the size of the work space to which the resource would normally be allocated. Obviously, the optimal work space will largely depend on the resource's work capability, although a planner may wish to reduce this value to allow more frequent allocation of the resource. The advantage of this is that it prevents one resource holding up large areas of the site for long periods of time. If the optimum value is constrained to being close to the minimum work area (see below) then there is the fastest possible turn-around of the resource, and hence splittablity of activities does not become important. This was discussed briefly in section (7.1).

7.2.4.2 Minimum work room

During the course of the scheduling process, there may be instances where a resource is available for work, and there is some work available, although less than the optimal work space. In this situation, it may be possible to have the resources working sub-optimally rather than leaving them idle. There is a limit to how small an area each resource may work in, however, and the minimum work room value reflects this limit. This value is then used by the scheduler to allocate otherwise idle resources to small areas. It may also be used to restrict the mobilisation of resources at the start of the contract until a suitably sized work area is formed.

7.2.4.3 Maximum work room

The use of this value is normally restricted to the low output resources. It prevents the allocation of this type of resource to large expanses of work. For example, on a construction site, a labourer with a shovel would not be told to start on the excavation on the foundations of a high-rise building, simply because it is an infeasible or unrealistic task, and generally the labourer could be better employed elsewhere. This maximum work room value effectively restricts resources to quantities of work to which they are suited.

7.2.5 Operating room

Preceding chapters have dealt with the limitations on the construction process due to the interference between resources. For example, the line of balance method incorporates distance or time buffers between resources to prevent any interference. This section illustrates how the model allows for this interference.

Most resources will require some operating room over and above that which it is actually working on, as described in section

(7.2.4). This operating room allows for resource dependent factors such as plant manoeuvres, safety, and noise. The implementation of the operating room can be thought of as a buffer surrounding an active work area, as illustrated in figure (7.2.5.1). This buffer is a restricted area within which no more resources may operate. The buffers between two resources are additive, i.e. they may not overlap one another.

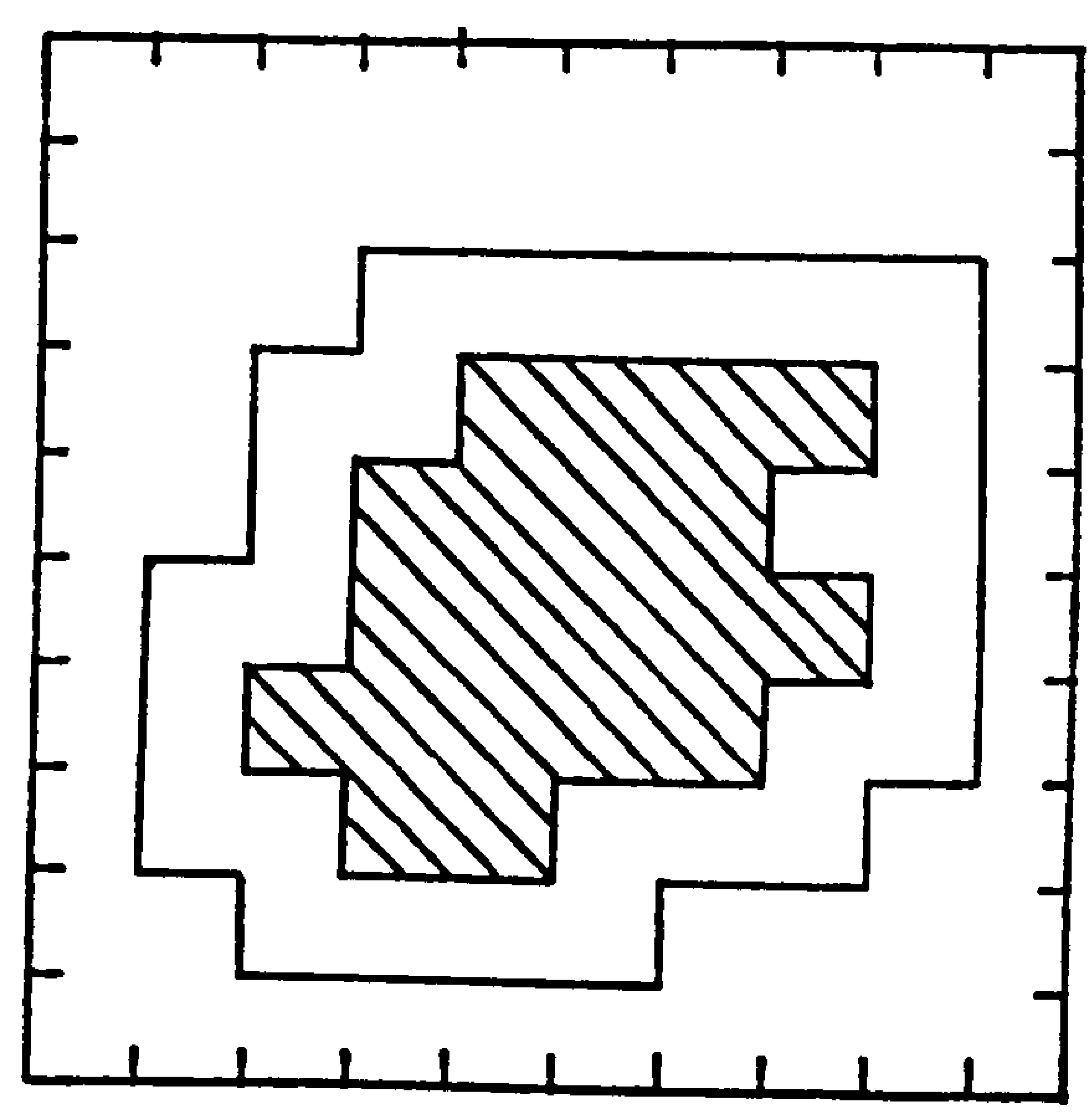


Figure (7.2.5.1) Operating room buffer

7.2.6 Time lag

The operating room described above illustrated how distance buffers could be handled. Time buffers may also be necessary in modelling the construction site. Unlike the operating room buffers, which only exist around active work areas, the time buffers, may exist long after the work has been completed. They may be used to restrict access to certain areas of the site because of the activities that have just been completed there, for example in the curing of concrete. The concrete curing time cannot be included in the concrete pouring activity for two reasons. The first is that concrete curing time is quite independent of the quantities of concrete poured, and hence cannot be feasibly modelled in the existing resource model. Secondly, the concrete curing time utilises no resources, and hence the concrete pouring gang should be free to move to other areas of the site.

The time lags are modelled as resources with no operating room buffers that commence immediately after the completion of the work type that requires them.

7.3 The Scheduler

7.3.1 Introduction

The processes involved in the scheduler are quite complex and consequently, it is proposed to discuss the working of the scheduler with reference to the process flowchart, figure (7.3.1.1).

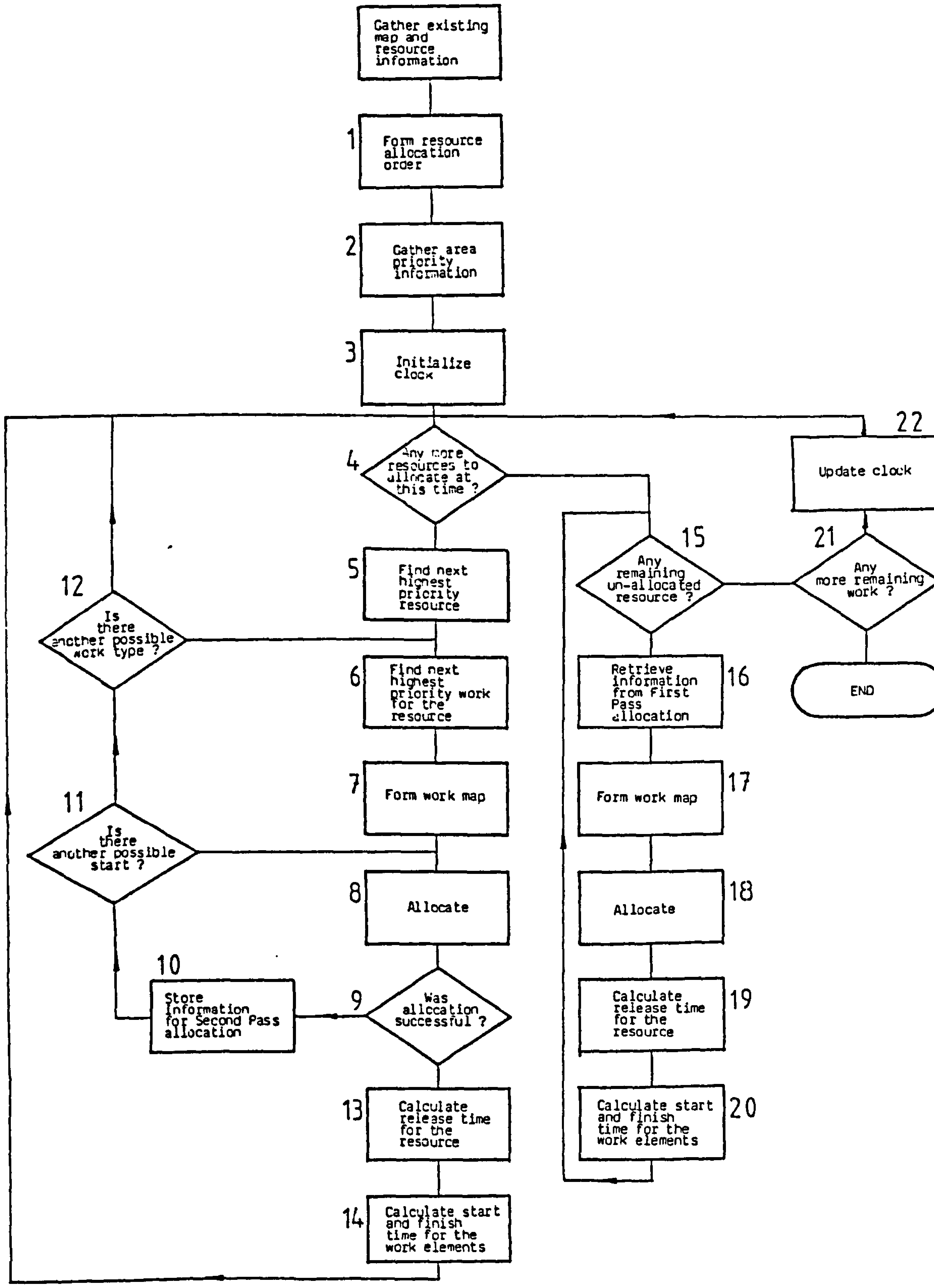
The scheduling process may be split into four sections. These sections are: (box numbers in [])

a) Initialisation [1..3]: sets up all the data structures and collects all necessary information to perform the schedule.

b) First Pass Allocation [4..14]: attempts to allocate the resources to the available work elements at optimal efficiency, and if successful calculates the start and finish times of the activities.

c) Second Pass Allocation [15..20]: attempts to allocate the idle resources sub-optimally if possible. To reduce interference between sub-optimally allocated resources and optimally allocated resources, the second pass allocation is carried out on completion of the first pass.

d) End Check [21,22]: checks for more work and updates the clock if necessary.



Figure(7.3.1.1) Process flow-chart for the scheduler

7.3.2 Initialisation [1..3]

7.3.2.1 Box 1 : Form Resource allocation order

This section forms the order in which the resources will be allocated. The allocation order may be specified by the user, but as a default, the order is determined by the cost per shift of all the resources, the most expensive first, least expensive last. This has the advantage that if resources are competing for the same area of work, or for adjacent areas of work, then the most expensive is not left idle or allocated sub-optimally.

A situation where this may not be suitable is where faster, more expensive resources, follow behind a slower, cheaper resource on a site with fairly confined work areas, such as a road. If the higher cost resources are allocated in this circumstance, then these resources may interfere with the progression of the initial resource, resulting in much leap-frogging of the resources. Generally in this sort of situation a more satisfactory allocation order is defined by the sequencing of the work. This sequence will allow the resource to progress with no leap-frogging.

7.3.2.2 Box 2 : Area Priority information

The area priorities are needed by the scheduler to select work areas and influence the passage of resources through the site. This section formulates the area priority information as discussed in chapter 6.

7.3.2.3 Box 3 : Initialize clock

The scheduler is an event driven scheduler, i.e. time updates are carried out when the situation on site changes, and not at fixed intervals. This usually occurs on the completion of some work, or the mobilisation of some resource on site. The clock needs to be able to handle this, and as a consequence is a "real-time" clock, i.e. it can handle part-days or part-shifts. This section resets the clock to zero.

7.3.3 First Pass Allocation [4..14]

7.3.3.1 Box 4 : Search for Unallocated resource

This decision box checks if there are any resources that have not been considered for allocation. If the result is false the scheduler proceeds to the second pass allocation for placement of resources sub-optimally. If the result is true, then the scheduler continues through to the first pass allocation.

7.3.3.2 Box 5 : Find next highest priority resource

This section finds the next available resource based on the resource allocation order formed in box [1]. This resource will either have just completed some work, or previously been idle. The scheduler will not interrupt already working resources for re-allocation, as discussed in section (7.1). The resource selected in this section is then used in the rest of this pass of the first pass allocation.

7.3.3.3 Box 6 : Find next highest priority work type

Each resource has many different types of work which it may carry out. These work types are ranked by the user. The scheduler will attempt to allocate them in this order. This section finds the next highest ranked work type for the resource chosen in box [5].

7.3.3.4 Box 7 : Form work map

This section essentially forms a work map of the site indicating areas of work of the type selected in box [6]. To facilitate all the checks needed for the allocation, the distribution of work is represented in a complex map indicating areas of:

a) Available work

b) Hidden work (i.e. work not yet available)

c) Both available and Hidden.

The formation of the work map also takes into account the proximity of any active work areas, and may restrict the use of areas that fall within the operating room buffers.

7.3.3.5 Box 8 : Allocate

This section forms the bulk of the first pass allocation, and will be discussed in three parts:

a) Formgroups

b) Lasso

c) Checks

7.3.3.5.1 Allocate[8] - Formgroups

One of the aims of the scheduler, as outlined previously, is to gather small areas of continuous work together to form a work area large enough for a specified resource to operate on. To achieve this, the work map, as formed in box [7], has to be processed so that the extent of any area of continuous work is known.

Figure (7.3.3.5.1) shows four representations of a small area of the site, with circles in figure (7.3.3.5.1)(a) representing the potential work areas. The formgroups algorithm progresses in a primary x direction with a secondary y direction i.e. from left to right, top to bottom (as with reading English), and the aim is to allocate a group number to each area of available work. The top left square (i) will receive a group number of 1. The adjacent square (ii) is adjacent to square (i) and it will also receive group number of 1.

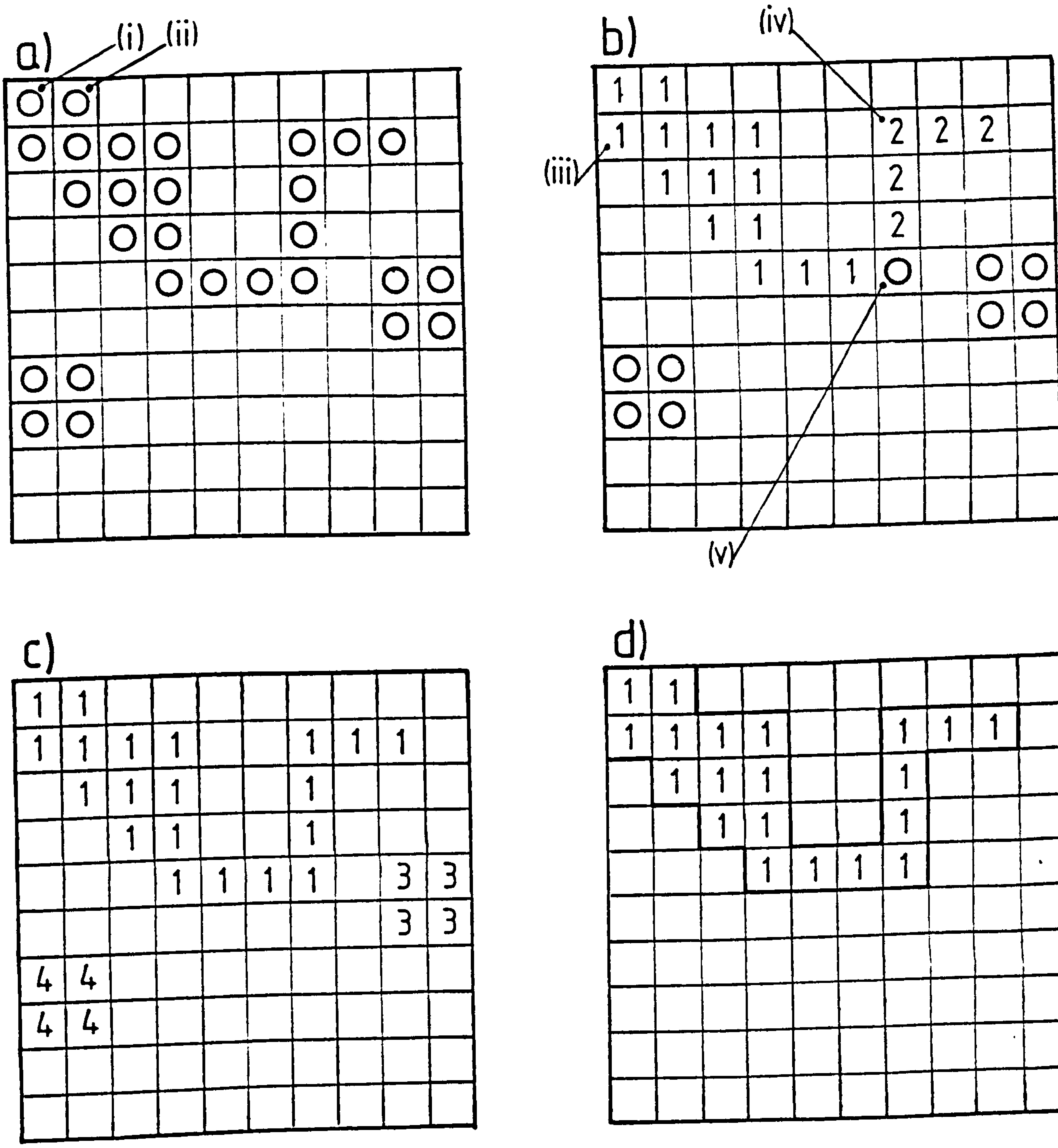


Figure (7.3.3.5.1) The Formgroups algorithm

The next square to be considered is square (iii), and as this is adjacent to squares with a group number of 1, it will also receive group number 1, and so along the rest of the second row until square number (iv) is reached. This square is not adjacent to any squares already containing a group number, so this is recognised as being another group, and receives a group number of 2. This process continues until the situation reaches that illustrated in figure (7.3.3.5.1)(b).

Grid square (v) in figure (7.3.3.5.1) is a adjacent to both group 1 and group 2. This shows that group 1 and group 2 are really the same group. The algorithm then needs to back-track and change all the group 2's to group 1's, thus joining the two groups together. The process is then continued from (v) until the whole map is sectioned off into contiguous groups, as illustrated in figure (7.3.3.5.1)(c).

In order to facilitate all the checking for the scheduler, all groups that are smaller than the optimum work room, or larger than the maximum work room for the resource being considered, are removed. This results in a feasible group map for the particular resource, as shown in figure (7.3.3.5.1)(d).

7.3.3.5.2 Allocate[8] - Lasso

This section of the scheduler ties-in the required number of grid squares to allow the allocation of the resource being considered. The number of grid squares being tied-in corresponds to the optimal work room of the resource.

The Lasso section has to decide on an area in which to bundle the work elements together. The information required for this is available from the group map as outlined above, and also the priority map which was discussed in chapter 6. The group map gives feasible areas of work for the resource and work type, and the priority map gives a bias to the more favourable of these. The algorithm selects the highest priority grid square within a feasible work area as it's start point, and all further bundling of the grid squares will be contiguous with this start square. This method may not necessarily lead to the highest possible overall priority bundling of the grid squares, but as it is unlikely that the priority map contains great irregularities within small areas, it is a good approximation to the best.

The selection of the succeeding work areas is also carried out on a priority basis, with only grid squares that are adjacent to previously selected squares being considered.

7.3.3.5.3 Allocate [8] - Checks

This section checks that the selected group, as formed in the section above does not violate some of the conditions applied to the first pass allocation. Some of the necessary checks for the allocation, such as operating buffers and size limitations of the resource, had previously been built into the formation of the work map. The main check that is necessary, therefore, is to ensure that no groups of less than the optimal work room in size are left as a consequence of the selected group. This ensures that the selection made at this time stage does not leave small sized groups which will have to be handled sub-optimally at a later time stage. Figure (7.3.3.5.3)(a) shows an area of potential work areas, and how small groups may be formed with a resource allocation size of 16 grid squares.

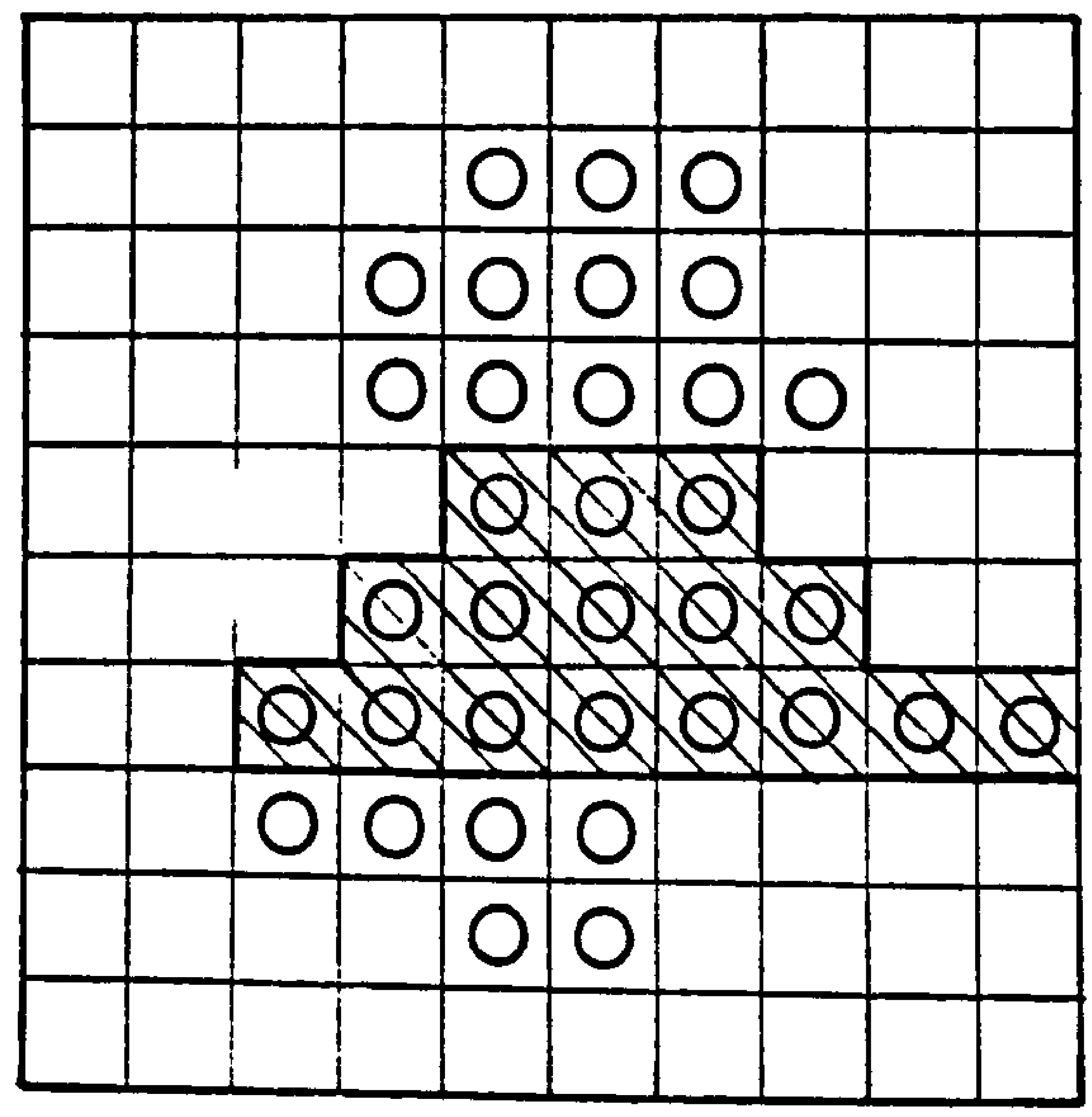


Figure (7.3.3.5.3)(a) Formation of small groups

There are two ways in which the small sized groups can be handled. If the small group contains available work . then the extra grid squares can be drawn-in and included to give a much larger area for allocation. If, on the other hand, the areas in the sub-groups contain hidden work then the whole selection area is invalid.

The reasoning behind this decision is that if the allocation is attempted at a different start point then a better solution may be arrived at with no sub-optimal usage of resources at a later date. If, however, a more suitable start point may not be found, then the initial selection may be carried out regardless in the second pass of the scheduler.

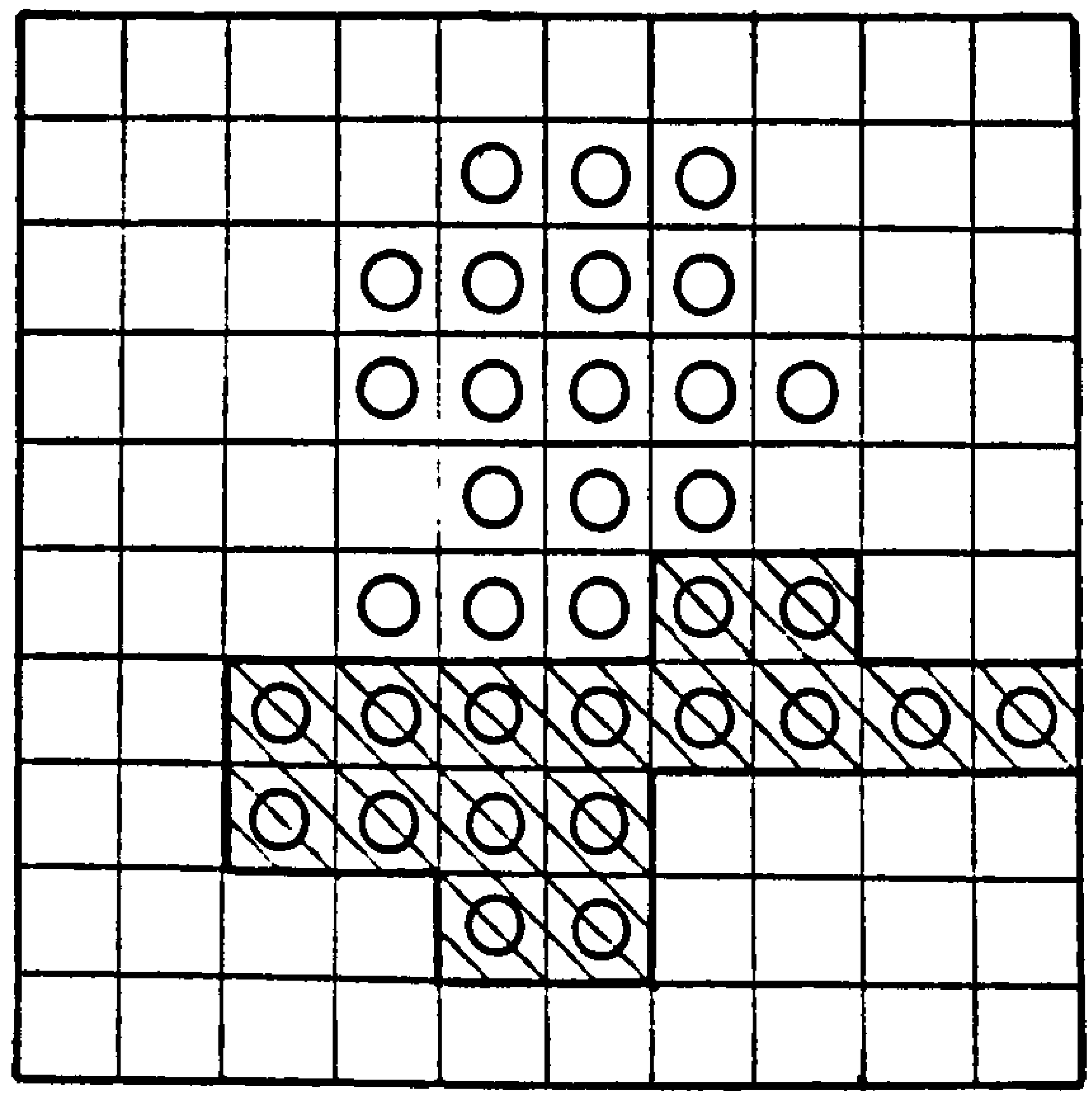


Figure (7.3.3.5.3)(b) Feasible selection of groups

Figure (7.3.3.5.3)(b) shows a feasible selection using the same work areas, which leaves a remaining group of 18 work elements. This selection will probably have a lower overall priority than the initial selection, but as there is no need for sub-optimal allocation at a later stage, then the second selection probably provides a more suitable solution.

7.3.3.6 Boxes 9,10,11,12 : Unsuccessful Allocation

This section describes the procedure if the selected work area does not satisfy the checks carried out in section (7.3.3.5.3).

7.3.3.6.1 Box 10 : Store information for Second Pass

This section evaluates the relative merit of any particular failure in the first pass. This is carried out so that if the resource is not allocated at the end of the first pass allocation then the information may be used in a second pass allocation.

In order for the scheduler to do this a ratio of the maximum feasible work area available and the resources optimum work area is formed:

Ratio = Maximum Work area / Optimum Work area

This ratio is stored by resource and work type. The upper limit of the ratio is limited to 1.0

If the allocation of the resource is totally unsuccessful for each work type, then the work type with the highest ratio for that resource will be used for the subsequent second pass of the scheduler. This means that the sub-optimal second pass allocation will allocate the resource to a work type as least sub-optimally as possible.

7.3.3.6.2 Box 11 : Check for another start

This box will check if there are any other possible start positions with the same resource and work type. The function of this section has already been more fully discussed in section (7.3.3.5.3).

7.3.3.6.3 Box 12 : Check for another work type

Because each resource may be capable of many different work types, a check is carried out for any such alternative work types for the resource being considered. If there are any, the scheduling procedure is repeated with this combination of resource and work type (boxes [6..9]). If, however, no more possible work types are available the resource is left unallocated and the scheduler proceeds the allocation of the next most important resource (box [4]). The unallocted resource may subsequently be allocated to a sub-optimal area, as specified by the ratio information (box [10]), in the second pass allocation.

7.3.3.7 Boxes 9,13,14 : Successful allocation

This section describes the procedure if the selection of a work area (box [8]) satisfies all the checks necessary for the first pass allocation.

Two sets of timings have to be evaluated in the event of a successful allocation. The first of these is the resource release time. This value is calculated by considering the total work load to be carried out in the allocation area. It is used so that the scheduler recognises when the resource has completed the area of work, and is available for re-allocation.

The second set of timings are the work element start and finish times. The start times for the work elements are simply given by the present clock time. The finish times are calculated in the same way as the resource release time, as above, with the addition of the time lag for the work type being considered. The area of work may not be freed until the finished times for the work elements. The timings for the work elements forms the basis of the output of the scheduler, and is stored with the general work element information.

After the calculation of the various sets of timings, the scheduler then repeats the whole allocation process (boxes [4..14]) for a different resource.

7.3.4 Second Pass Allocation [15..20]

The second pass allocation of the scheduler attempts to place unallocated resources to areas on the site as efficiently as possible, given that they were not successfully allocated in the first pass. The information gathered in the first pass indicates the work type each resource will perform, and as such a much less complicated system of looping is present in the second pass allocation.

7.3.4.1 Box 15 : Find Un-allocated resource

This decision box finds if there are any resources that have not been allocated in the first pass and not yet considered in the second pass. The order in which the second pass investigates the resources is the same as the resource allocation order which was formed in box [1] in the Initialisation stage. If an un-considered resource is found then the scheduler proceeds to the box [16] and attempts to place the resource and work type sub-optimally. Alternatively, if none are found then the scheduler proceeds to the End-check section, boxes [21..22].

7.3.4.2 Box 16 : Gather Information for Second Pass

This section gathers the information from the first pass allocation regarding the work type that is likely to yield the best possible usage of the resource. The uncertainty involved is developed as a consequence of possible first pass allocation of resources that are lower in the allocation order. This subsequent first pass allocation of resources may alter the availability of certain areas of the site because of the operations buffers. Short of doing a complete "dummy-run" for the second pass, however, this information will yield the most confident results given the inherent uncertainty.

7.3.4.3 Box 17 : Form work map

This section performs the same operations as box number [7] with the work type chosen above.

7.3.4.4 Box 18 : Allocate

This section, like it's predecessor box [8] in the first pass allocation, forms the major part of the second pass allocation. It's function is the same as that in the first pass with two exceptions.

The first exception is that the number of work elements to be allocated will probably not be the optimum work area as used in the first pass (see section 7.3.3.4.2), but will range between the minimum work area and the optimal work area.

The second difference occurs in the checking of the allocation. The second pass allocation will only check for small sub-groups (see section 7.3.3.4.3) of less than the minimum work area.

If the allocation of that resource and work type is unsuccessful, then the scheduler loops back to box [15] to find another resource to allocate. If, however, the allocation is successful, then the scheduler proceeds to boxes [19] and [20].

7.3.4.5 Boxes 19 and 20 : Timing calculations

These boxes perform the same calculations as discussed in section (7.3.3.6). The scheduler then loops back to box [15] to find another resource to allocate.

7.3.5 End-check

7.3.5.1 Box 21 : Check for more work

This box checks if there is any more work to be completed on the construction site. If there is some uncompleted work the scheduler proceeds to update the clock in box [22] and then repeats the cycle. If there is no more work to be done the schedule is completed.

7.3.5.2 Box 22 : Update clock

This section of the scheduler finds the next earliest release time for an active resource, or the next earliest finish time for the work area. This is when the site will change in form, i.e. the next event. The clock is updated and then the cycle is repeated (from box [4]) for the new clock time.

CHAPTER 8

TEST RUNS ON THE ROAD AND CULVERT PROJECT

8.1 Introduction

This chapter is intended to illustrate the use of the model in simulating a simple construction site. The test runs were carried out using a site similar to that discussed in chapter (4), the road and culvert example. There were two main reasons for choosing this example. Firstly, any results produced may be evaluated subjectively with reference to the work carried out in chapter (4). Secondly, the linear style of project, such as a road, allows the reasoning behind decisions made by the scheduler to be illustrated. This is because the progress of the project is measured in one dimension only, as opposed to a more general site where three dimensions may be considered.

Chapter (9) details a second set of test runs on three more projects and direct comparisons are made between the plans produced by the scheduler and those by contractors in industry.

The aims of this chapter, however, are to discuss the following:

a) Initial input to the scheduler
b) Effects of different priority balances
c) Effects of different optimum distance allocations
d) Effects of different resource allocation orders
e) Effects of different access positions
f) Effects of different numbers of resources
g) Effects of different grid sizes.

8.2 Initial input to the scheduler

The following information is required by the scheduler before the start of any schedule:

a) Job information
b) Logic information
c) Map information
d) Resource information
e) Priority information
f) Priority balance information
g) Resource allocation order

8.2.1 Job information

Plate (1) shows one of the input screens for the job information on the computer. It consists of 5 columns.

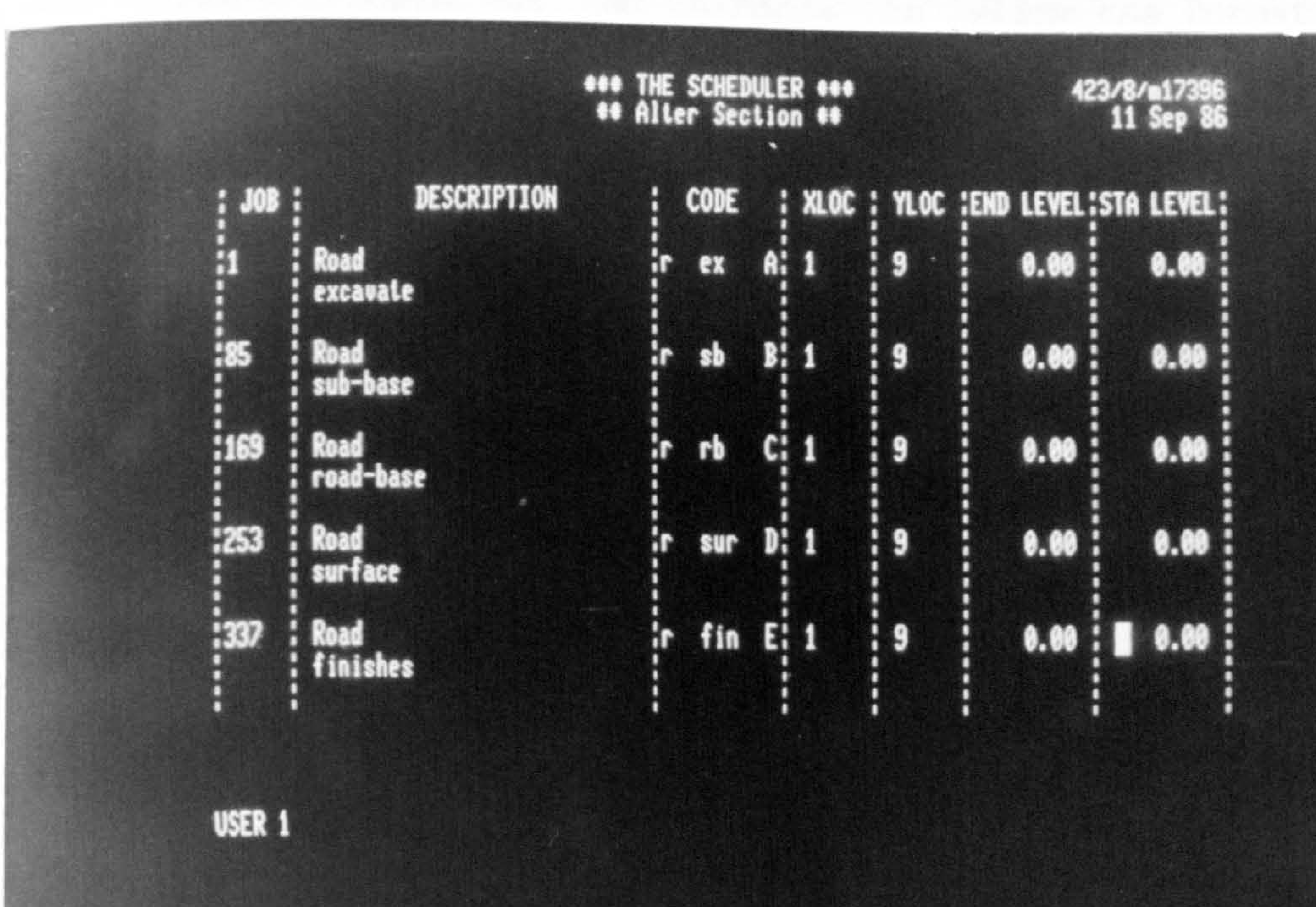


Plate 1 - Job input screen

a) Column 1: This column contains the job number, which is a unique number for every work element in every work array.

b) Column 2: This column contains the name of the work element, and usually consists of two parts.

i) Structure

ii) Work type

The name of the work element is useful for the user to identify the particular work element, and also useful in output. It bears no direct relevance to the running of the model.

c) Column 3: This column contains the job code. The job code is a summary of both the structure and the work type which is used by the model. For activity 1, for example, Road 1 : excavate, the job code is rl_ex, where rl is the structure sub-code, and ex is the excavate sub-code. This code is used throughout the scheduling process in the formation of the structure priority values, and in the allocation of resources to work areas.

d) Columns 4 and 5: These columns contain the start and end levels of the job. These values are used firstly to calculate the work content of each job, and secondly to allow the formation of the logic for the jobs in the work arrays using the Level method as discussed in section (5.3).

The job information constitutes the major proportion of the information necessary for the scheduler. The input of information in the form as shown in plate (1) is very tedious, especially if a very fine grid system is used. Consequently, faster methods of input have to be considered for effective use of the scheduler. Such methods include copying routines (not shown) that copy job information from one grid square to many others.

A second and more effective method of achieving fast input of job information would be obtained by integrating the schedulerwith a drafting/CAD package. This would allow the automatic formation of all the job information, at any scale, very quickly and with minimum effort by the user.

8.2.2 Logic Information.

A large proportion of the logic formation is carried out automatically using the level method. There are cases, however, where the Level method is not applicable. An example is that of steel fixing and formwork for concrete pouring. In some cases, depending on the available work space, formwork will precede steel fixing, and in others, steel fixing will precede formwork. For such activities, it is necessary to form rules concerning their precedence.

The scheduler contains two rules files. The first is a unique project rule file which is used solely for the project in question. This file is formed during the first run of the scheduler and contains information prompted from the user in situations that cannot be handled by the level method. The second file is a standard rules file which may be applied to any project. This file is used primarily to reduce the quantity of prompting during the first and subsequent runs of the scheduler.

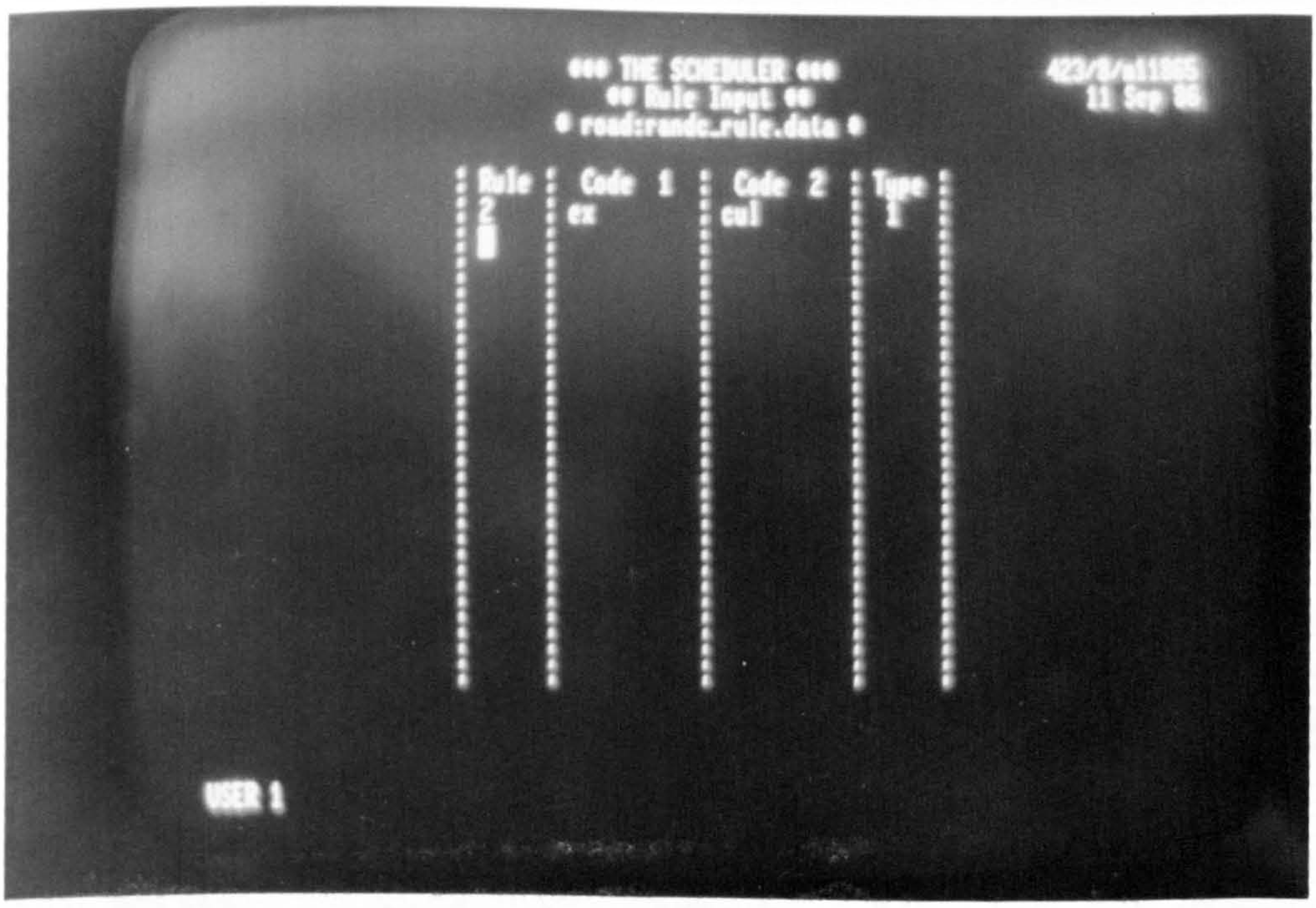


Plate 2 - Logic Rule editing screen

The logic rule information may subsequently be editedby the user. Plate (2) shows the computer screen for logic rule information editing. In this example, road excavate (ex) precedes culvert (cul).

8.2.3 Map information

The map information is formed from the job information and the logic. The map consists of a set of work arrays stored by a grid position in x and y. The jobs in the map are placed in their respective work arrays during the job information input. On completion of the logic formation, the work elements in the work arrays are sorted into the order in which they will be carried out.

8.2.4 Resource information

Plate (3) shows the resource information form for an excavate gang. The screen may be split into two parts. The top part consists of general resource information, namely the resource name and cost, whilst the bottom part of the screen are resource characteristics that are specific to the work type that the resource is required to carry out. The resource team illustrated in plate (3) is able to carry out only excavation, but could feasibly carry out other work types if the other columns were completed.

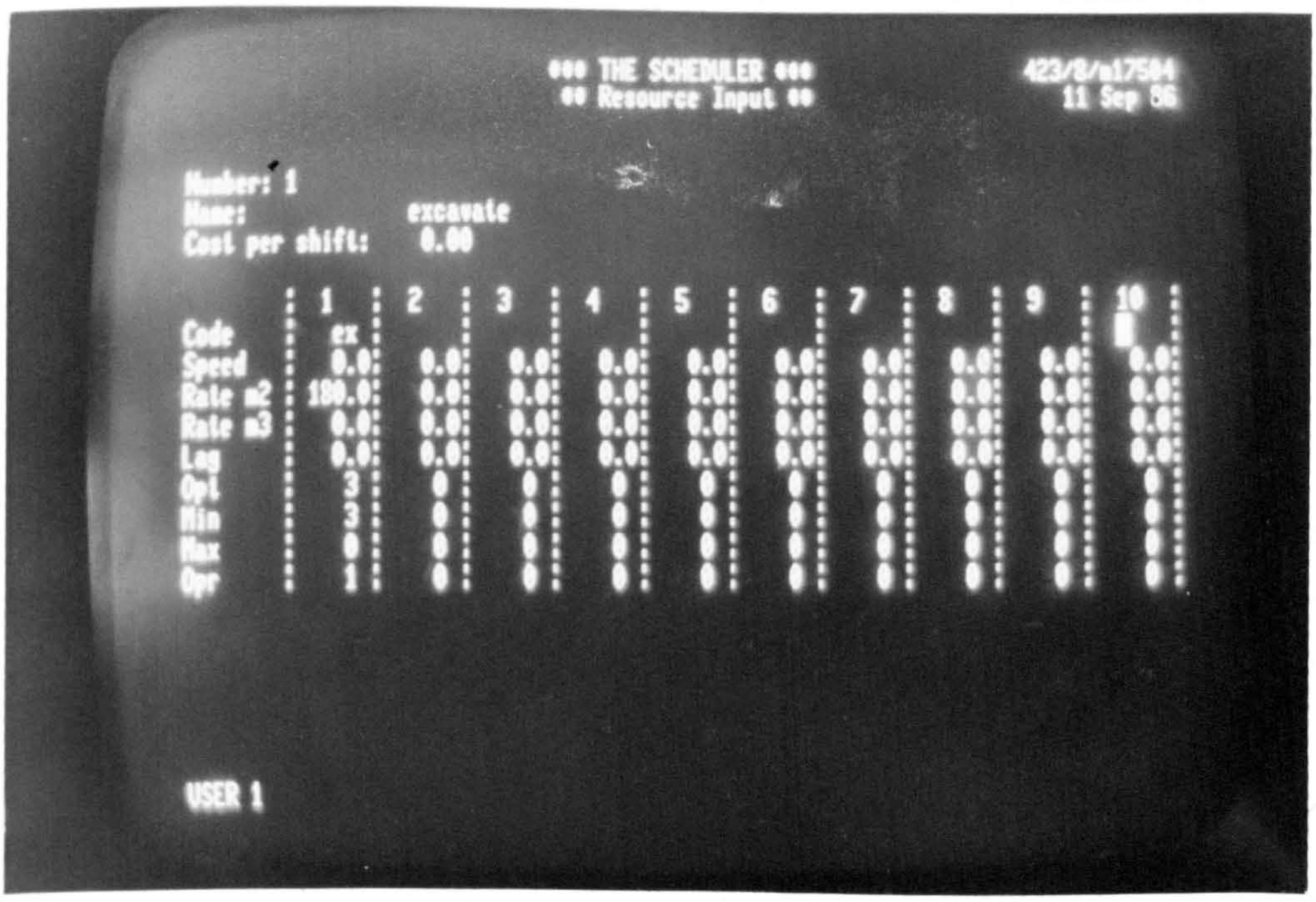


Plate 3 - Resource input screen

For each work type there will be different values for each of the following:

Code:	Work code that corresponds to that in the job information.
Speed:	Transfer speed of resource across the site in metres per shift.
Rate m2:	Rate of work in square metres per shift.
Rate m3:	Rate of work in cubic metres per shift.
Lag:	Pure time lag after completion of work.
Opt:	Optimum working space in grid squares.
Min:	Minimum working space in grid squares.
Max:	Maximum working space in grid squares.
Opr:	Operating room buffer in grid squares.

8.2.5 Priority information

Recall, the three types of priority:

a) Structure
b) Access
c) Resource

The last of these is a dynamic priority that is formed automatically at each allocation stage. The first two priorities, however, are input by the user.

Plate (4) shows the computer screen for input of structure priority. The scheduler searches the map until it finds an area which contains a structure. It then prompts the user for a structure priority for that structure. This method of formation is not automatic, although section (6.2) discusses possible methods and criteria for the automatic formation of structure priority.

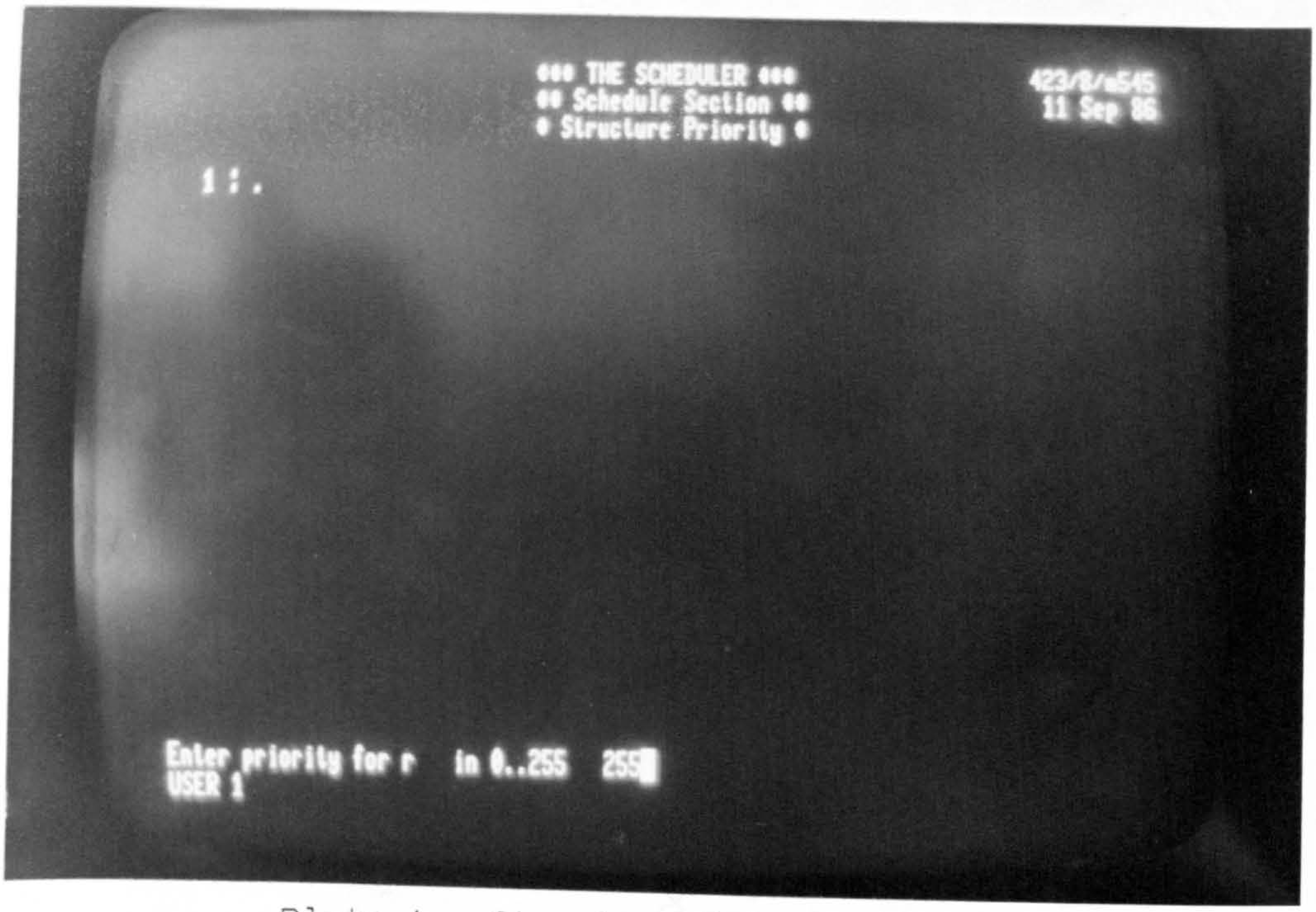


Plate 4 - Structure Priority input screen

Plate (5) shows the computer screen for the input of the access priority. The access priority formation algorithm requires the access points to be specified as positions in x and y with an associated priority value. The priority value may be used to give some access positions a slightly higher weighting than others. An example of this weighting is discussed later in connection with a set of test runs. The algorithm then calculates the access priority map as discussed in section (6.3).

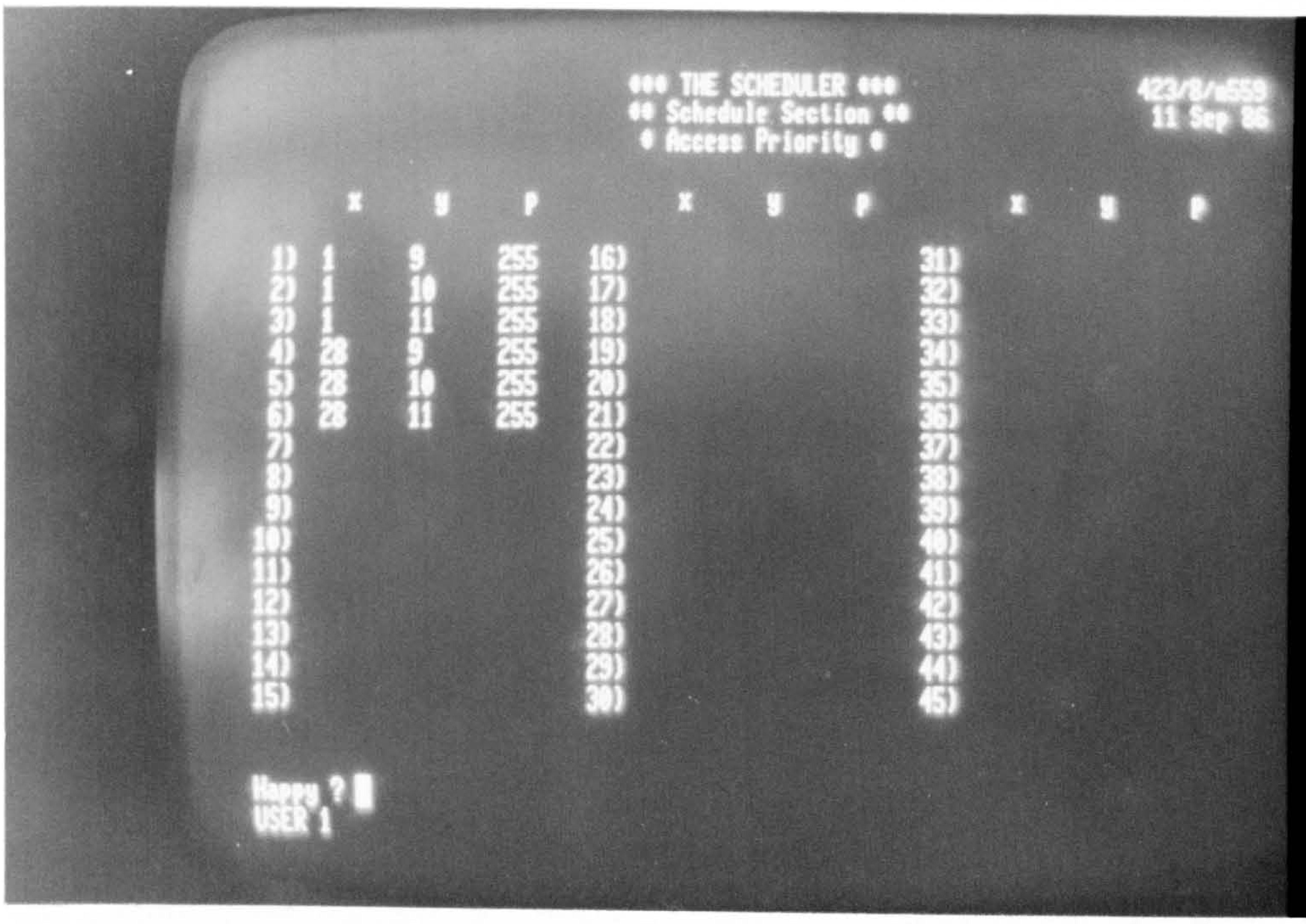


Plate 5 - Access Priority input screen

8.2.6 Priority Balance information

The priority balance is input by the user at the start of each schedule. Plate (6) shows the priority balance screen.

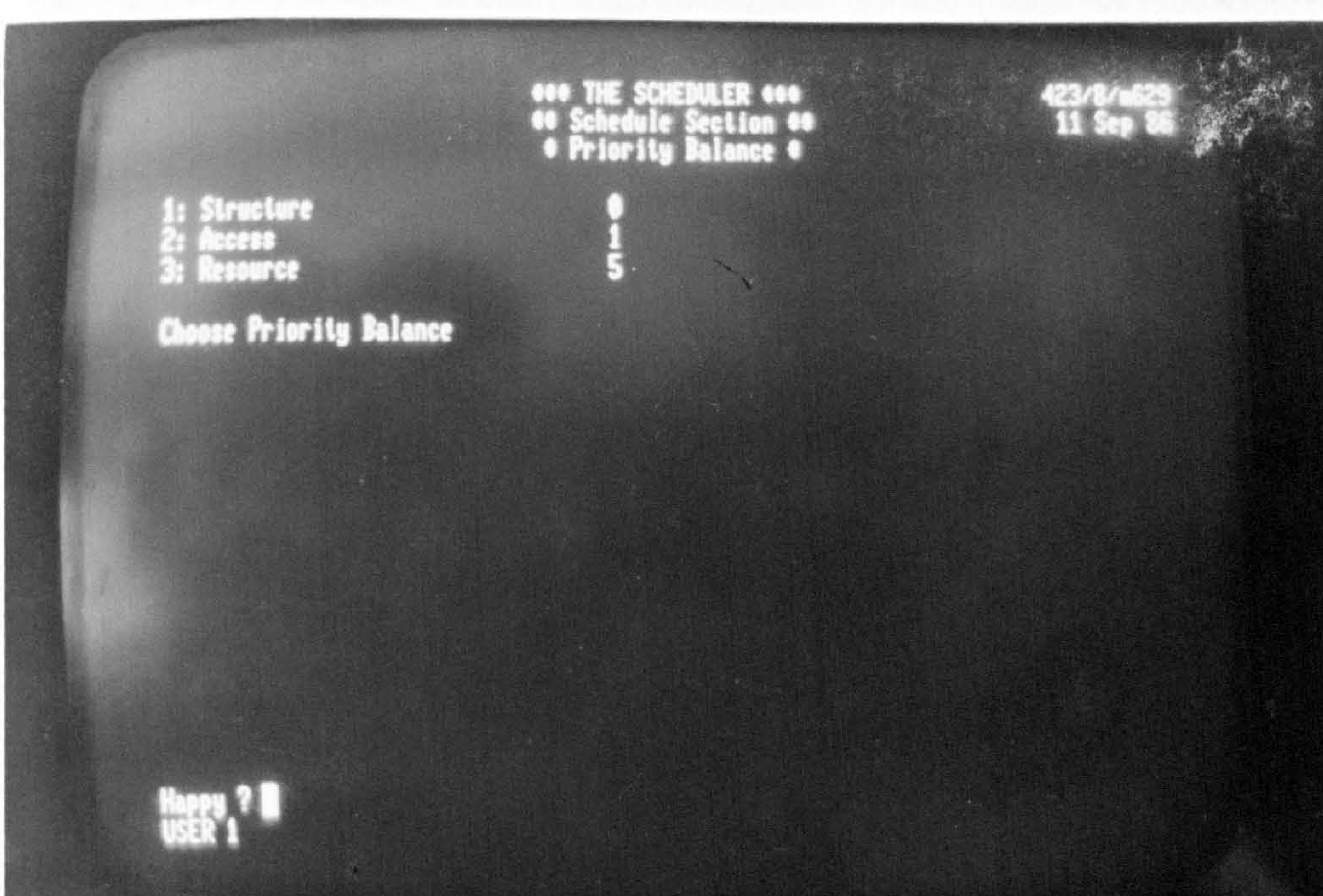


Plate 6 - Priority balance input screen

8.2.7 Resource Allocation order information

Plate (7) shows the computer screen for the resource allocation order. This order may be specified by the user, or may be formed automatically based on the cost of each resource. The automatic formation of resource allocation orders often results in disruption to the schedule (as discussed earlier in section (7.3.2.1)).

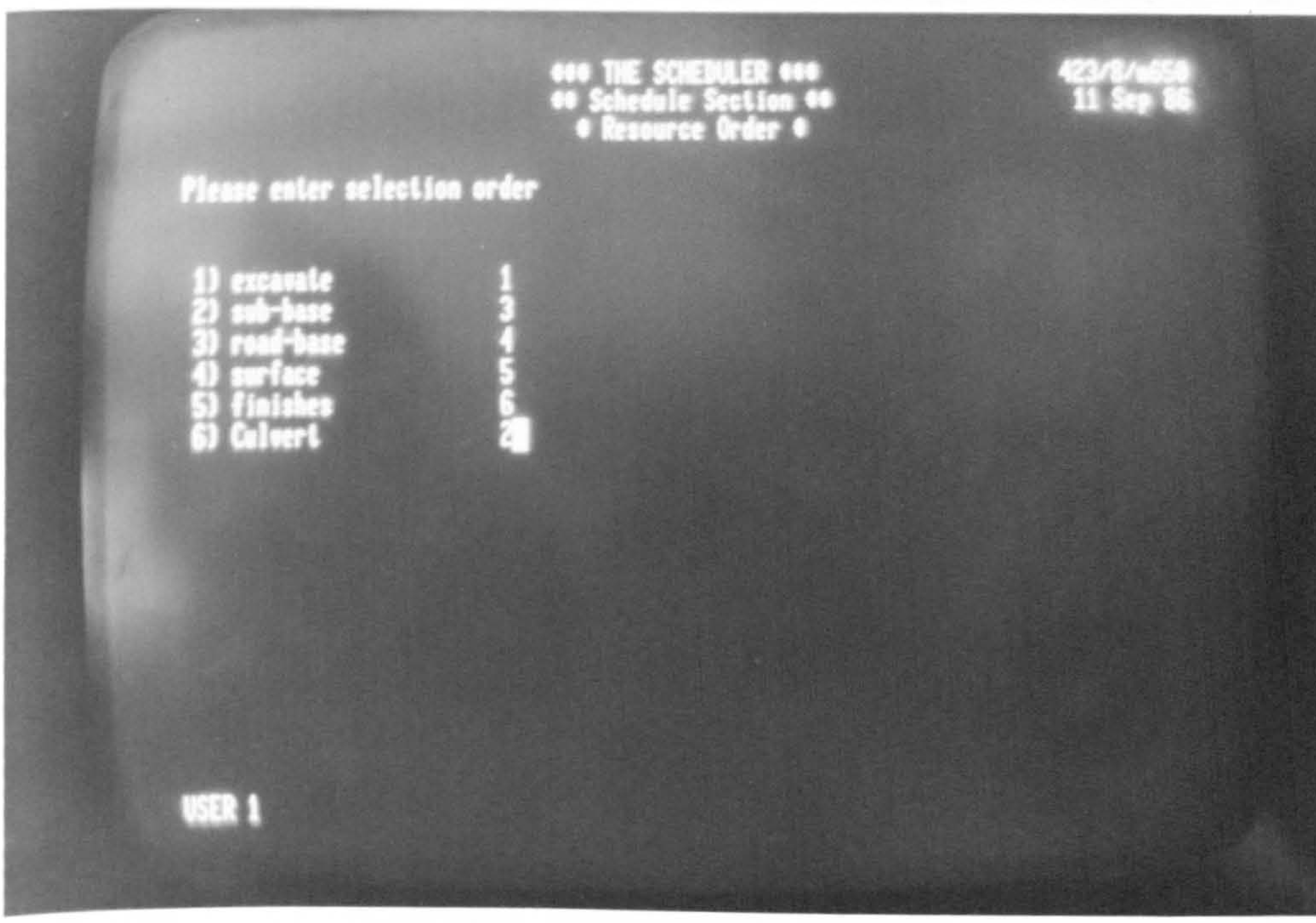


Plate 7 - Resource Allocation order input screen

8.2.8 The scheduler

During the schedule various information is displayed on the screens of the computer. Plate (8) shows one of the display screens which shows the start and finish information of the activities at any particular time.

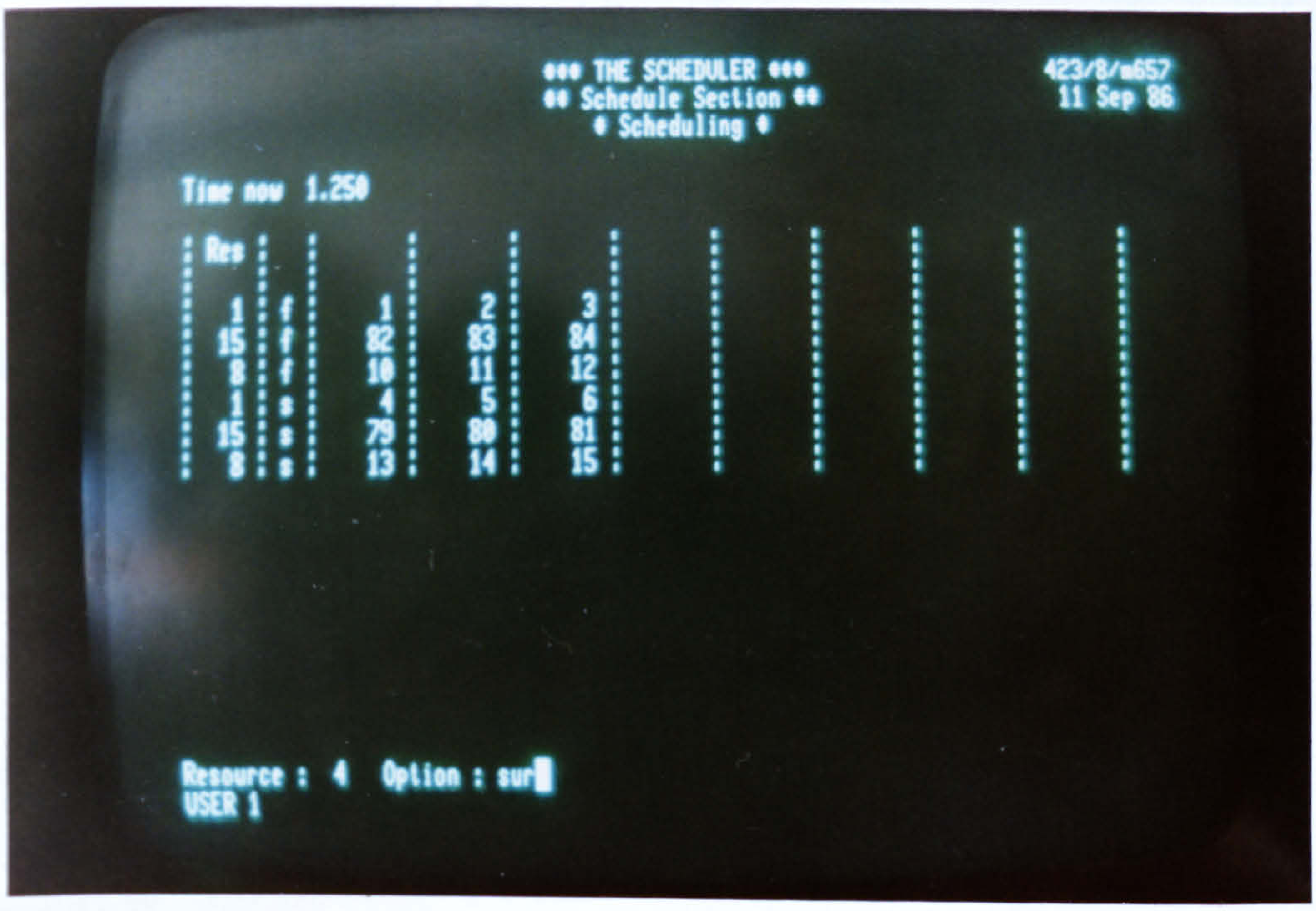


Plate 8 - Start and finish time information

Plate (9) shows a graphical representation of the road and culvert project. It shows the different resource teams moving about the site, and is useful in highlighting inefficiencies in resource movement during the schedule.

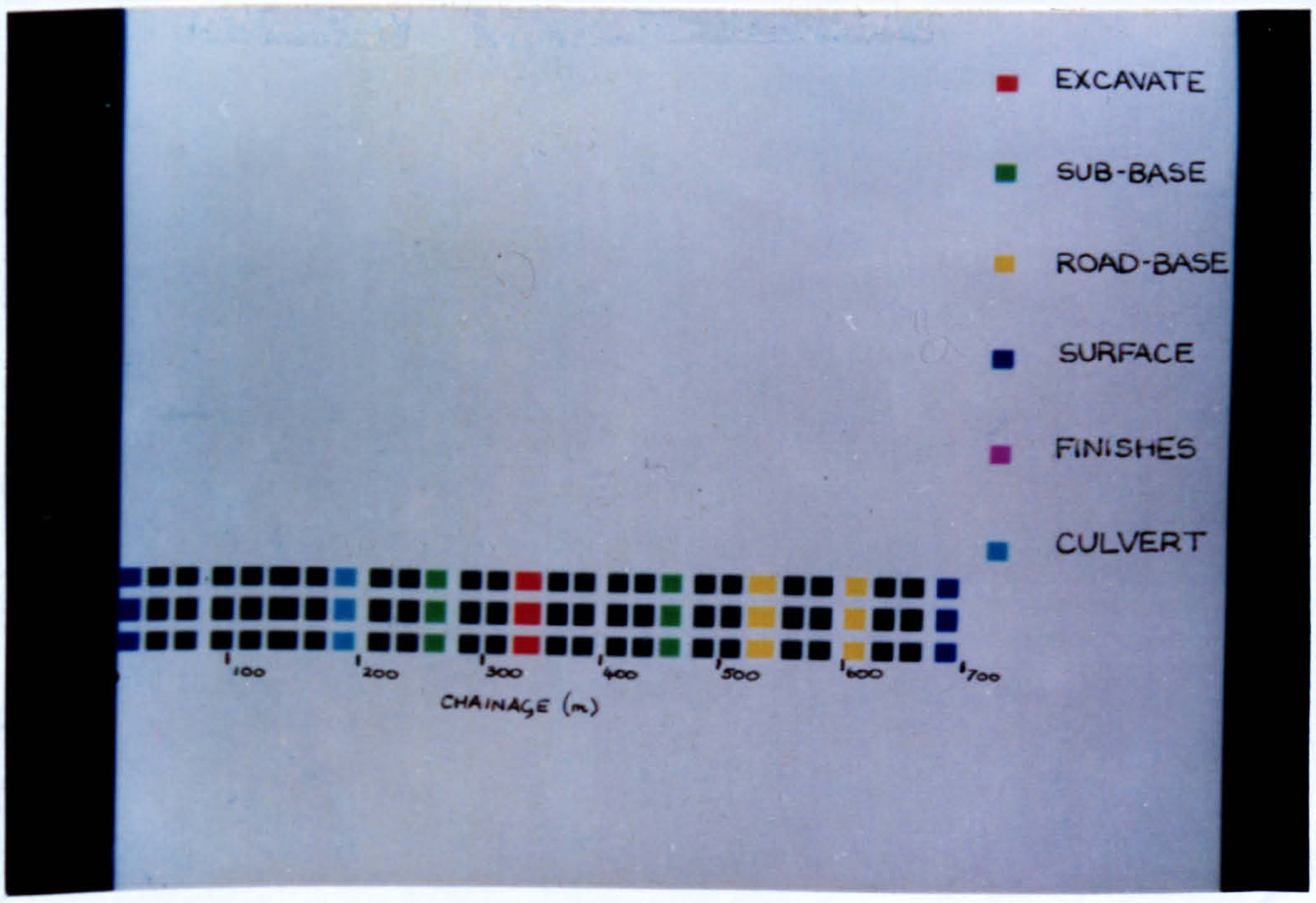


Plate 9 - Site map

The resultant information of a schedule is the start and finish time for each work element on the site and the resource utilisation.

8.3 The test runs

The aims of the test runs on the road and culvert example are to investigate the effects of:

a) Priority balance - section (8.3.2)
b) Optimum allocation size - section (8.3.3)
c) Resource allocation order - section (8.3.4)
d) Access - section (8.3.5)
e) Resource numbers - section (8.3.6)
f) Grid size - section (8.3.7)

on the plans produced by the scheduler. Many plans were produced, and they are all discussed in their relevant sections, as indicated above.

8.3.1 Performance indicators for the test runs

There are two ways in which the plans produced by the scheduler may be evaluated:

a) Quantitively
b) Qualitively

The quantitive measures of performance used to evaluate the test runs are the project duration and the resource utilisation. The project duration is simply calculated by finding the difference between the start time and the end time for the plan. The resource utilisation values are slightly more complicated to calculate. The method adopted is similar to the situation that occurs on a construction site, where a resource is hired when it is first required, and fired immediately after it is last used. The resource utilisation is then expressed as a percentage of the total work time and the total time on site (including idle time) for each resource.

The qualitive performance indicators are more difficult to define, as the aesthetic "goodness" of a plan is very subjective and often difficult to justify. One measure that one generally strives for in a plan is continuity in resource progress with minimum resource movement. This may be measured quantitively by considering the number of transfers for each resource team. A transfer may be defined as the movement of a resource to a non-adjacent area. Generally the higher the number of transfers the more "broken-up" the plan appears.

8.3.2 Priority balance test runs

Test runs 1-45 were carried out to investigate the effect of the priority balance on the plans produced by the scheduler. Of these, the time chainage charts for runs 1-36 are illustrated in appendix B, as figures (B1) to (B36). All the other diagrams referenced in connection with the priority balance test runs may be found at the end of this section.

Nine different priority balances were used for these test runs. They were:

Structure	Access	Resource	a/r	log10(1000*a/r)
0	1	100	0.01	1.00
0	1	10	0.10	2.00
0	1	5	0.20	2.30
0	1	2	0.50	2.70
0	1	1	1.00	3.00
0	2	1	2.00	3.30
0	5	1	5.00	3.70
0	10	1	10.00	4.00
0	100	1	100.00	5.00

The structure priority is held at zero because there is effectively only one structure being considered in this project.

The test runs were carried out with access at chainages 0 and 700 on a grid square size of 25m along the length of the road and 3 x 3m across the road. The following optimum distance allocations (in metres) were used for the runs.

Run	Exc	S-B	R-B	Surf	Fin
1- 9	50	25	25	50	25
10-18	100	50	50	100	50
19-27	25	25	25	25	25
28-36	50	50	50	50	50
37-45	100	100	100	100	100

8.3.2.1 Runs 1-9

This set of test runs were performed with optimum distance allocations set at 50m for the excavate and surfacing teams, and 25m for the sub-base, road-base and finishes teams. Figures (B1) to (B9) in appendix B show the time chainage chart for test runs 1-9. Figure (8.3.2.1.1) shows the plot of resource utilisation against priority balance. There is only a slight trend that is noticeable for this graph, with a small reduction in resource utilisation with higher (a/r) ratios. A peak in resource utilisation occurs for test run number 4 at (a/r) = 0.5 (or log10(1000*a/r) = 2.70). Test run 4 also exhibits the least number of transfers of (0,6,6,7,10) for excavate, sub-base, road-base, surface, and finishes respectively. These values represents 76.5% of the average number of transfers for runs 1-9.

The figure (8.3.2.1.2) is a graph of project duration against priority balance for all the test runs carried out in this section (i.e. runs 1-45). For runs 1-9 the minimum project duration occurs for run number 1 and is 43.33 weeks. Test run 4 compares reasonably favourably with a project duration of 43.58 weeks.

8.3.2.2 Runs 10-18

Figures (B10) to (B18) in appendix B show the time chainage charts for test runs 10-18. This set of runs were carried out with optimum allocation distances of 100m for the excavate and surface teams, and 50m for the sub-base, road-base and finishes teams.

Figure (8.3.2.2.1) is a plot of the resource utilisation for this set of test runs. Priority balance ratio of (a/r) = 0.5 again shows interesting characteristics. In this instance, however, a large trough in resource utilisation occurs. The corresponding time chainage chart, figure (B13), shows considerably less continuity in resource progression for this value of (a/r), with transfers of (0,7,6,3,6), which represents 119.3% of the average transfer values. In contrast, the minimum transfers of (0,4,4,3,5) occur for test run numbers 14-16, figures (B14) to (B16) in appendix B.

The minimum project duration for this set of test runs is 51.67 weeks for runs 14 and 18. This is illustrated graphically in figure (8.3.2.1.2). This is significantly larger than those obtainedin the previous section. It can be explained to a large extent by considering the effect of optimum distance allocations and buffers. Consider the time chainage charts for test run 1 (appendix B, figure (B1)) and test run 10 (appendix B, figure B(10)). In test run 1 the sub-base may follow the excavate by 50m with no discontinuities in its progression. In test run 10, the sub-base may also follow the excavate by 50m, but the optimum distance allocation of 100m for the excavate results in the sub-base progression being discontinuous. This first occurs at chainage 50-100 at time 7.5-10.0 weeks. This discontinuity will occur wherever smaller allocation distance resources follow those with larger allocation distances. This feature is discussed in more detail in further test runs.

8.3.2.3 Runs 19-27

Runs 19-27 were carried out with optimum distance allocations set at 25m for all the resources. Appendix B, figure (B19) to (B27) show the time chainage charts for test runs 19-27. Figure (8.3.2.3.1) is a plot of the resource utilisation for these runs. The irregularities at priority balance ratio (a/r) = 0.5 are not as pronounced as those in previous runs, although they are still apparent. The project durations are almost uniform across the set of test runs with a minimum of 39.17 weeks occuring for runs 24-26, as illustrated in figure (8.3.2.1.2).

The number of transfers for this set of runs, with the exception of run 23, are all within a smaller tolerance. The time chainage chart for run 23 (figure (B23)), is significantly more discontinuous than those for the other runs in this set, and consequently exhibits a large number of transfers. The reason for the high number of transfers for this run may be due to the interference of the two sets of resource teams which occurs around chainages 300 - 450.

The uniformity of results across this set of runs may be attributed to the resource teams uniform optimum allocation distances. In the previous two sets of runs, interference may have occured because of mis-matched resource allocation sizes.

It is interesting, at this stage to compare the time chainage charts for test runs 19-27 with the line of balance chart (figure (4.4.4) that was produced in the work on the extended line of balance method in chapter 4. Although direct quantitive comparisons may not be made because of the different assumptions made for each model, the general shape of the charts may be compared. The overlay to figure (B25), shows how the scheduler has produced satisfactory line of balance style charts, with a degree of similarity to the previous charts.

8.3.2.4 Runs 28-36

Runs 28-36 were carried out with optimum distances of 50m for all the resource teams. The corresponding time chainage charts are illustrated as figures (B28) to (B36) in appendix B.

This set of runs also exhibits very uniform results. The lowest project duration occurs for runs 28-30 and is of 45.83 weeks, which may be seen graphically in figure (8.3.2.1.2). The transfer values are also not subject to any major variations, although a minimum is obtained for run 32.

Figure (8.3.2.4.1) is a plot of the resource utilisation for runs 28-36. The resource utilisation is relatively uniform across the nine priority balances, with a slight peak occuring around the priority balance ratio of (a/r) = 0.5.

8.3.2.5 Runs 37-45

This set of test runs were performed with the optimum distance allocation for all resources set at 100m. The time chainage charts are not illustrated, although the resource utilisation and project duration information is displayed in figures (8.3.2.5.1) and (8.3.2.1.2) respectively.

The most striking feature of the resource utilisation values are their large fluctuations. These fluctuations all occurin the test runs where the resource priority was dominant (i.e. with low (a/r) ratio values). This is surprising as one would expect generally low and fluctuating resource utilisations in situations where the resource priority is not dominant. The reason for this is that the plans produced from runs 41 to 45 are identical. This apparent cut off or step in the graph is noticeable in many of the previous sets of runs, and is due to the priority balance not changing the overall priority map sufficiently to alter the decisions made by the scheduler. The resource utilisation figures therefore generally exhibit large fluctuations.

The project durations are, as expected, higher than those in previous runs, and also show the characteristic fluctuation at priority balance ratio (a/r) = 0.5.

8.3.2.6 Conclusions of the priority balance runs

The most important feature of the priority balance test runs is the peak or trough that occurs in both the resource utilisation and the project durations around the priority balance ratio (a/r) = 0.5. This characteristic may be explained when one considers the values of the respective priorities at this priority balance.

The access priorities at the ends of the road (chainages 0 and 700) are 255, and they fall to 1 at chainage 350. Consequently there is a difference of (255-1)/14, which is approximately 18, across one grid square along the length of the road.

Similarly, the drop across one grid square along the length of the road for the resource priority is (255-1)/28 which is approximately 9.

When these values are multiplied by their respective priority balances they become:

18*0.33 = 6 for the access priority

9*0.67 = 6 for the resource priority.

This equality in the difference in priority values across one grid square along the length of the road will either serve to hinder or help production. This may be explained as follows:

Consider a resource team working from chainages 350 to 700 (i.e. towards higher access priority). For this resource team, a priority balance of (a/r) = 0.5 will make all the priority values from chainage 350 to 700 equal. Usually, however, two resource teams work from chainage 0 and from chainage 700, until interference occurs between them at around chainage 350. One of the teams then becomes dominant over the other by virtue of the resource allocation order. The equality in the priority difference will either have the effect of producing a transfer, as occured in figure (B23) with the sub-base team, or not, which occured with the sub-base team in figure (B24). These different strategies have the effect of producing these fluctuations. The effect of this type of transfer may have been more suitably highlighted if non-zero transfer times had been considered for this set of runs. The inclusion of these, and other features, however, may have complicated what was intended as a simple illustration of the working of the scheduler.

Outside of the area of fluctuation there seems to be no significant trends in either the project durations, resource utilisation or transfer values. Again, the inclusion of non-zero transfer times may have improved the more heavily resource priority weighted schedules in comparison with the access weighted schedules.

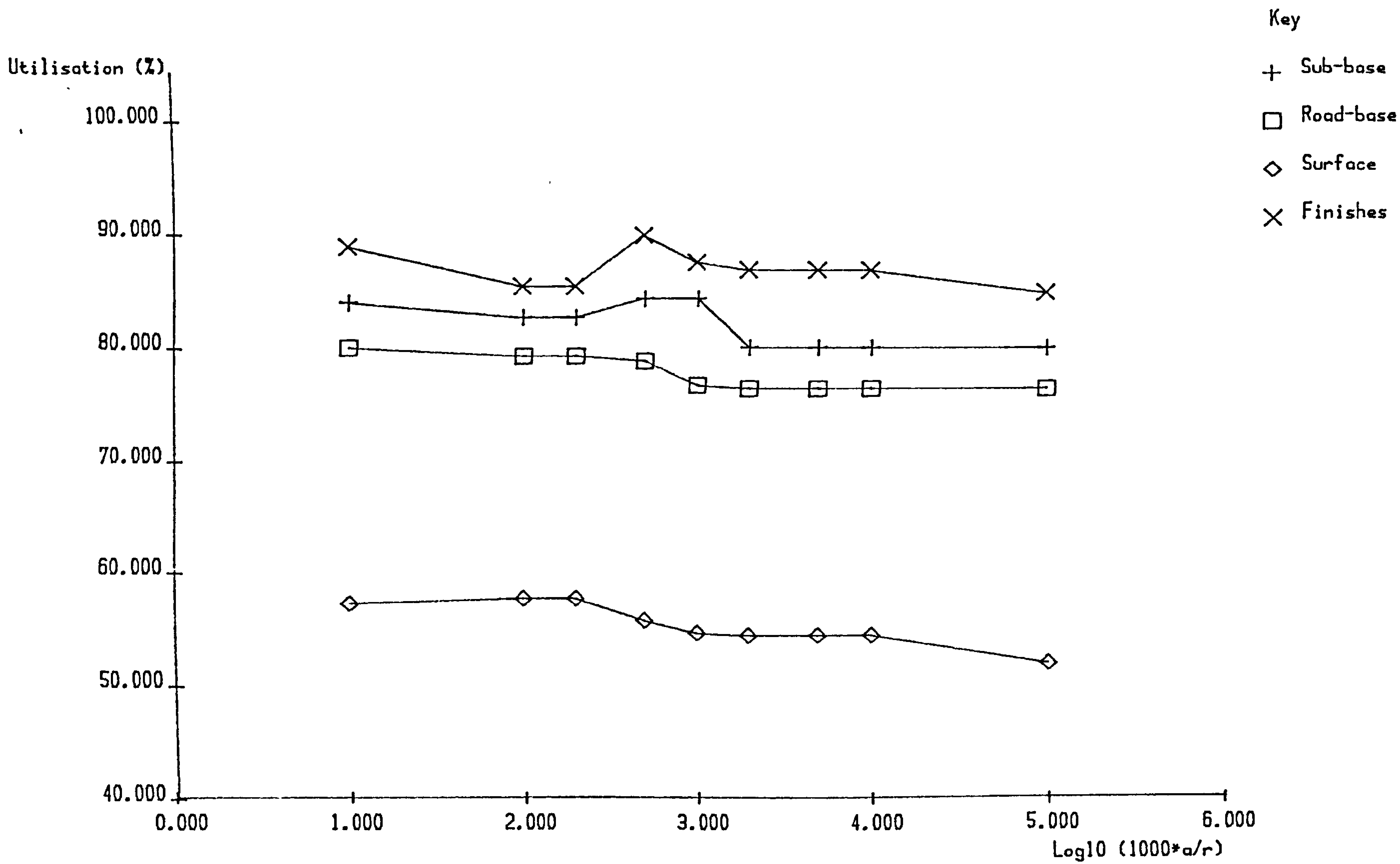


FIGURE NUMBER (8.3.2.1.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 1 - 9

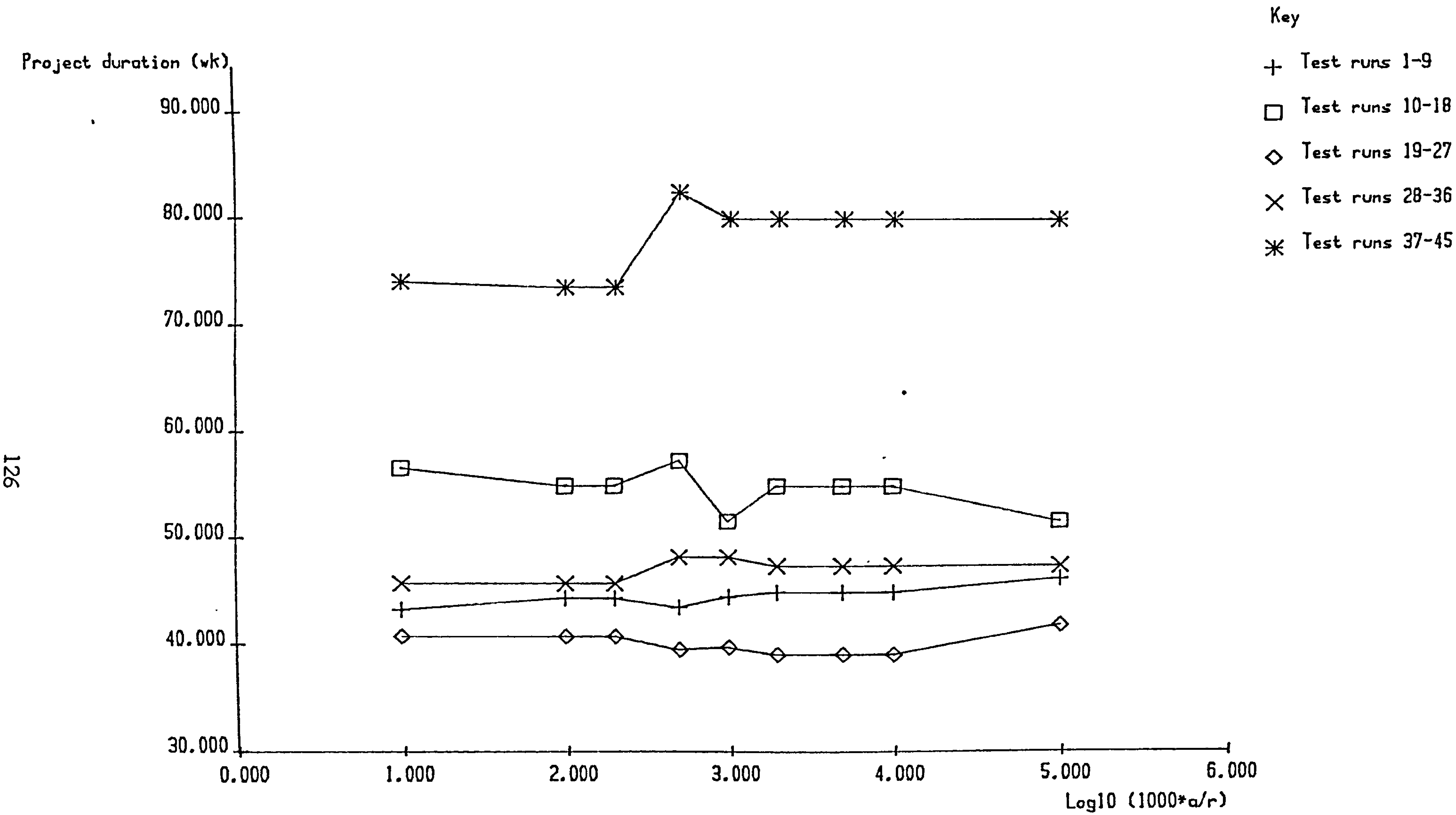


FIGURE NUMBER (8.3.2.1.2) PROJECT DURATION against PRIORITY RATIO

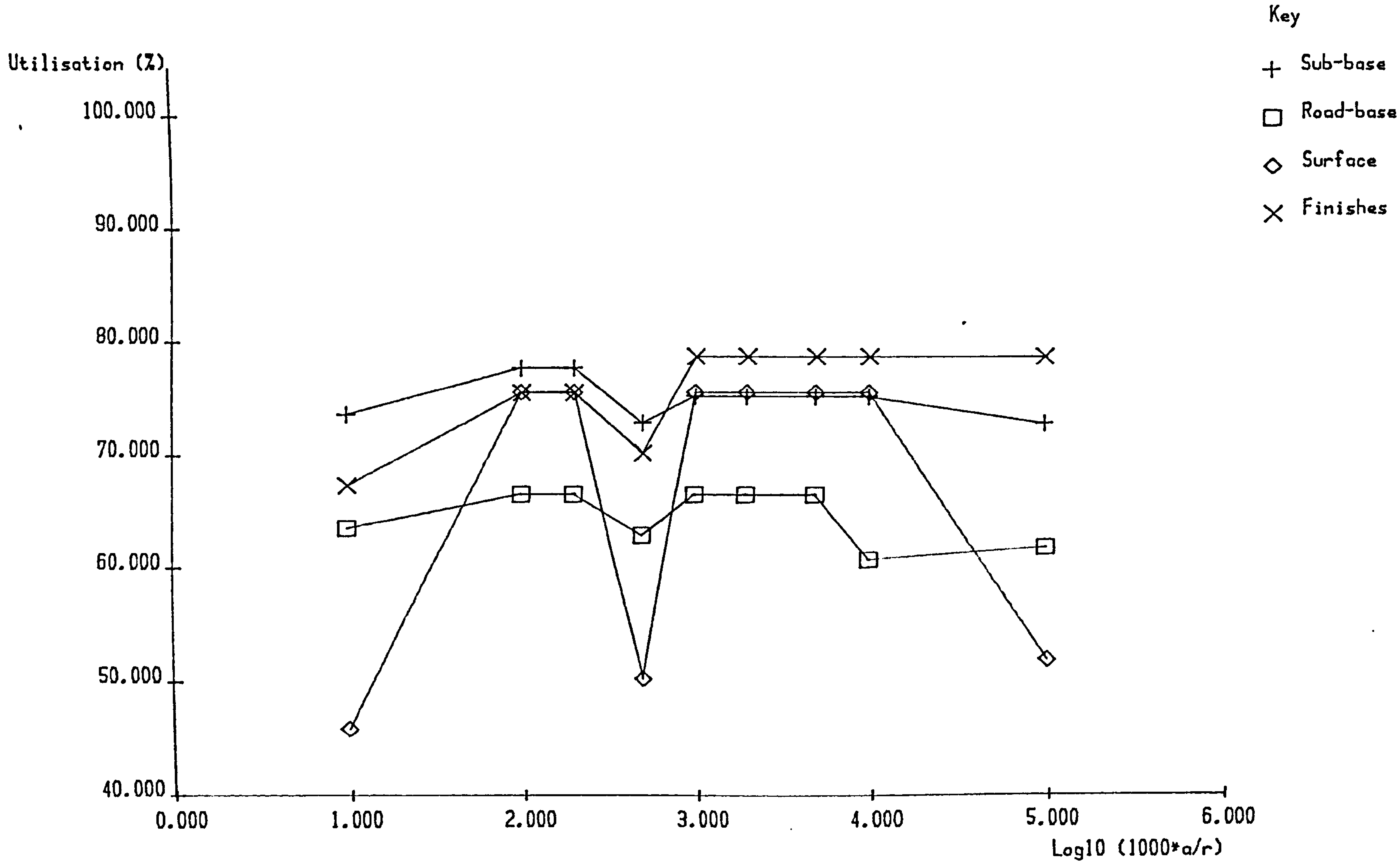


FIGURE NUMBER (8.3.2.2.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 10 - 18

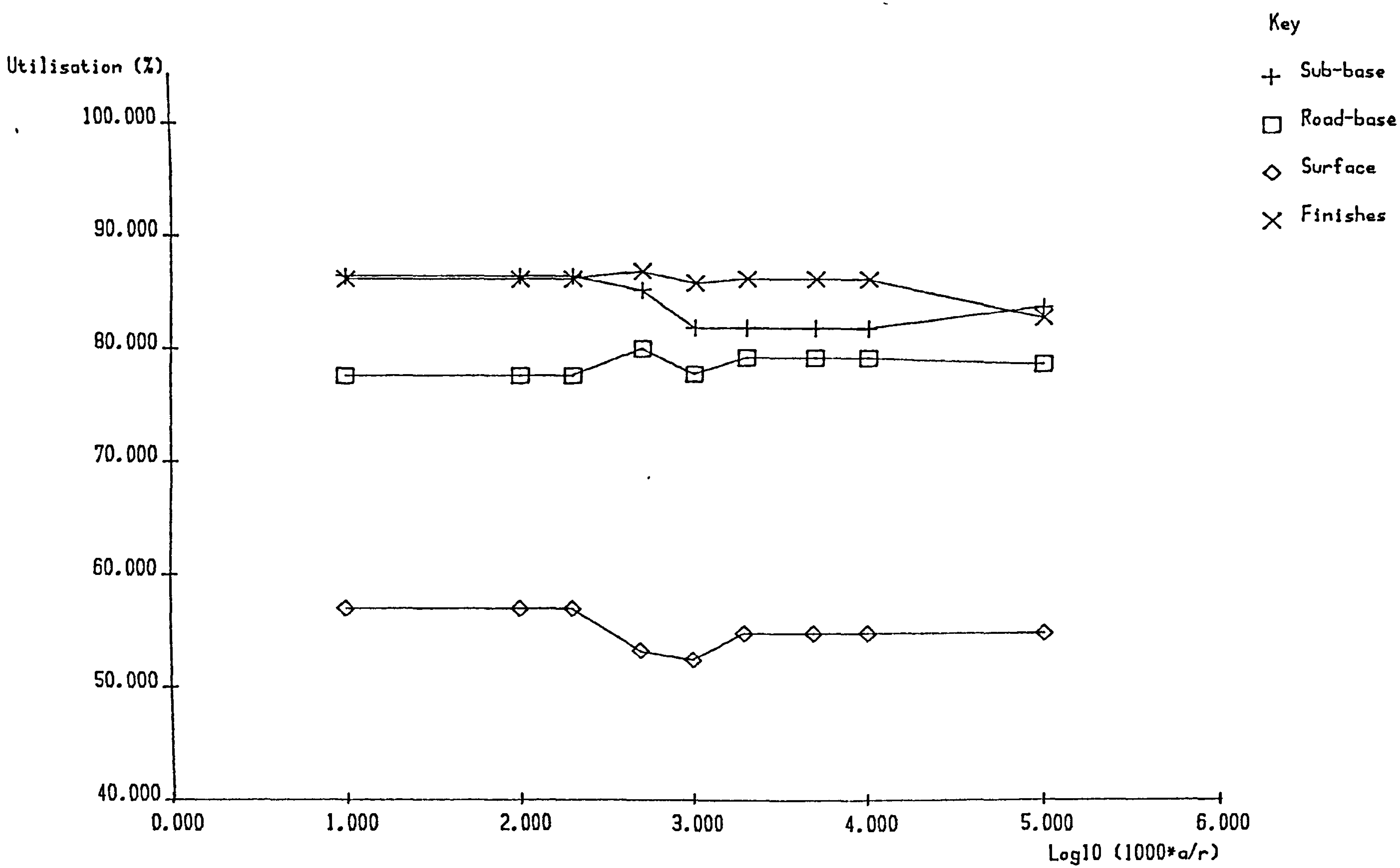


FIGURE NUMBER (8.3.2.3.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 19 - 27

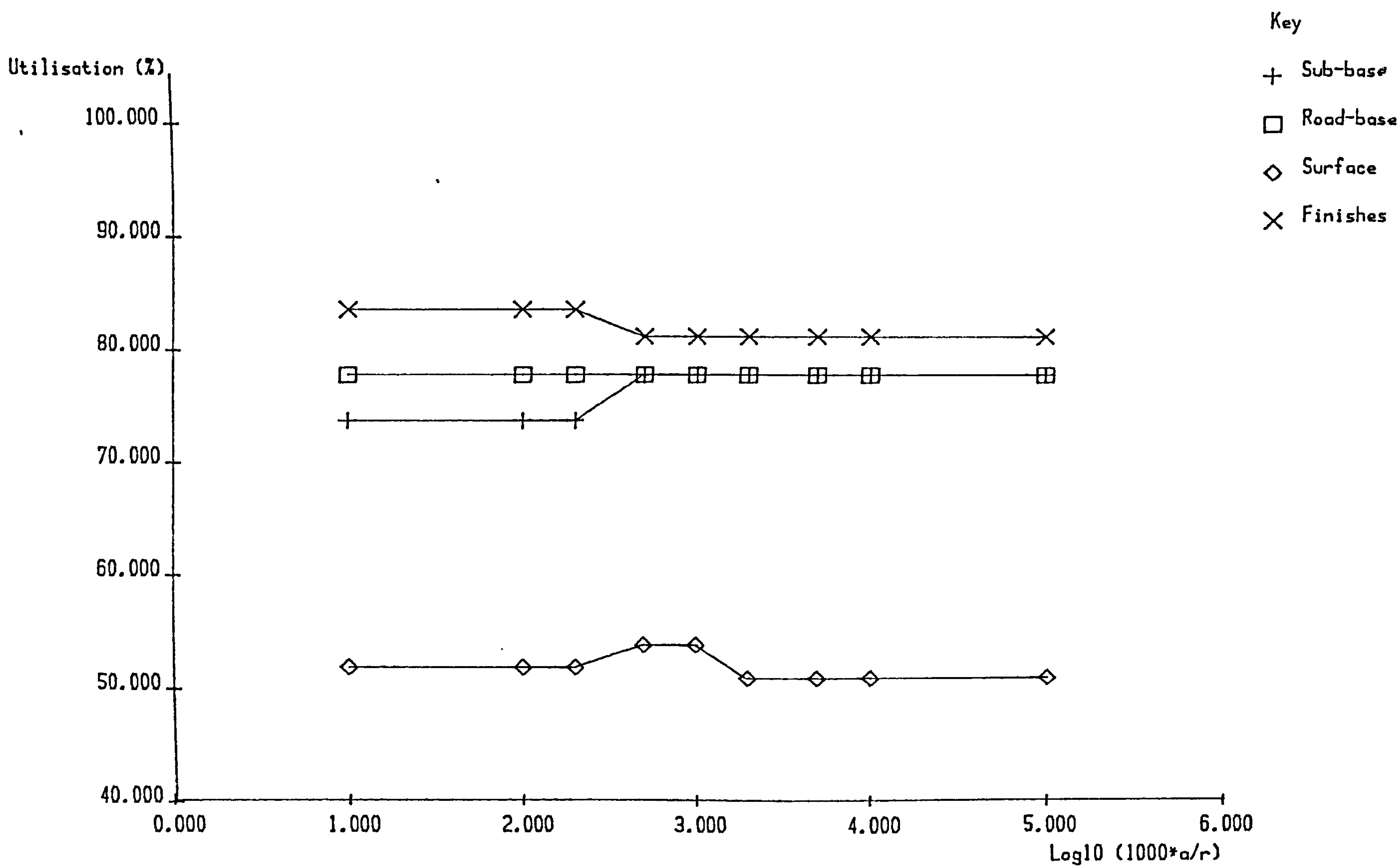


FIGURE NUMBER (8.3.2.4.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 28 - 36

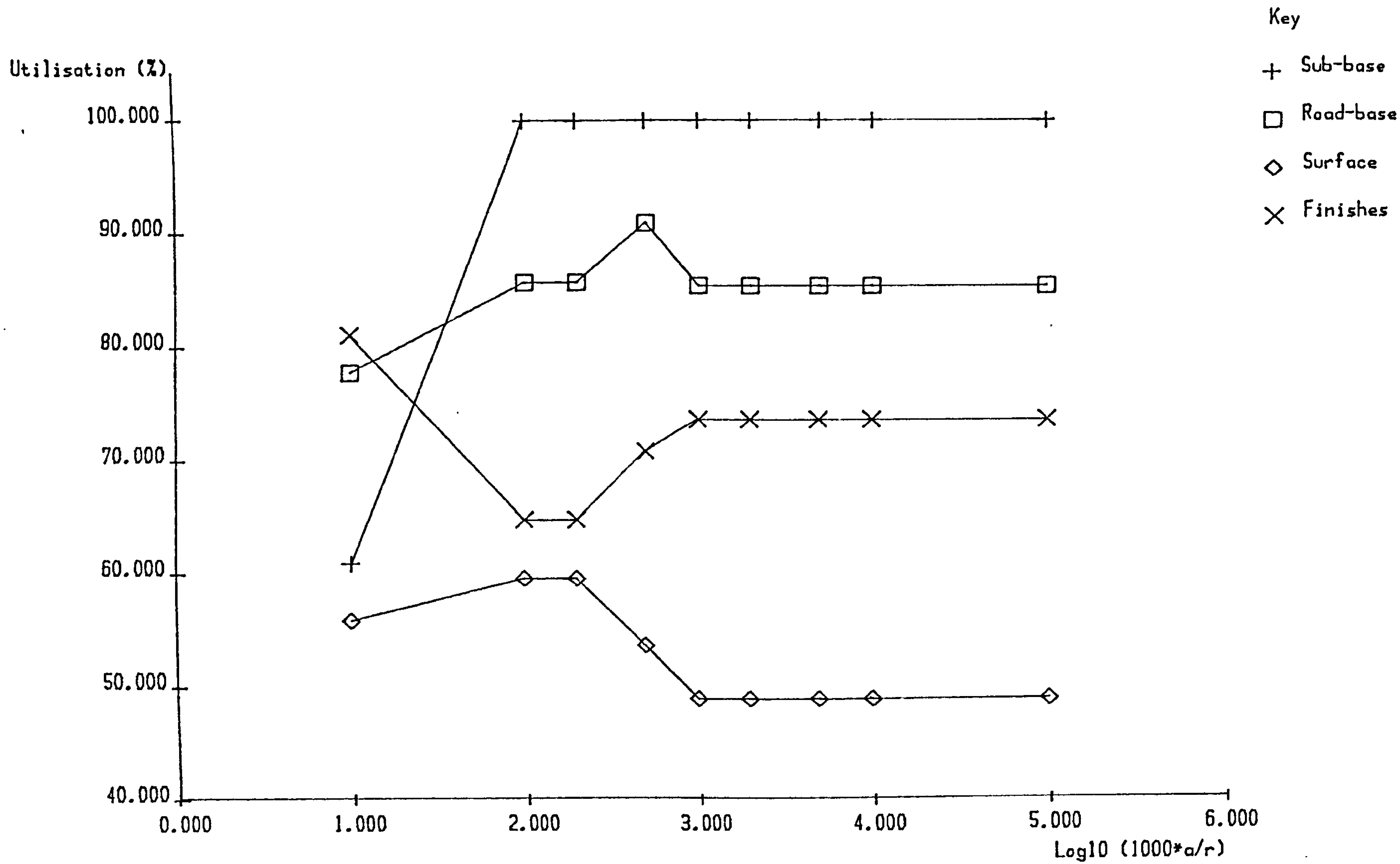


FIGURE NUMBER (8.3.2.5.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 37 - 45

8.3.3 Optimum allocation distance test runs

The preceeding series of test runs (runs 19-45) provided the necessary information to illustrate the effect of the optimum allocation distances on the plans produced by the scheduler. Figure (8.3.3.1) shows the average resource utilisation for the optimum allocation distances of 25m, 50m and 100m, and figure (8.3.3.2) shows the average project duration also for distances of 25m, 50m and 100m. These figures may be found at the end of this section.

The resource utilisation values do not have any significant trends, although with the "hire and fire" policy for the resource utilisation calculations this is perhaps not unexpected.

The project duration for the 3 optimum allocation distances does follow a distinct trend, with project duration increasing with increased allocation distance. The reason for this trend is illustrated by considering figure (B19) in appendix B, for 25m allocations, and figure (B28) for 50m allocations. In both examples the sub-base team follow the excavate teams by 50m. In figure (B19), this distance buffer represents a time difference between the teams of 3.75 weeks. In figure (B28), however, this 50m distance buffer represents a time lag of 5.00 weeks. This delay is due to larger areas of the site being worked on at any one time. The plans produced with smaller allocation distances therefore tend to have a more continuous progression or "roll-over".

In the line of balance work carried out in chapter 4, the work by the resource was assumed to be carried out in a continuous manner with the work at any elemental chainage being performed instantaneously. This work is thus represented as a single line on a line of balance chart. The project durations produced (ignoring drainage) in the line of balance work as illustrated in figures (4.3.6) and (4.4.4) were 37 and 38 weeks respectively. Extrapolation of the line in figure (8.3.3.2) to a similar optimum allocation distance of zero yields projects durations of around 37-38 weeks. This is significant because it illustrates that certain assumptions made in the formation of the scheduling model produce increased project durations. It may be argued that the instantaneous roll-over, which is assumed in the line of balance method, is an unreal situation for many resources and work types on a construction site. Johnston (32) discussed this with reference to earthworks in highway construction (see chapter (3)), where plant such as scrapers take a finite time to complete work at any chainage. Other plant, such as road surfacing plant, however, does approach continuous production of work, with the surfacing team moving slowly but without interruption along the road.

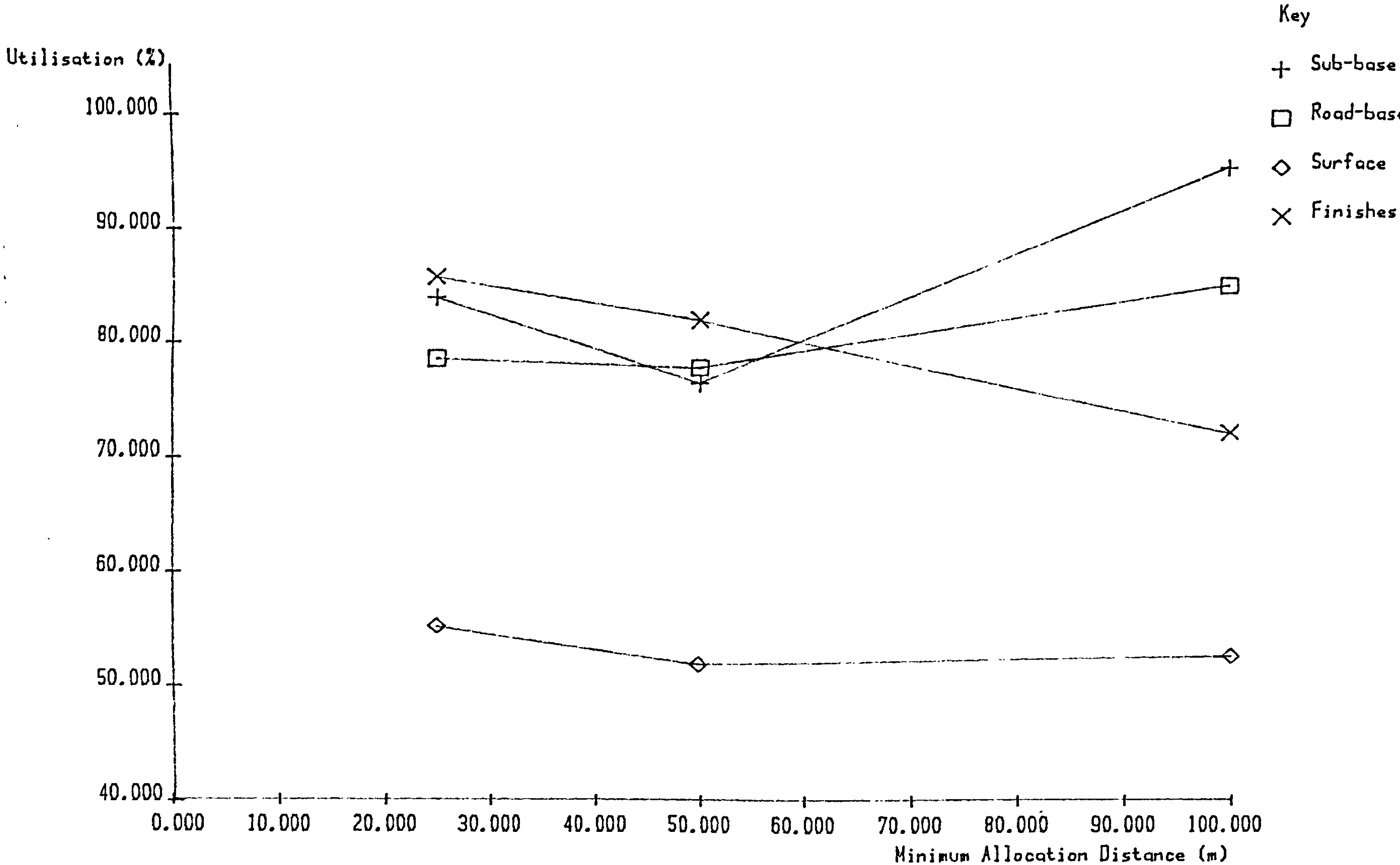


FIGURE NUMBER (8.3.3.1) AVERAGE RESOURCE UTILISATION against RESOURCE MINIMUM ALLOCATION DISTANCE

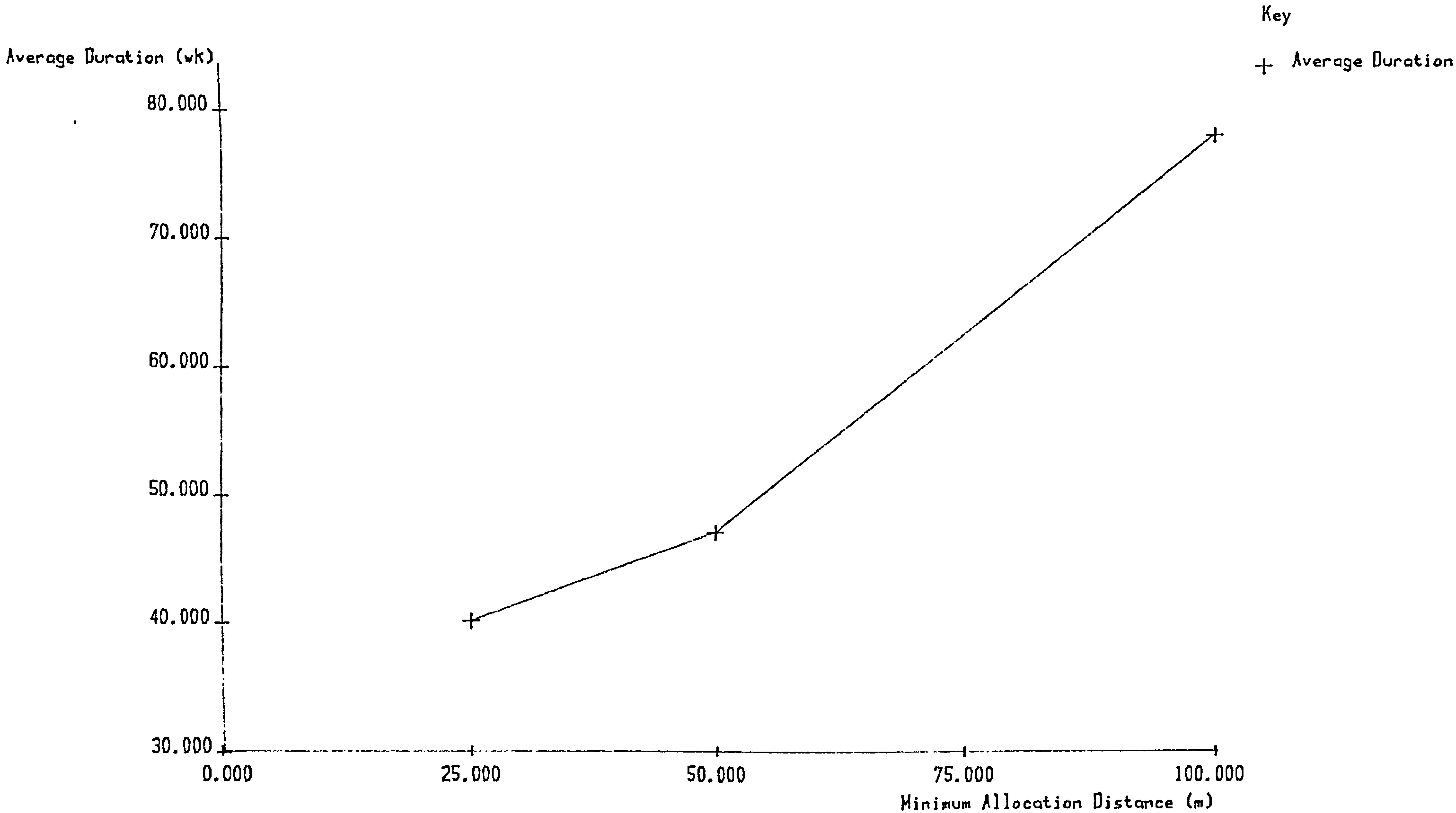


FIGURE NUMBER (8.3.3.2) AVERAGE PROJECT DURATION against RESOURCE MINIMUM ALLOCATION DISTANCE

8.3.4 Resource allocation order test runs

Test runs 46-54 were performed to investigate the effectof the resource allocation order on the plans produced by the scheduler. The allocation order adopted for all the previous runs was excavate, culvert, sub-base, road-base, surface and finishes (as illustrated in plate (7)). The allocation order for test runs 46-54 was changed to culvert, excavate, sub-base, road-base, surface and finishes. The change in the allocation order does not affect the order of work in the work arrays containing culvert work, however, as the excavation still has to precede the culvert work. Where the culvert work and excavation occur in adjacent grid squares, however, the culvert work will take precedence.

Figures (8.3.4.1) and (8.3.4.2), at the end of this section, illustrate the resource utilisation values and the project durations respectively over a range of priority balances. These show a large degree of similarity with those produced for test runs 19-27 (i.e. with the original allocation order). This is probably due to the ability of any resource to move to any other active areas outside the interference zones of other working resources, allowing for maximum resource usage.

The minimum number of transfers occurs for runs 46-48 and is similar to the value obtained for test runs 19-27. On the whole, however, the average number of transfers generally are significantly larger than those for test runs 19-27. Comparisons of the time chainage charts in appendix B, figures (B46) to (B54) with figures (B19) to (B27), confirm this, with significant discontinuities occuring around chainage 200. These discontinuities are caused by the culvert work being allocated before the earthworks around chainage 200.

The value of this set of runs is not in the plans produced, as they are generally inferior to those produced in earlier runs, but the demonstration that the scheduler is able to respond to different influences and information.

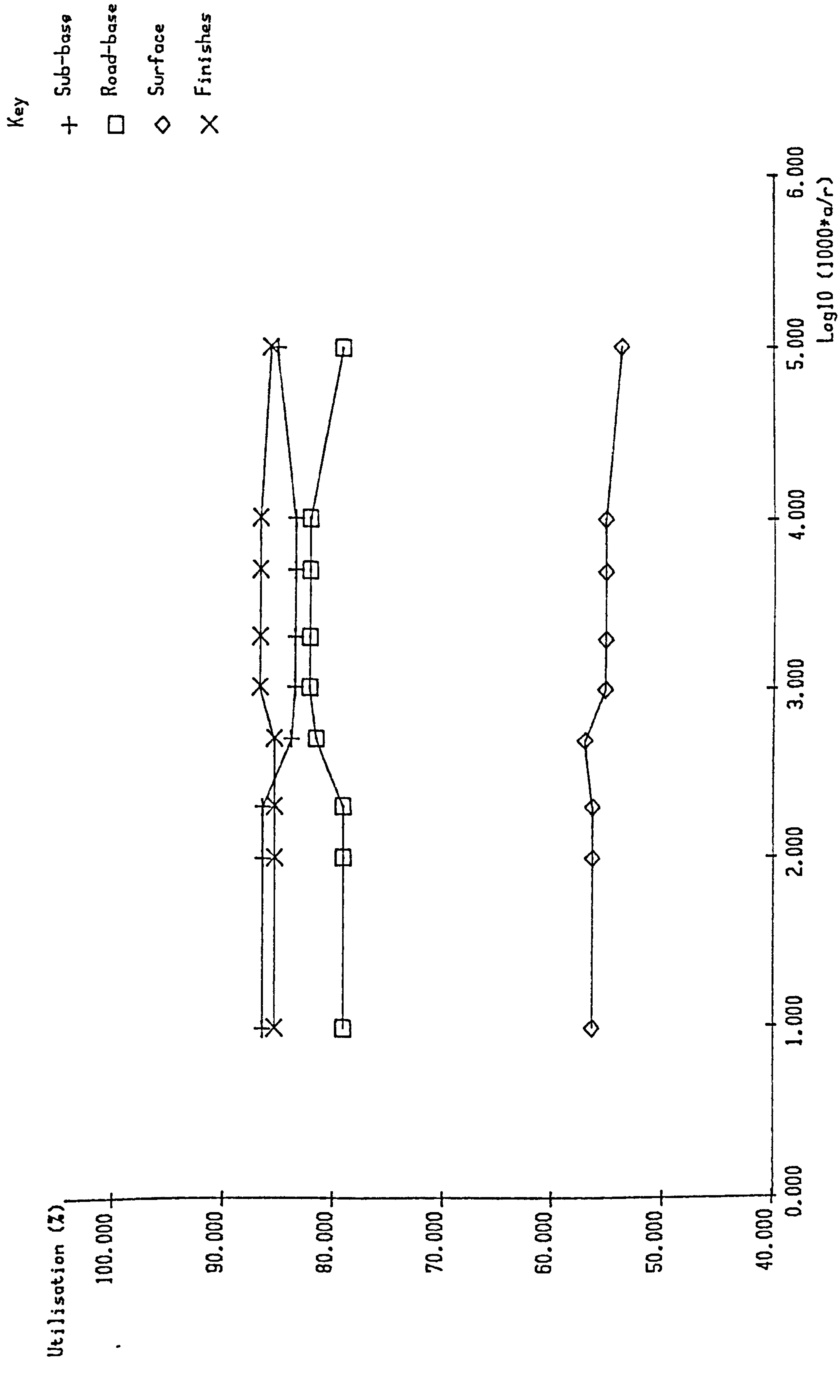


FIGURE NUMBER (8.3.4.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 46 - 54

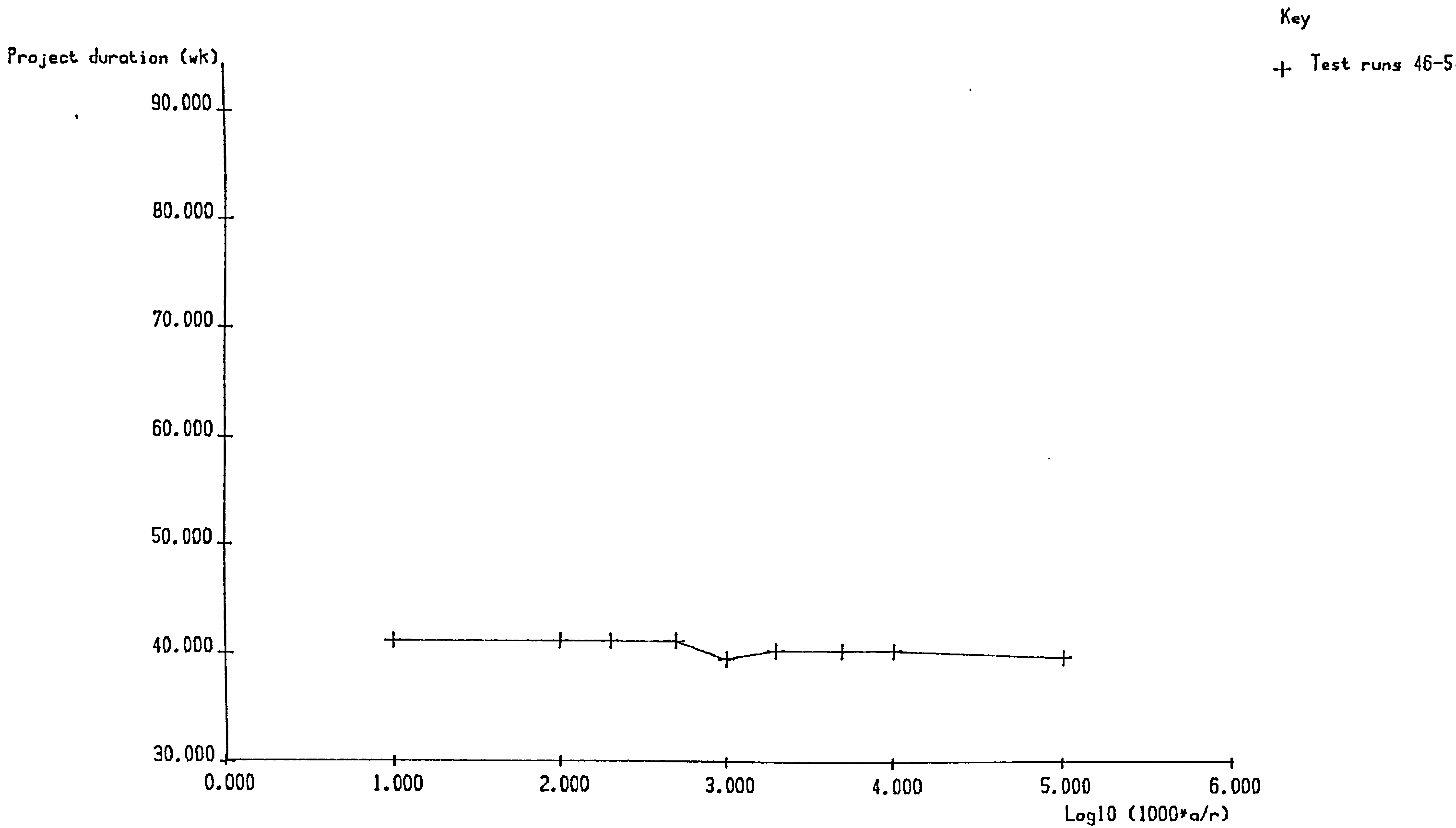


FIGURE NUMBER (8.3.4.2) PROJECT DURATION against PRIORITY RATIO

8.3.5 Access position test runs

Two sets of test runs were performed to investigate the effect of different access positions. For the first set, test runs 55-63, access was provided at chainages 200 and 700, and for the second set, test runs 64-72, access was provided at chainages 0 and 400. They were carried out with the original resource allocation order of excavate, culvert, sub-base, road-base, surface, finishes, and a optimum allocation distance for all the resources of 25m. Direct comparisons with runs 19-27 may therefore be made.

8.3.5.1 Runs 55-63 - Access at chainages 200 and 700

Figures (8.3.5.1.1) and (8.3.5.1.2) are the plots of resource utilisation and project duration for test runs 55-63, and may be found at the end of this section. Figures (B55) to (B63) in appendix B are the time chainage charts for these runs.

The resource utilisation plots, figures (8.3.5.1.1) and (8.3.2.3.1) for runs 55-63 and 19-27 respectively, have significantly different forms. Test runs 55-63 generally have a much higher average utilisation figure, coupled with a much larger variation.

Comparison of the project duration plots, figures (8.3.5.1.2) and (8.3.2.3.1), for test runs 55-63 and 19-27, shows that the new access patterns produce marginally higher values for the project durations.

The higher project durations and higher resource utilisation for runs 55-63 may appear to be incongruous, although may be explained by considering the time chainage charts for these runs. These charts may be found in appendix B, figures (B55) to (B63).

It is possible to identify three distinct strategies that were adopted by the scheduler in the test runs.

The first strategy is illustrated in figures (B55) to (B57) and consists of the resource teams working from chainage 700 towards lower chainages, and from chainage 200 also towards lower chainages. This may be summarized for the excavate and culvert work as shown in figure (8.3.5.1.3).

The second strategy is shown in figure (B58), and consists of the resource teams working from chainages 200 and 700 towards chainage 450. This is illustrated in figure (8.3.5.1.4).

The final strategy is exhibited in the remaining time chainage charts, figures (B59) to (B63). This strategy is what may be called "leap-frogging", as it consists of the resource teams continually changing from one position to another. Figure (8.3.5.1.5) shows the simplified chart for the leap-frogging strategy.

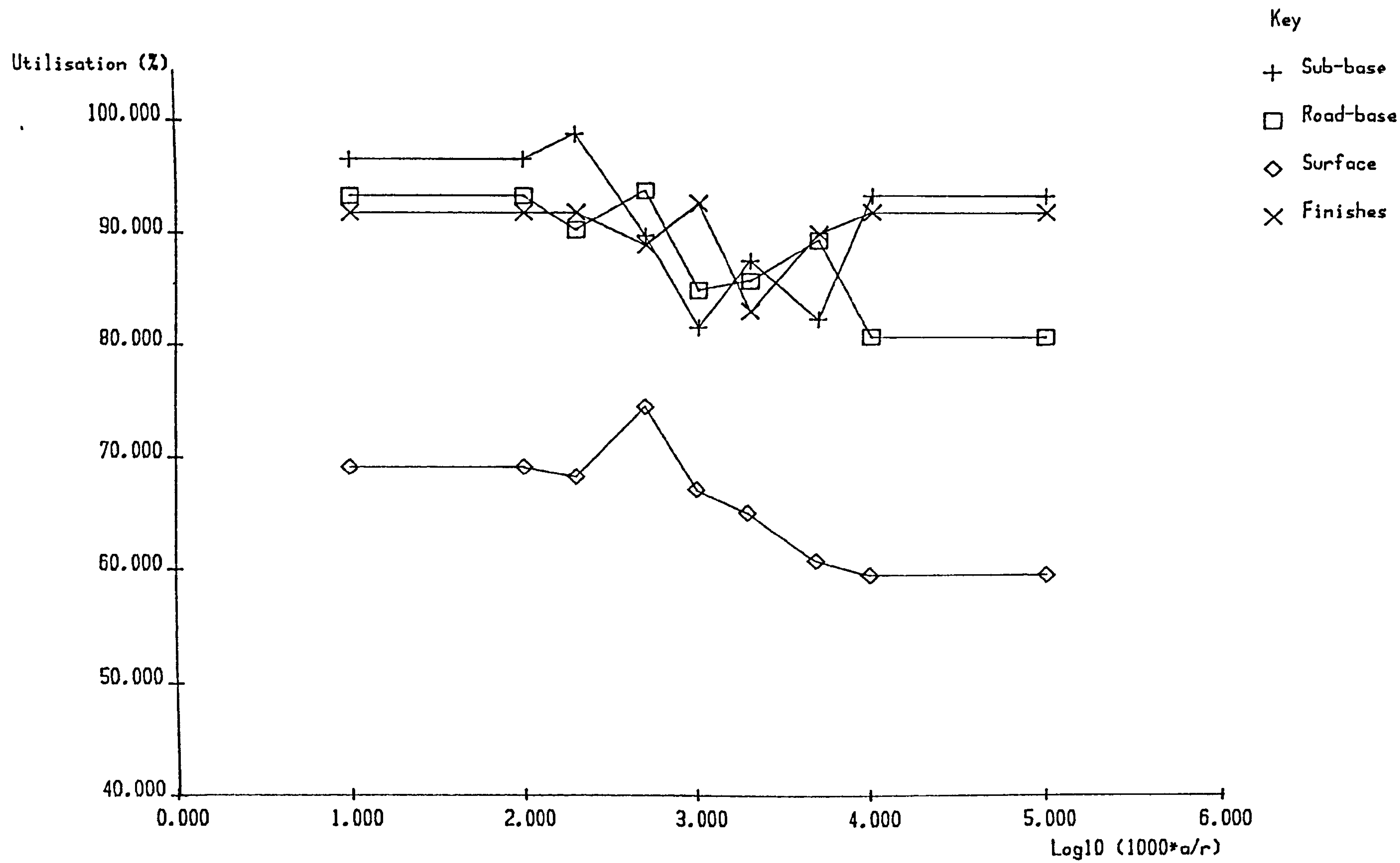


FIGURE NUMBER (8.3.5.1.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 55 - 63

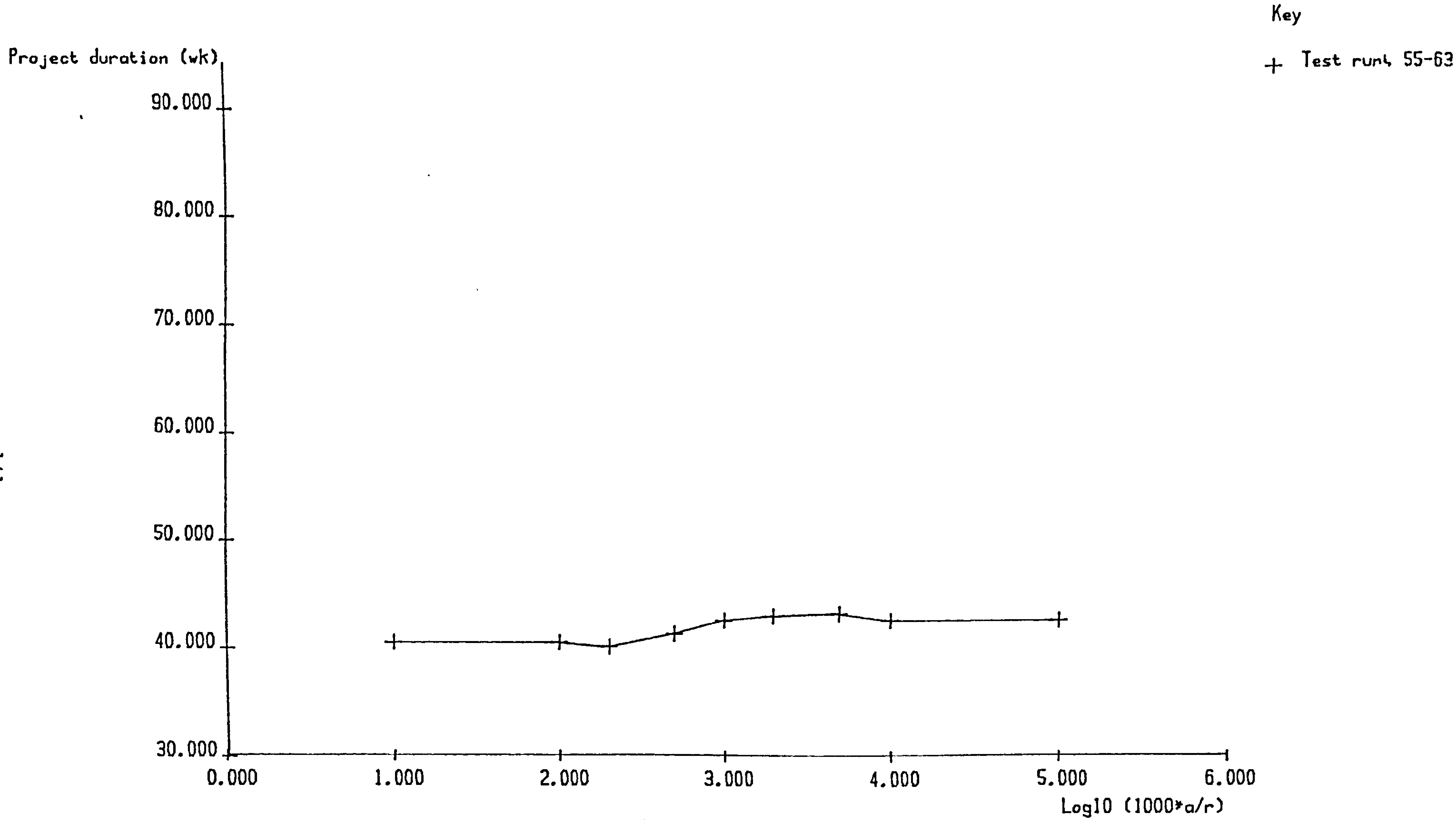


FIGURE NUMBER (8.3.5.1.2) PROJECT DURATION against PRIORITY RATIO

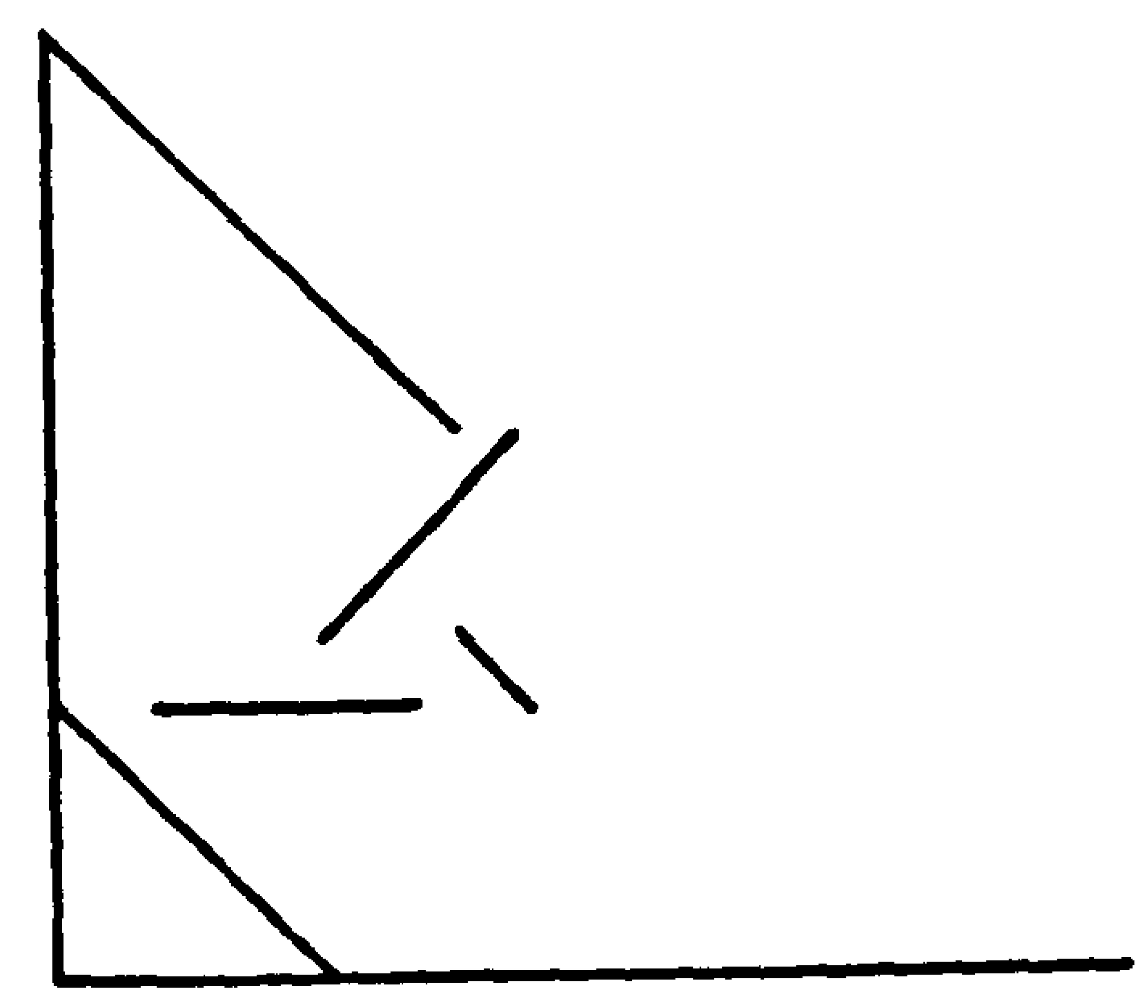


Figure (8.3.5.1.3) Strategy 1

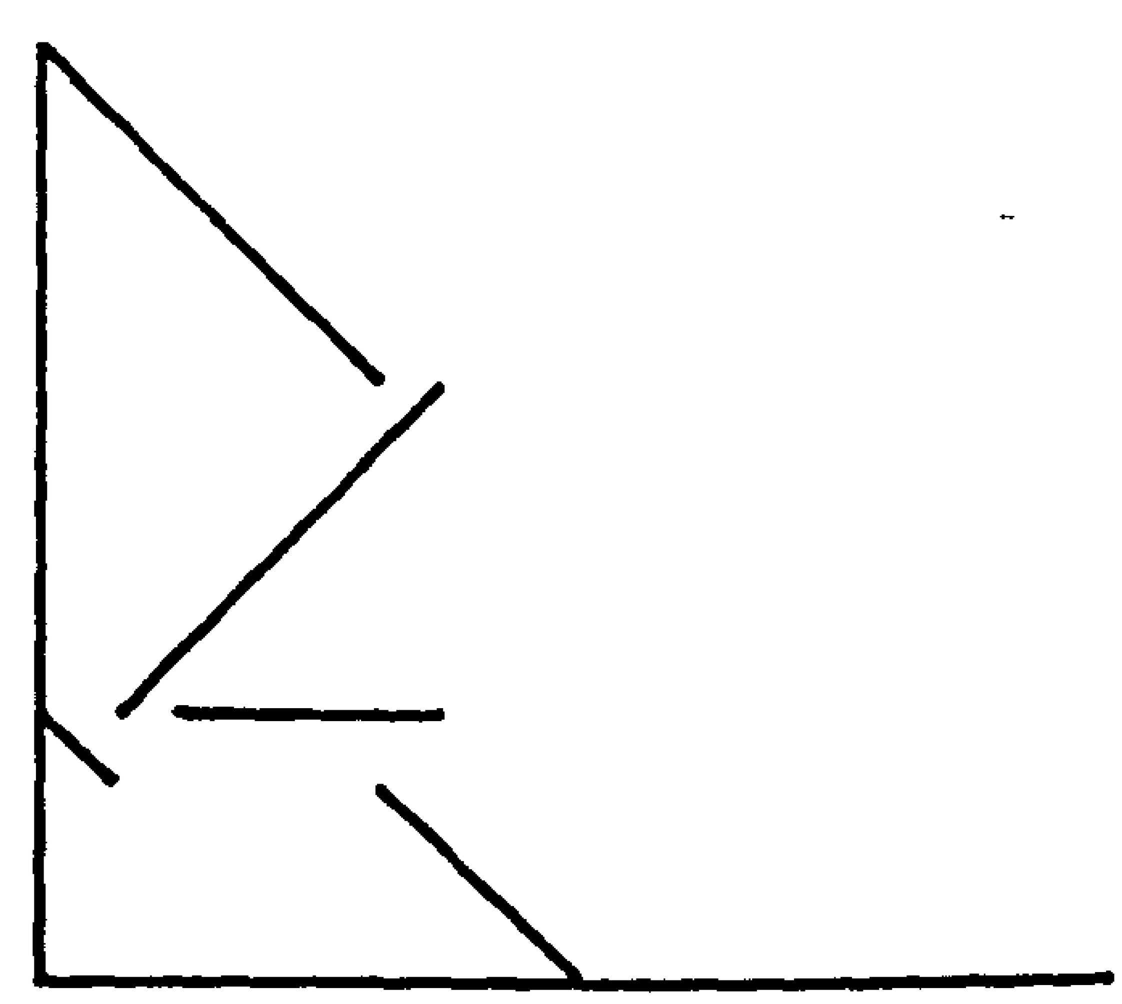


Figure (8.3.5.1.4) Strategy 2

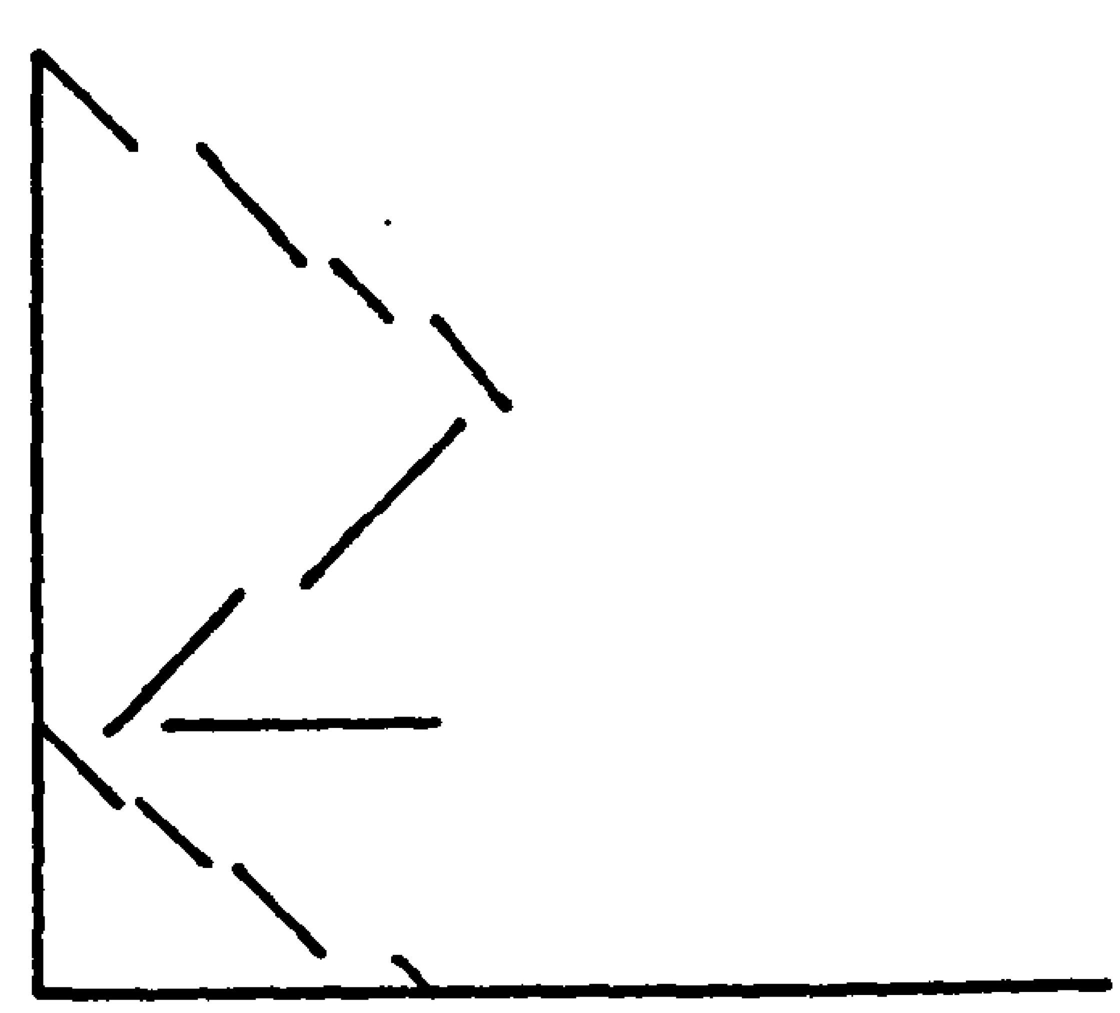


Figure (8.3.5.1.5) Strategy 3

8.3.5.2 Runs 64-72 - Access at chainages 0 and 400

Figures (8.3.5.2.1) and (8.3.5.2.2) show the resource utilisation and project duration plots respectively, for test runs 64-72, and are situated at the end of this section.

The resource utilsation values again show a high degree of variation, although do not exhibit such high average values as those obtained for the previous set of runs. The average utilisation values are closer in value to those produced for test runs 19-27, as shown in figure (8.3.2.3.1).

The project duration values for this set of runs are around 40-41 weeks, with very little variation across the nine different priority balances.

The time chainage charts, figures (B64) to (B72) in appendix B., also exhibit three different strategies. The first of these is illustrated in figures (B64) to (B66) and may be summarised as in figure (8.3.5.2.3). The second may be found in figure (B67) and is further illustrated in figure (8.3.5.2.4). The final strategy is the leap-frogging strategy and is shown in figures (B68) to (B72), although it is best illustrated in figures (B71) and (B71). Figure (8.3.5.2.5) is a simplified diagram of this strategy.

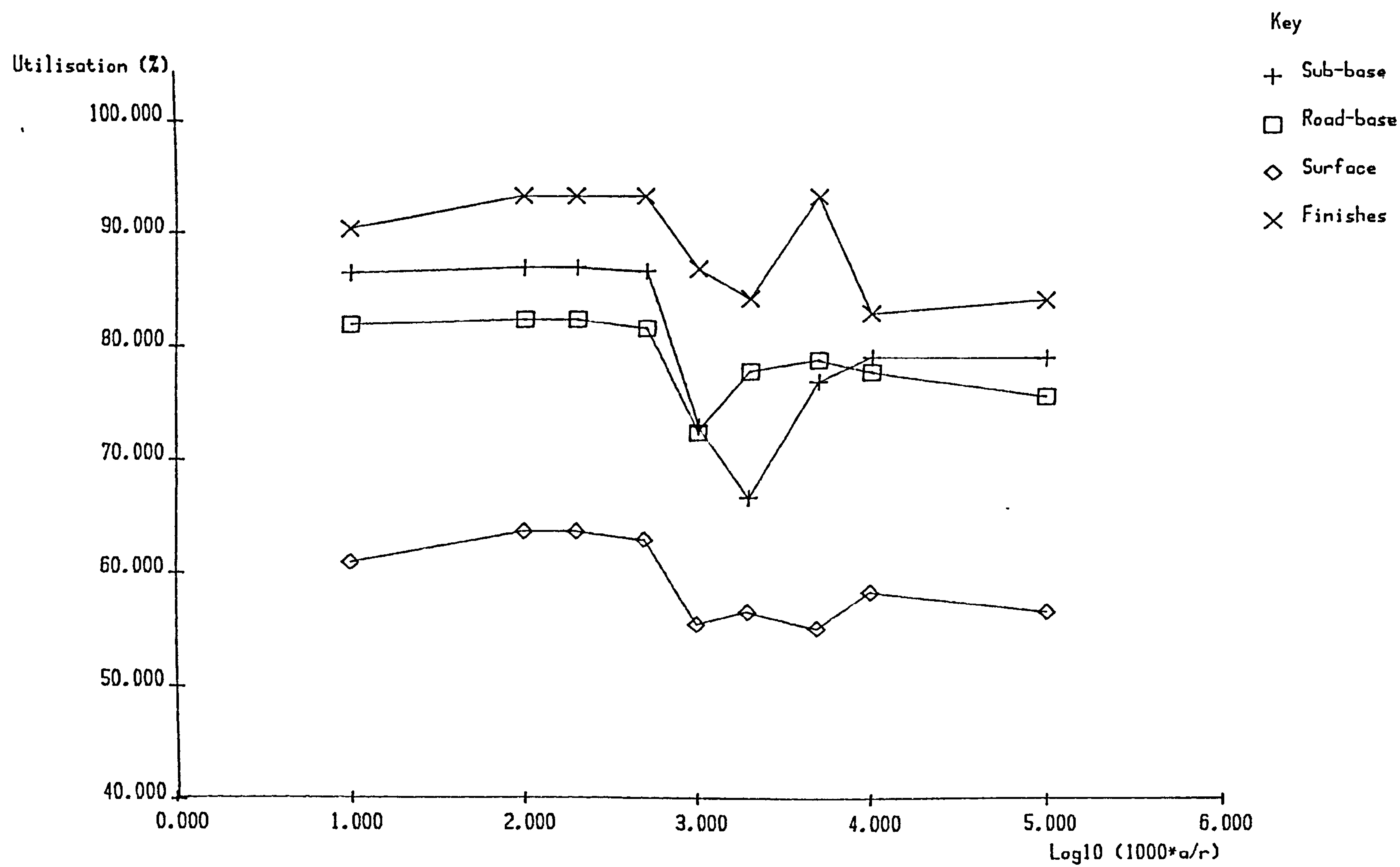


FIGURE NUMBER (8.3.5.2.1) RESOURCE UTILISATION against PRIORITY RATIO for Test Runs 64 - 72

FIGURE NUMBER (8.3.5.2.2) PROJECT DURATION against PRIORITY RATIO

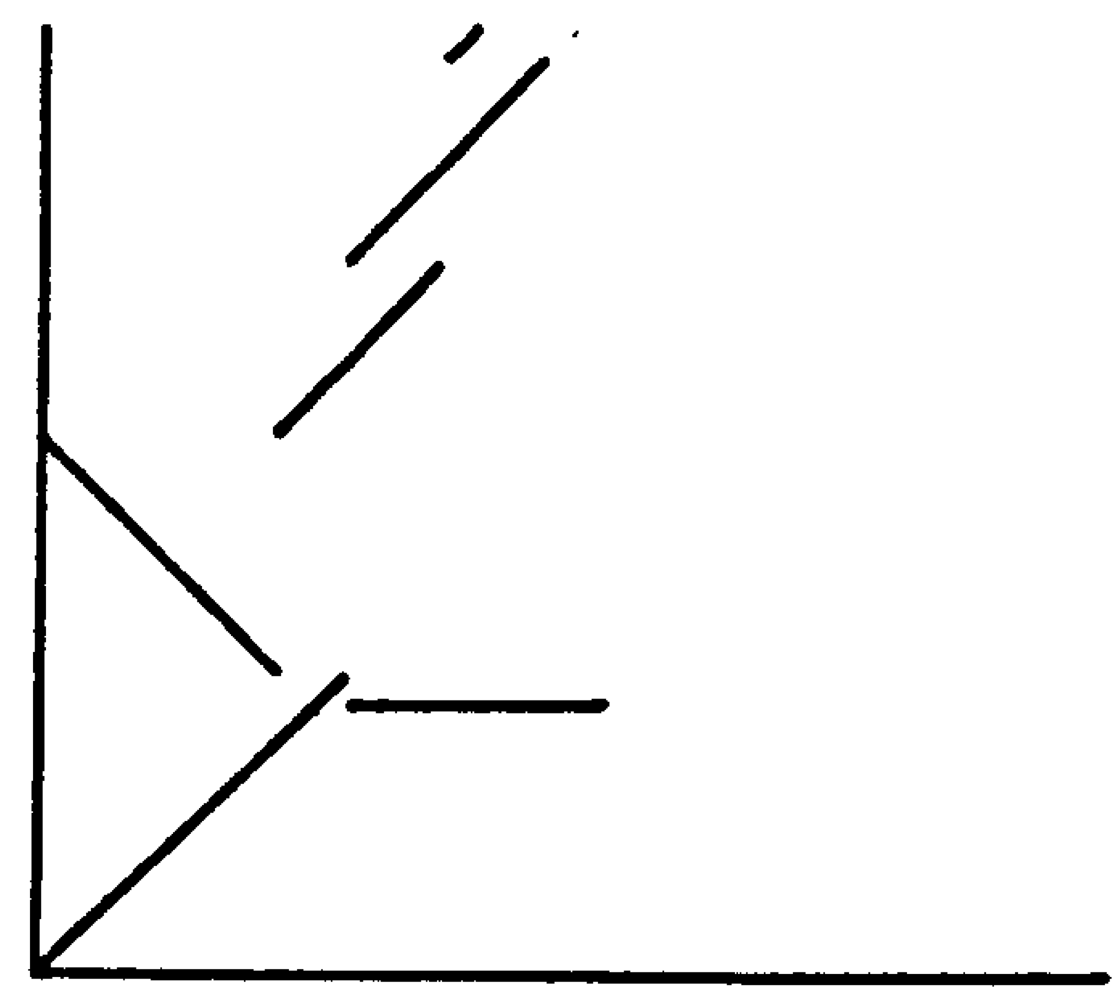


Figure (8.3.5.2.3) Strategy 1

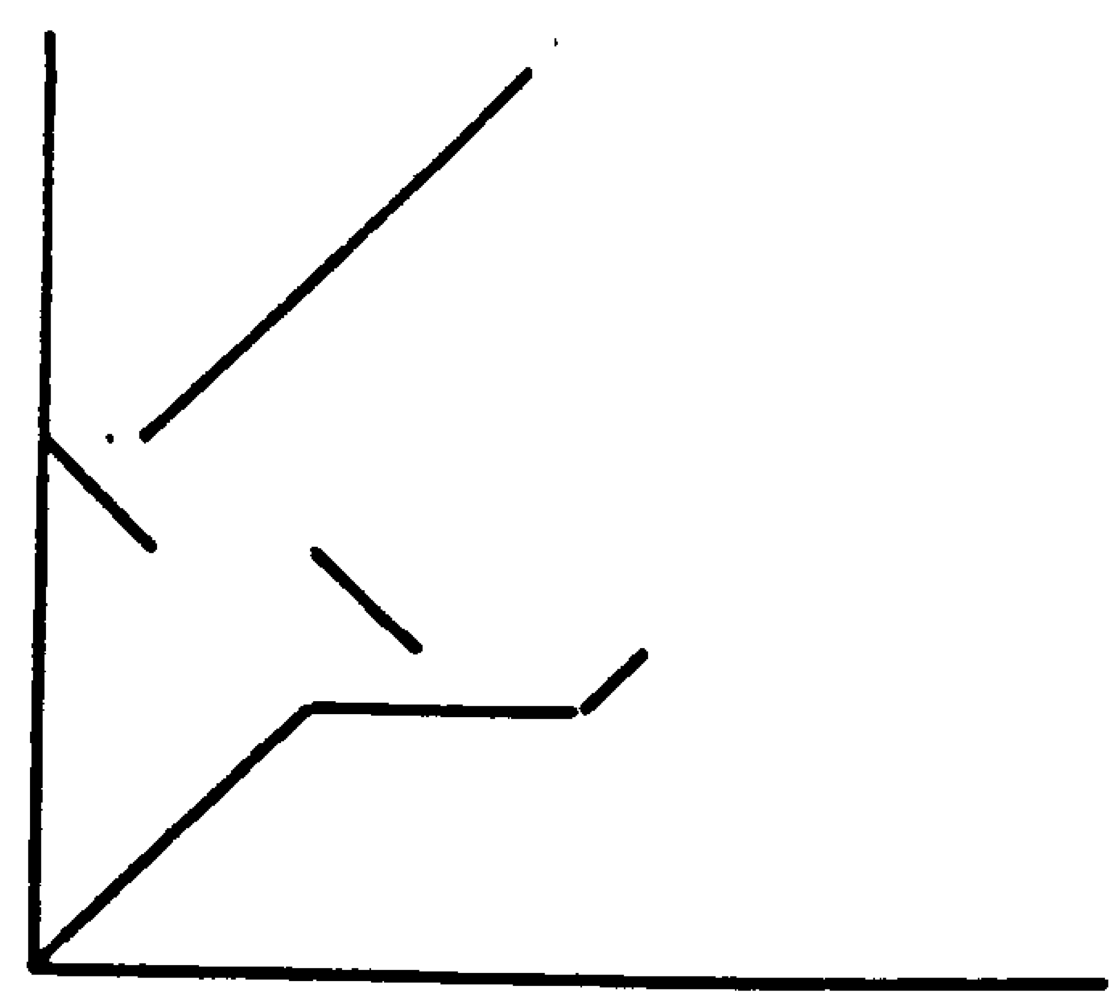


Figure (8.3.5.2.4) Strategy 2

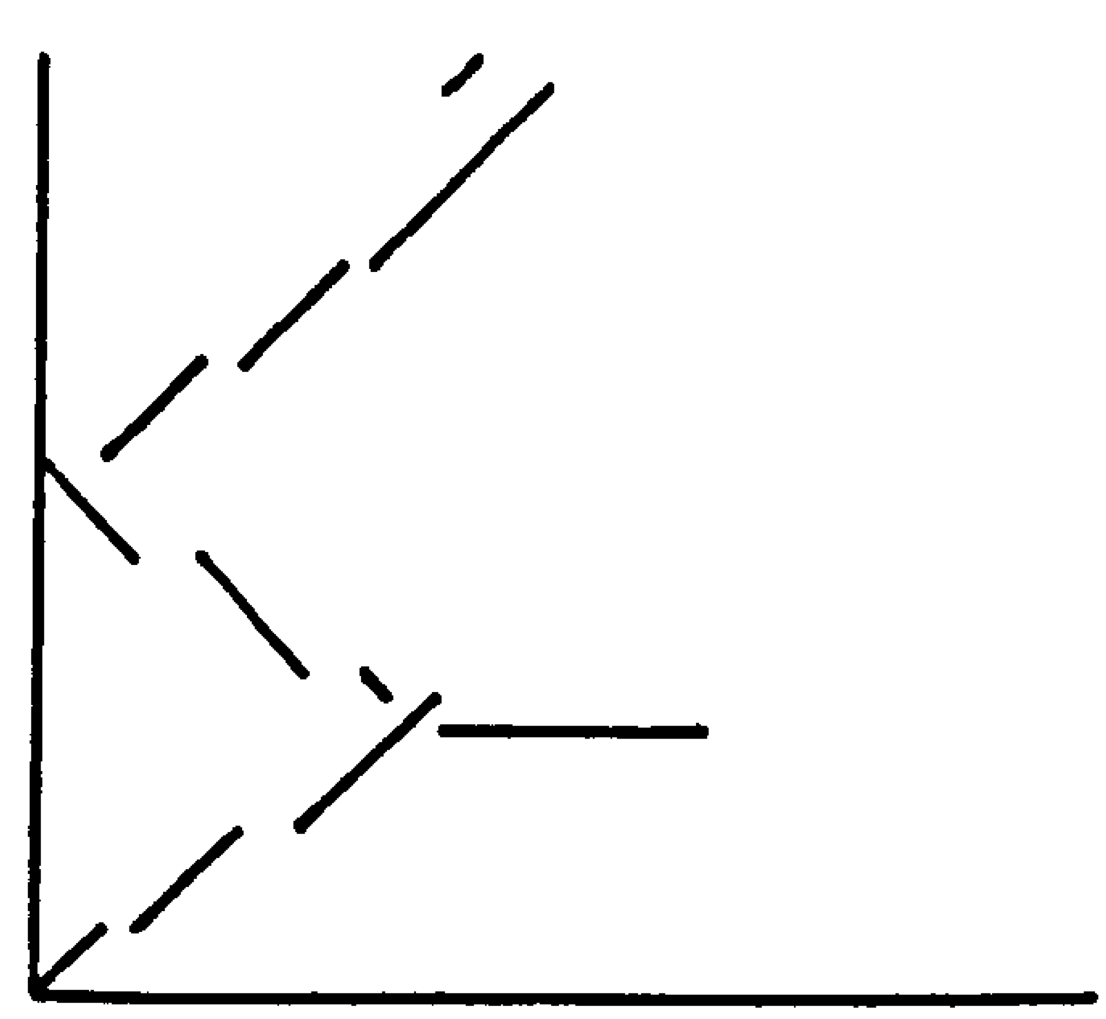


Figure (8.3.5.2.5) Strategy 3

8.3.5.3 Conclusions of the access runs

The two sets of runs performed under this heading illustrate, most importantly, that the scheduler is able to produce satisfactory plans given different access positions.

The different strategies in test runs 55-63 and 64-72 are a consequence of the number of "work-faces" that exist with these two combinations of access points. The intermediate access points (i.e. at chainage 200 and 400) provide two such work-faces (i.e. one in the positive chainage direction and one in the negative), whilst the end access points (i.e. at chainages 0 and 700) provide only one. This means that for access points at 200 and 700, and at 0 and 400, there are three positions in the map with equal access priority, at any time. It follows then, that in the runs where access is the dominant priority, the leap-frogging situation occurs. The time chainage charts (B59) to (B63) and (B68) to (B72), all exhibit leap-frogging and all have high (a/r) priority balance ratios.

Comparisons of the resource utilisations and project durations for this set of test runs is, to a large extent, an academic exercise, because in reality, the time spent in transfers in the leap-frogging situations would effectively eliminate them as viable plans. A better method of evaluating plans in such situations is to consider the number of transfers for each plan. Use of this evaluation method indicates that the plans with very low (a/r) priority balance ratios (i.e. where resource priorities are dominant) are "better". The introduction of non-zero transfer times during the schedule (which is possible in the model) will give more realistic higher project durations and lower resource utilisations for the plans in which leap-frogging occurs.

The plans produced show that the provision of extra access routes (with an intermediate access) does not necessarily produce more efficient plans, unless they are accompanied by extra resources to utilise the extra "work-face".

8.3.6 Resource numbers test runs

This set of test runs were carried out to investigate the ability of the model to handle mismatched numbers of resource teams and access positions. The previous section, showed that the access points may introduce either one or two "work-faces", depending on their position in the road. This set of runs were performed with three resource teams for each work type, and with different numbers of access postions. The optimum allocation distance was set at 25m for all the resource teams, and a priority balance of (a/r) = 0.1 was adopted. This low ratio gives a higher weighting to resource priorities and was chosen to prevent leap-frogging.

8.3.6.1 Runs 73 and 74

These runs were carried out with access points at chainage 0 and 700. The time chainage charts are shown in appendix B, figures (B73) and (B74).

The access positions of 0 and 700 provide two possible "work-faces", and consequently there is one set of resource teams too many. The scheduler utilises this extra set of resource teams by "overlapping" them either at the lower chainage end of the road, as in figure (B73), or at the higher chainage end of the road, as shown in figure (B74).

Overlapping is a consequence of the static formation of the access priorities. Recall, that the resource priorities were described as being dynamic because they are reformed after each stage of the schedule. The access priorities, however, are formed at the start of the schedule, and remain the same throughout. This means that at the start of the schedule, all the positions between chainages 0 and 700 are feasible work areas. In reality, however, access would generally be provided after some initial earthworks, and also perhaps, for the chainages 200 to 400 by the completion of the culvert. A dynamic approach to access priority formation would prevent overlapping simply because the third team would not have the necessary access to work areas.

A dynamic approach to access priority formation would therefore leave one of the sets of resource teams totally redundant. This resource team may perhaps be utilised by doubling-up two resource teams to produce a larger, faster team. This was discussed earlier in section (3.3) with reference to the line of balance work.

Generally, the plans produced by the scheduler have lower project durations, than those obtained in earlier runs, although the reductions in the project durations are small when one considers the extra resources used. The disproportionately small reduction in project duration indicates that the resources were often redundant during the course of the schedule due to interference with other resources. This is significant because it shows that there is a limit to the extent a plan may be improved by the introduction of extra resources.

8.3.6.2 Runs 75-78

Test runs 75-78 were carried out with four access positions at chainages 0, 200, 400 and 700. Figures (B75) to (B78) inappendix B show the time chainage charts for this set of runs. The access priorities were slightly manipulated so that the runs had start positions of chainages 0,200 and 400; 0,200 and 700; 0,400 and 700; and 200,400 and 700 for test runs 75-78 respectively.

For each run there was one totally redundant access point, and without exception the redundant point was the one that was not used as a start point. The reason for this was that the priority balance used was very heavily resource weighted, and consequently once a resource had started it was largely constrained to work in immediately adjacent areas. If a highly access weighted priority balance had been used then leap-frogging would have occured between all six possible "work-faces".

The project durations produced are lower than those produced in the two resource team plans, however once again, they were restricted by interference between the resources.

8.3.6.3 Conclusions of the resource number runs

Once again, the value of this set of runs is in the time chainage charts produced. In the production of these plans, the scheduler has shown that it is able to respond satisfactorily to different combinations of resource numbers and access positions.

A further important point that these runs has revealed is that the introduction of extra resources does not necessarily result in a proportionate improvement in the plans produced. Contractors in industry have known this is the case, and that the interference between all the plant and labour is the cause of the relatively poor performance. The scheduler has successfully modelled this situation.

8.3.7 Grid size test runs

This set of runs was carried out to investigate the effects of the grid size on the plans produced by the scheduler.

One of the initial assumptions made in the model formulation was that the size of the grid squares would be small. This is mainly due to the bundling of the grid squares in the allocation of resources to work areas, and that the grid size should reflect the minimum work area of the smallest resource. Ordinarily, this might be 0.5m x 0.5m for a labourer with a shovel. For all the previous runs in the road and culvert example, the minimum work area and minimum work buffer considered were lengths of 25m along the road. This set of test runs was performed on four grid sizes of 12.5m, 25m, 50m and 100m, with different optimum distance allocations of 12.5m, 25m, 50m and 100m where possible. A priority balance of (a/r) = 2.0 was used as this value gave no signifcant weighting to either access or resource priorities and also does not fall in the highly variable area of priority balances around (a/r) = 0.5.

Test runs 100-103 were carried out on a small 12.5m grid. Of these, only the time chainage chart for the 12.5m optimum distance allocation is illustrated in appendix B, as figure (B100).

Test runs 104-105 were performed on a 50m grid, and finally test run 106 was performed on a 100m grid. Runs on the 25m grid were carried out in earlier sets of runs, and are runs 24, 33 and 42.

Figure (8.3.7.1) shows the project durations for all the test runs. The results obtained for grid sizes 12.5m and 25m are identical (except for the 12.5 optimum distance allocation run which is infeasible on a 25m grid). This supports the assumption that the grid size only needs to be as small as the minimum resource allocation or buffer.

The results generally have a trend towards higher project durations with larger grid sizes. This is because the grid size may become greater than the buffers operating on the resources, and consequently default to the grid size. The combination of increased buffers and large allocation areas also introduces a degree of variability into the plans, as exhibited on the 100m allocation line at a grid size of 50m. This seemingly large trough is put into perspective when one considers that a single allocation of 100m for surfacing, for example, takes approximately 13 weeks. Consequently, only slight modification in the allocation of resources could account for this variability.

Figure (B100) in appendix B is presented largely for interest as it shows that line of balance style charts are produced with very small grid sizes and allocation areas.

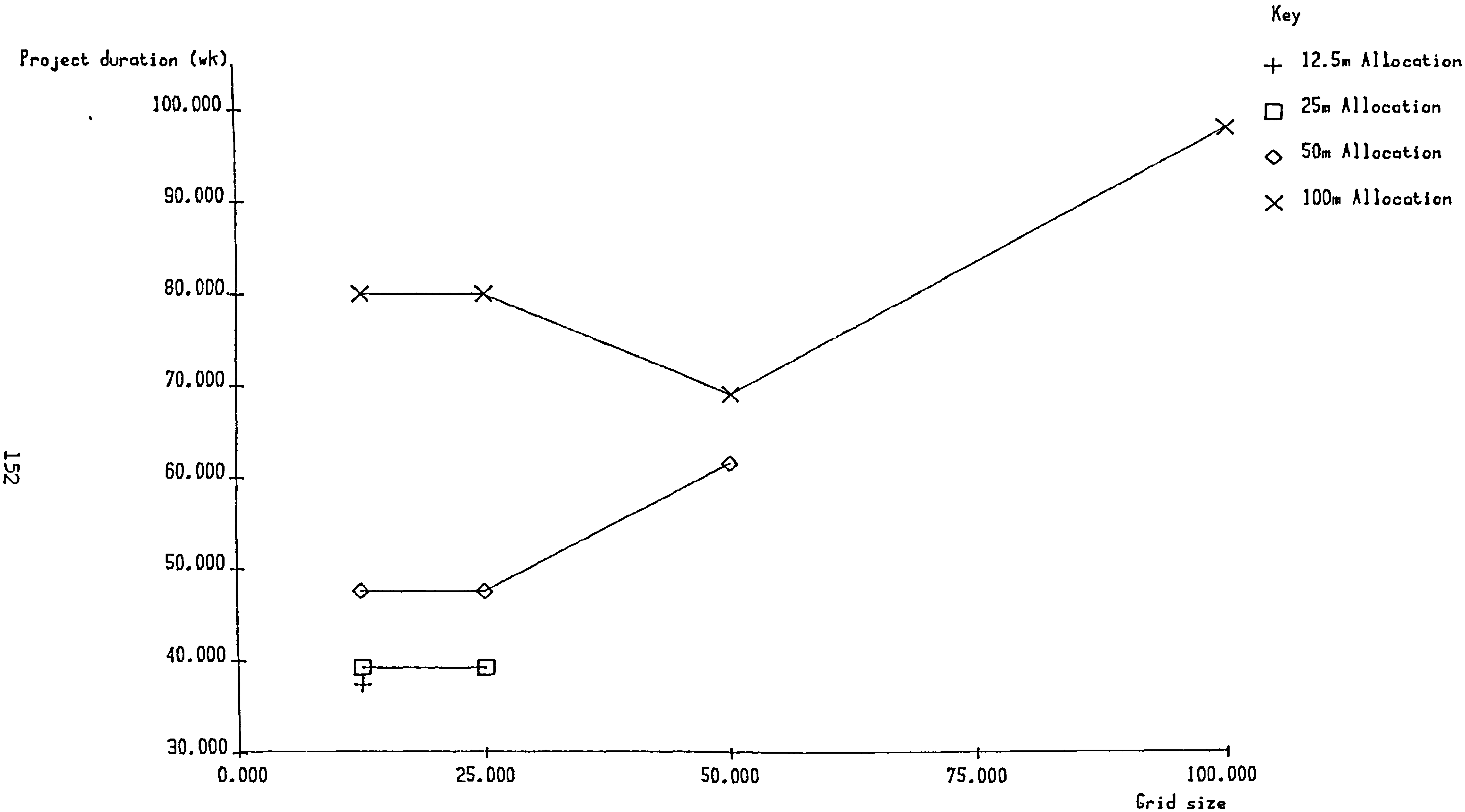


FIGURE NUMBER (8.3.7.1) PROJECT DURATION against GRID SIZE

CHAPTER 9

FURTHER TEST RUNS

9.1 Introduction

Chapter 8 dealt with the application of the model to a simple road and culvert project, with a view to illustrating the general working and decision making of the model.

Often, however, planning models are able to handle simple projects, but are unable to model true construction site situations. The aim of this chapter is to discuss the application of the model to three more projects and to compare the plans produced with those produced by two contractors in industry.

The three projects are:

a) Factory project
b) Road project
c) Tank project

and each is discussed individually in the next three sections, with the figures for each occuring at the end of their respective section.

9.2 The Factory project

Plate (10) shows the sheet of information used by the contractors to produce plans for the factory project. The project basically consists of a floor slab of reinforced concrete, 20 columns, 15 roof trusses, and 6 purlins spanning each pair of trusses.

The contractors were required to produce barcharts for the factory project including the following activities:

a) Blinding concrete
b) Steel fixing to base
c) Formwork to base
d) Concrete to base
e) Column erection
f) Beam erection
g) Truss erection
h) Purlin erection.

The information did not include any recommended work sequencing, either by activity or area, so that the plans produced reflected the contractors' own preference in work method.

9.2.1 The contractors' factory plans

The plans produced by the contractor were remarkably similar in terms of duration, sequencing of activities, and sequencing of work areas.

Figures (9.2.1.1) and (9.2.1.2) show the barcharts produced by the contractors. The general sequence of activities adopted by both was blinding, steel fixing, formwork, concrete, columns, beams, roof truss, purlins.

The durations of the activities varied slightly, although insignificantly in terms of overall project durations. The "staggering" of the consecutive activities is also very similar between both plans.

The similarity in the plans provides a difficult test for the scheduler, as there is very little scope for differences in the plans.

9.2.2 The computer factory plans

The factory project was included in this series of test runs because in chapter 5 it was identified as a potential problem. Recall, that the scheduler is unable to handle inter-grid square logic connections. In the factory problem, these inter-grid logic connections exist between the tops of the columns to all the grid squares constituting a roof truss or a beam.

The solution to the problem lies in the nature of the construction of the roof truss. As the roof truss is prefabricated, it has to be positioned as one. This may be modelled by the scheduler by specifying an optimum and minimum allocation area for the roof truss erection resource team as that of the whole roof truss. Although clumsy, it does reflect the true nature of the problem, and does achieve the required result. Careful formation of the work map for the project will also prevent the situation in which two half roof trusses are constructed across the top of one column.

Because the plans produced by the contractors were very similar, a common set of durations and buffers were adopted for the computerised plans. Two runs were performed, the first was with a general sequence of work across the plane of the roof trusses, and the second with the direction of work across the plane of the beams. Figures (9.2.2.1) and (9.2.2.2) show the barcharts for these runs respectively.

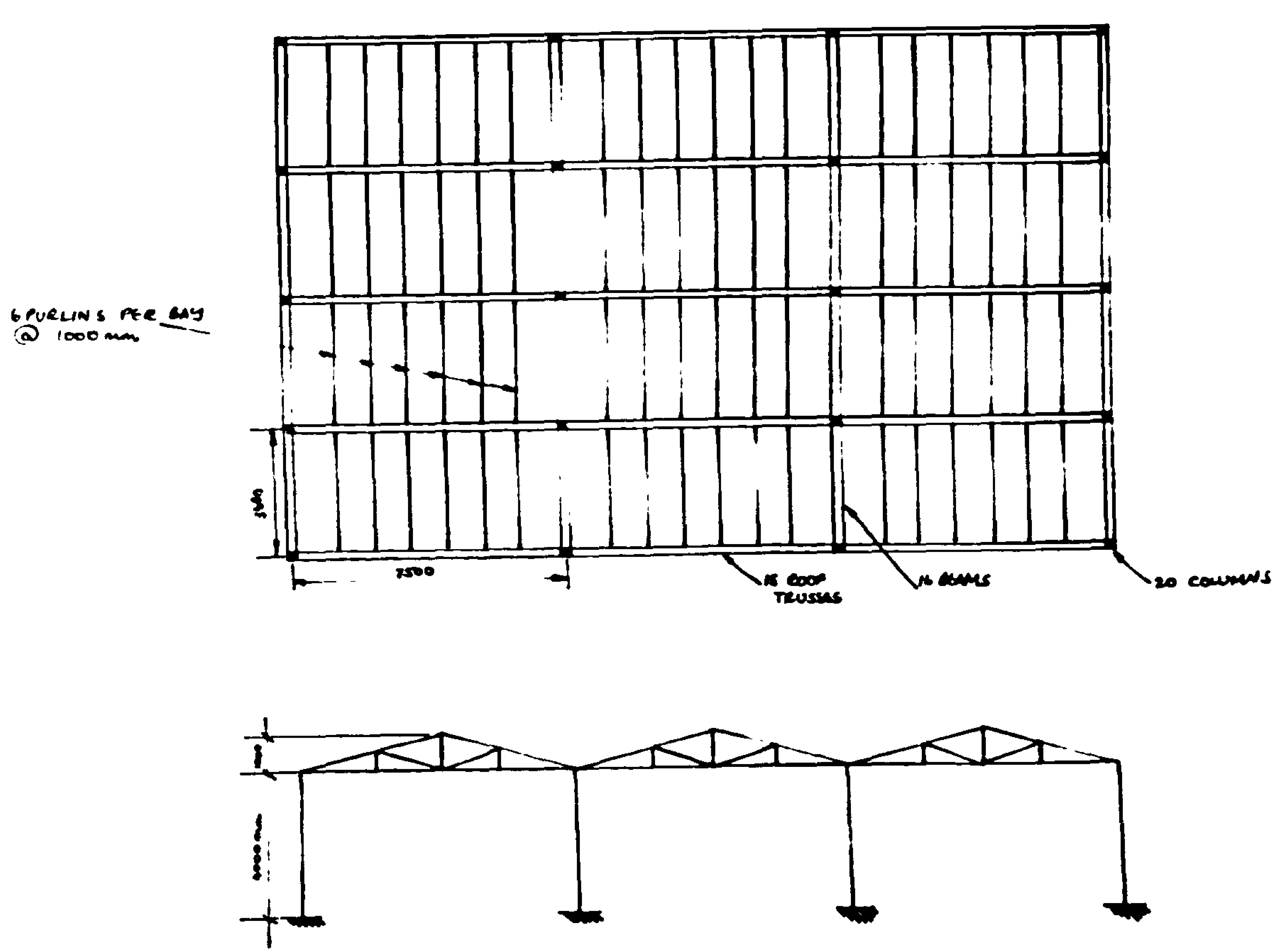
Figures (9.2.2.1) and (9.2.2.2) show that the concreting activities (i.e. blind, steel, formwork and concrete) are the same (except for slightly different durations) as those produced by the contractors. Differences in the plans mainly occur in the steel erection activities. The most noticeable difference is that there is much less staggering of the activities with the computer runs. This is because these runs performed the erection whenever it was possible, for example, when two adjacent columns were completed. This suggests that the staggering on the contractors' plans were not due to the hold-ups in the construction of the preceding activities, but rather were introduced into the plans by the contractors themselves. The introduction of the staggering may be due to a number of reasons, although two reasons are immediately apparent. Firstly, the contractors may have included resource limitations, such as craneage, in the plans. Secondly, the contractors may have limited the production to prevent interference between all the erection teams. The absence of the staggering in the computerised runs has reduced the project durations by about 5 to 7 days.

Examination of figures (9.2.2.1) and (9.2.2.2) reveals that the two different directions of work has produced different sequencing of the steel erection activities. In figure (9.2.2.1) where the predominant direction of work is across the plane of the roof trusses, the trusses precede the beams. In figure (9.2.2.2) the opposite occurs. This difference is simply a consequence of the order of completion of the columns, and this in turn is a consequence of the finishing order of the concreting activities.

9.2.3 Conclusions to the Factory runs

The scheduler has produced satisfactory plans for the factory project. The method used for controlling the steel erection, although clumsy, has worked. In future developments of the model, a more robust method of handling inter-grid logic links will hopefully be produced.

FACTORY FLOOR & STEEL ERECTION



NOTES:

1) CONCRETE FLOOR 18m X 22.5m x 0.5m THICK
2) BLINDING CONCRETE 0.05m THICK
3) ALL STEEL PREFABRICATED
4) COLUMNS BOLTED TO CONCRETE FLOOR
5) STEEL SIZES:

TYPE	LENGTH	WEIGHT
COLUMN	4.0m	34kg
PURLINS	3.5m	20kg
BEAM	3.5m	11 kg
ROOF TRUSS	7.5m	[illegible]

6) NO CLADDING

* PLEASE PRODUCE A PLAN INCLUDING:
  SLAB – BLIND
  – STEEL FIXING
  – FORMWORK
  – CONCRETE
  COLUMN ERECTION
  BEAM "
  TRUSS "
  PURLIN "

* IF POSSIBLE PLEASE INDICATE THE ENVISAGED DIRECTION OF WORK

* PLEASE GIVE ESTIMATED RATES OF WORK.

Plate 10 - Factory project information sheet

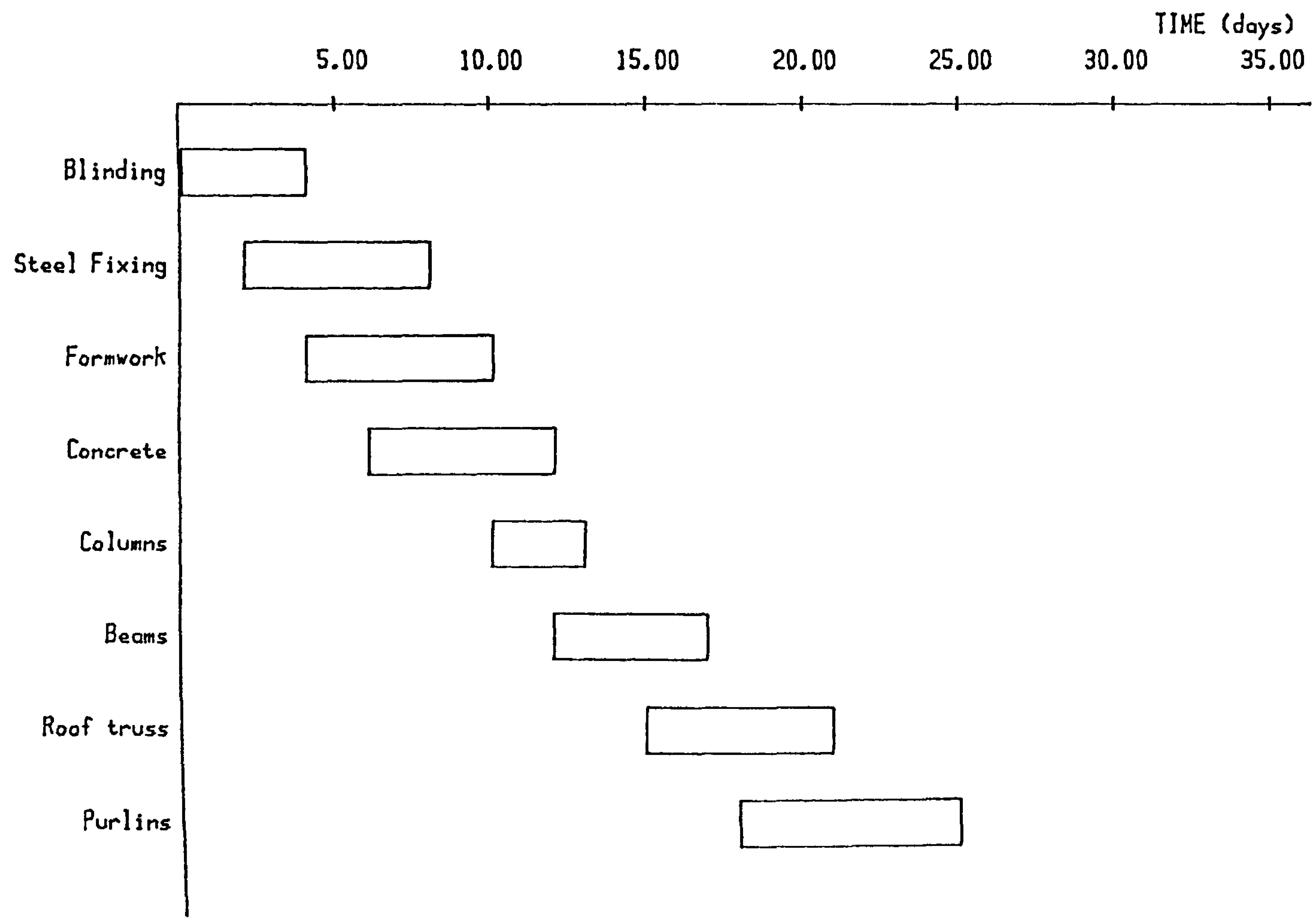


FIGURE NUMBER (9.2.1.1) CONTRACTOR No. 1 Factory Plan

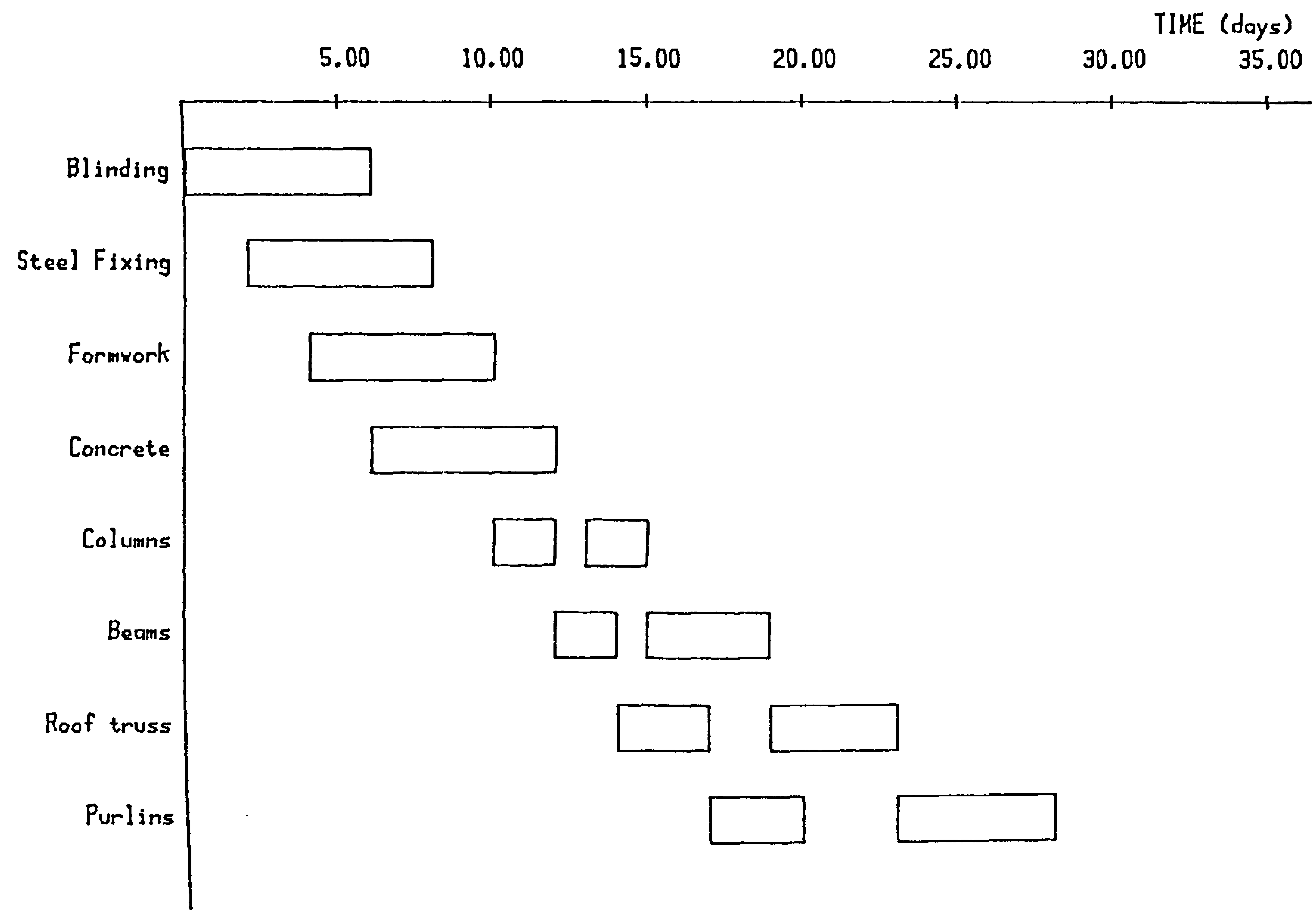


FIGURE NUMBER (9.2.1.2) CONTRACTOR No. 2 Factory Plan

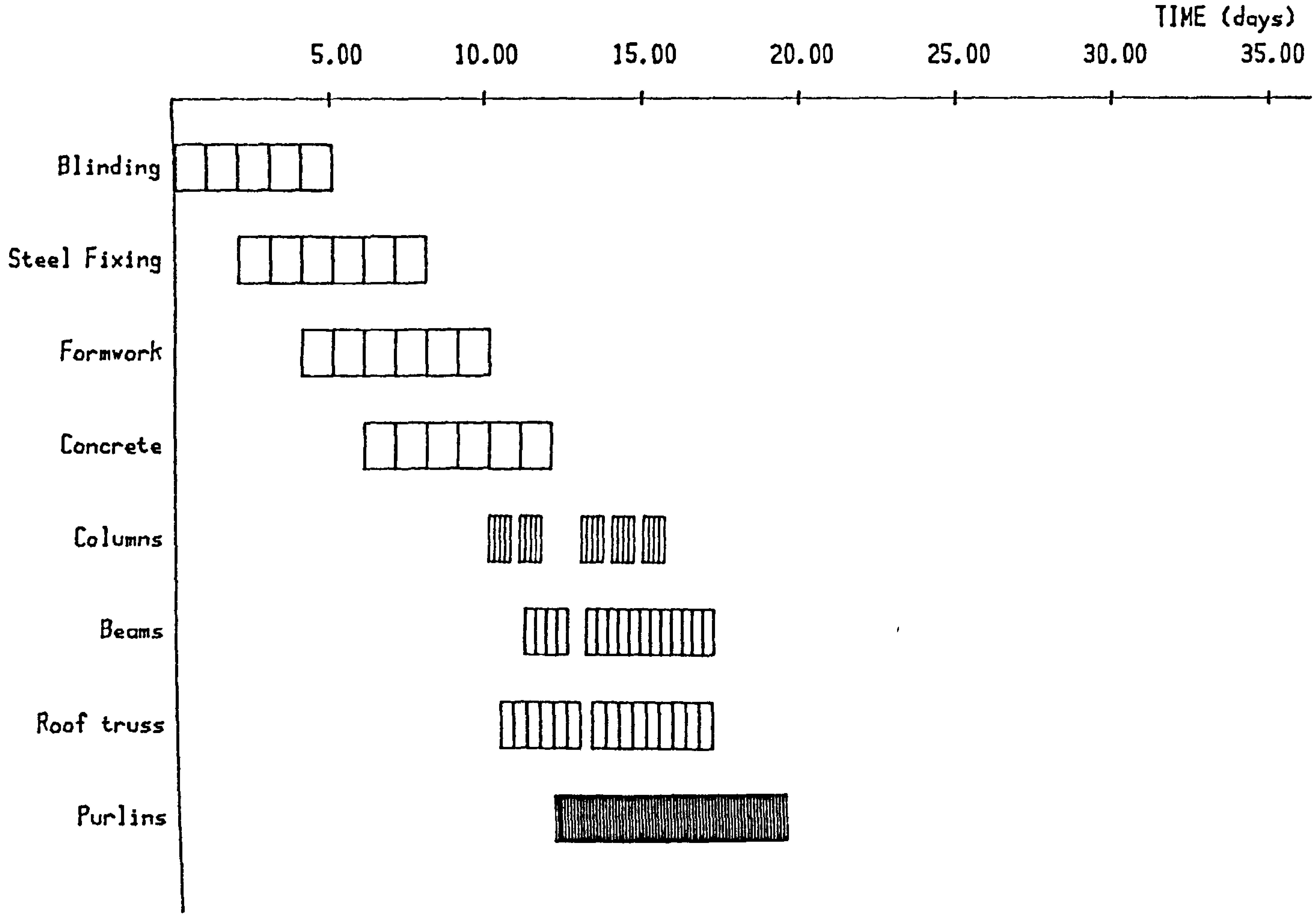


FIGURE NUMBER (9.2.2.1) FACTORY TEST RUN

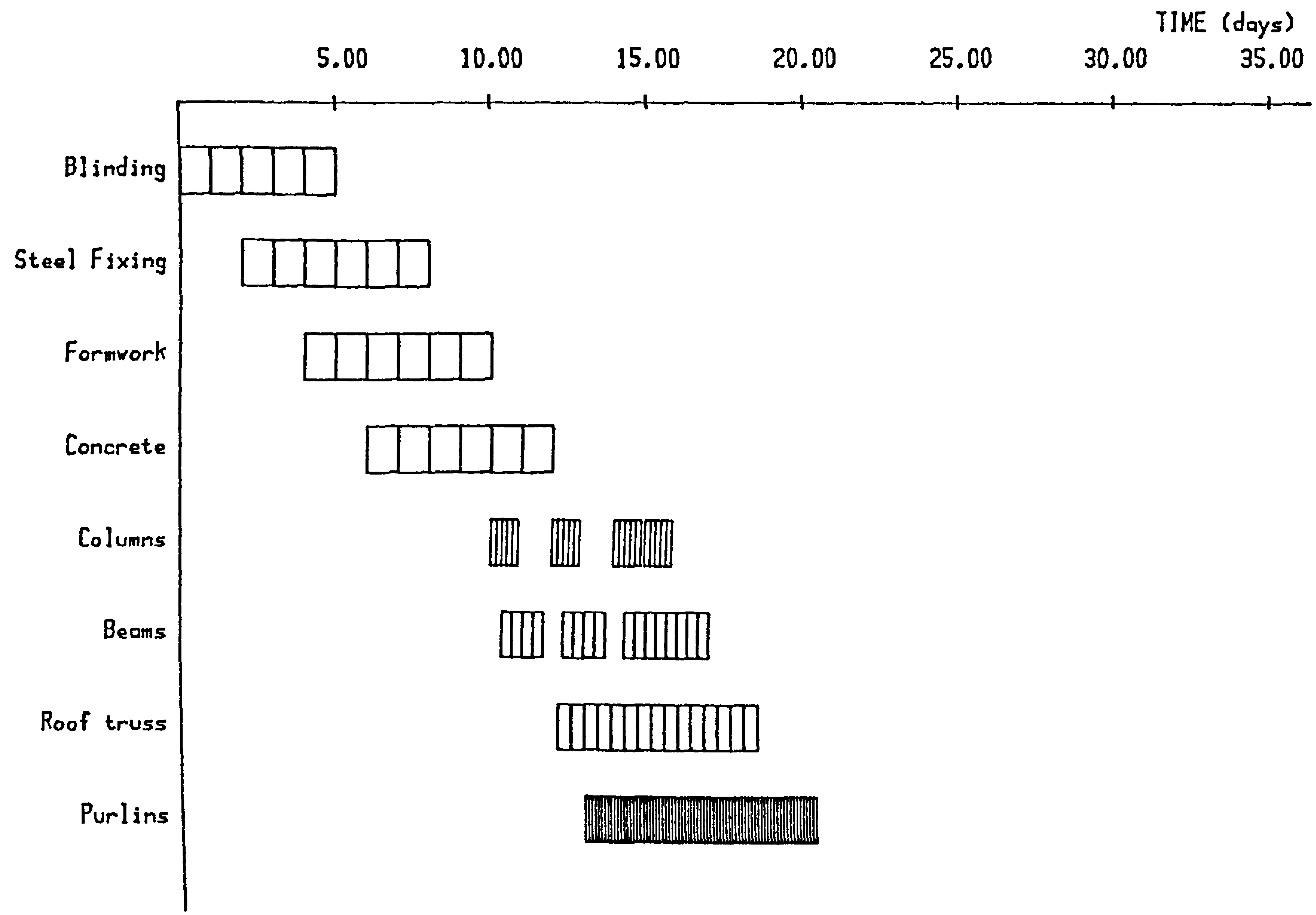


FIGURE NUMBER (9.2.2.2) FACTORY TEST RUN

9.3 The Road project

Plate (11) shows the information sent to the contractors concerning the road project. This project consists of a 450m stretch of road. The contractors were asked to produce a time chainage chart for the road including the following activities:

a) Earthworks (cut and fill)
b) Kerbs
c) Sub-base
d) Road-base
e) Base course
f) Wearing course
g) Bedding for paving slabs
h) Lay paving slabs
i) Gullies (including ancilliary pipework)
j) Drainage

9.3.1 The contractors' road plans

Figures (9.3.1.1) and (9.3.1.2) show the two plans produced by the contractors. The two plans have very different rates of work for the resource teams and slightly different orders of work at any chainage. An interesting similarity between the plans is that the contractors have not allowed any interruption in the working of the teams. The previous work in the line of balance sections illustrated that continuous working of resources may result delays in the project duration if "fast" teams are sandwiched between "slow" teams. Continuous working, however, does allow maximum resource utilisation.

The large variations in the rates of work chosen by the contractors are simply due to the perceived make-up of all the resource teams.

9.3.2 The computer road plans

The differences in the two contractors' plans meant that a common set of rates of work and buffers could not be used for the computer runs. Consequently, four runs were carried out for this project, two for each set of rates and buffers.

Figures (9.3.2.1) and (9.3.2.2) show the two plans for the first contractor's rates of work. The first of these, figure (9.3.2.1) may be thought of as an "earliest start" time chainage chart. The discontinuities in the production of the teams has prevented any of the delays due to the sandwiching of the fast activities, as discussed above, and consequently yields a short project duration of around 25 days. This compares favourably with the contractor's own plan of 31 days, as illustrated in figure (9.3.1.1). The second barchart, figure (9.3.2.2), was produced by delaying the starts of the fast activities. This prevents discontinuities occuring and yields a plan almost indentical to the contractor's own plan, figure (9.3.1.1).

A similar set of plans was produced for the second contractor's rates of work and buffers. In this case, figure (9.3.2.3) is the "earliest start" chart, and figure (9.3.2.4) is the plan that conforms to the contractor's own. Figure (9.3.2.3) is interesting because the barchart may be split into two parts at chainage 250. This has occured because the rates of work of the teams are such that leap-frogging may be achieved between the two parts of the road.

9.3.3 Conclusions to the Road runs

The scheduler has successfully reproduced the plans produced by the contractors, by using their rates of work and distance buffers.

The "earliest start" time chainage charts produced by the scheduler may be of use if the project duration is too long, however, the contractors' plans tend to suggest that the maximum utilisation of the resources is of overriding importance. The use of these simple, resource efficient plans may negate the need for the "clever" line of balance techniques which includes variable rates of work, must links and minimum distances, as discussed in chapter 4.

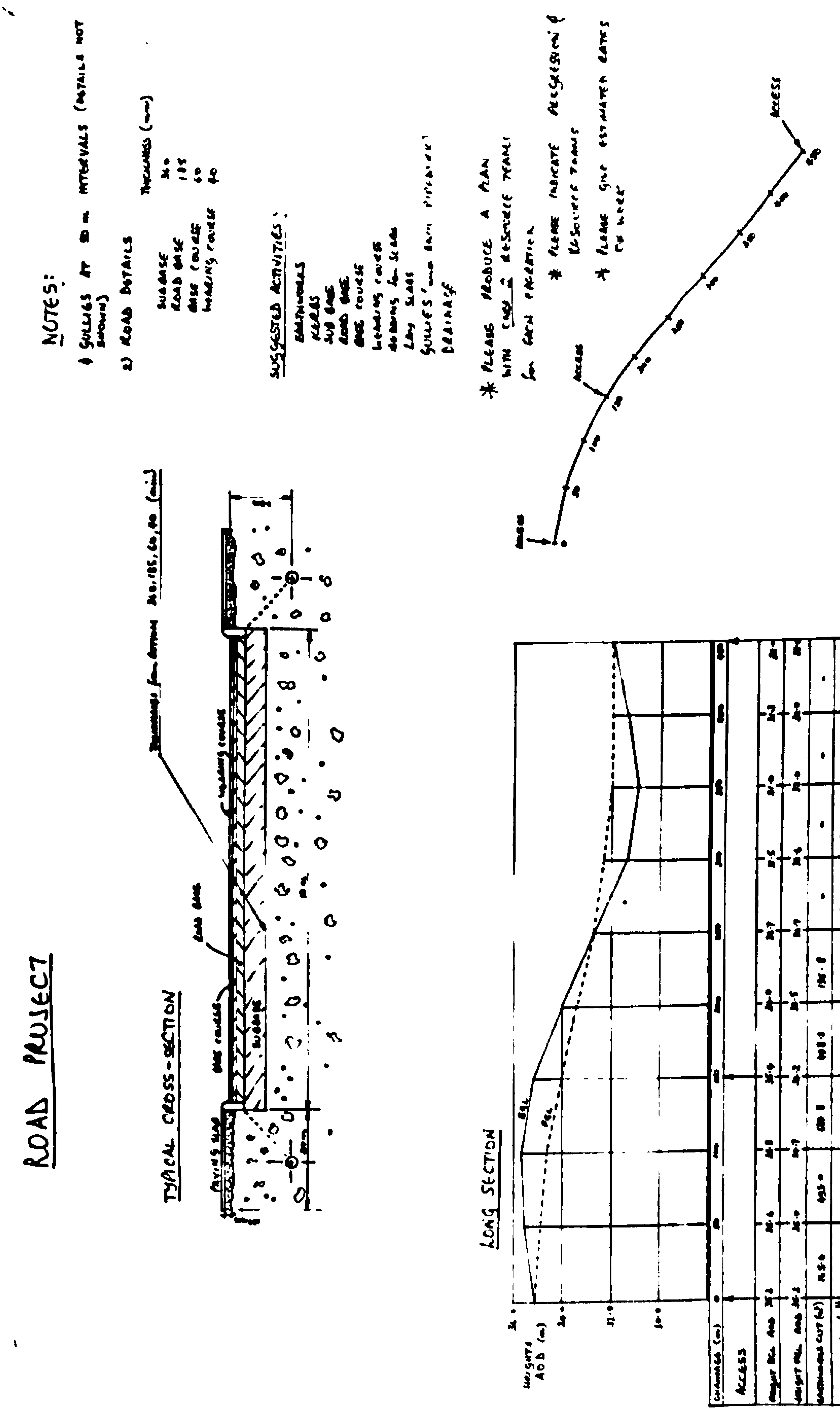


Plate 11 - Road project information sheet

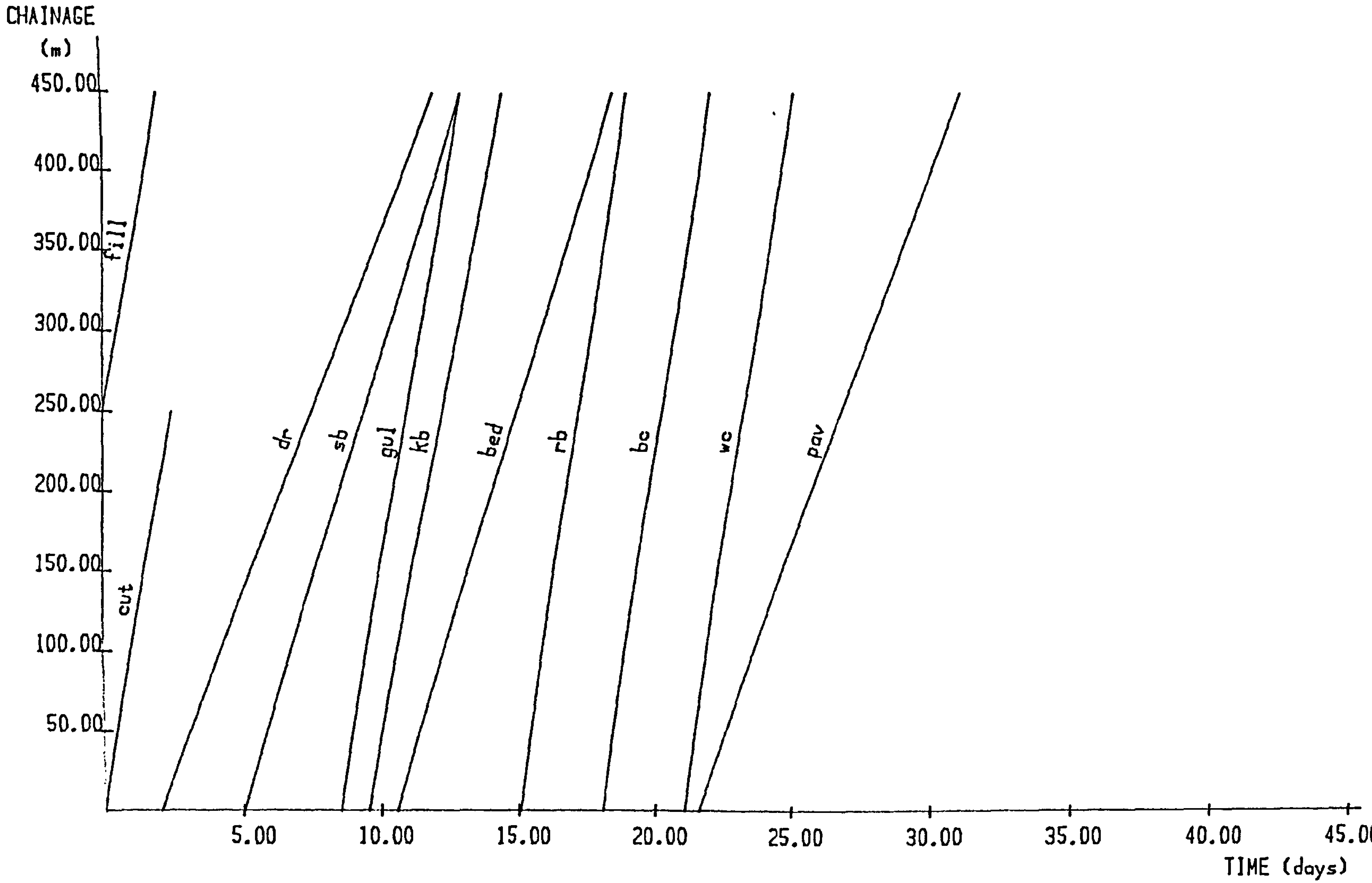


FIGURE NUMBER (9.3.1.1) CONTRACTOR No. 1 Road Plan

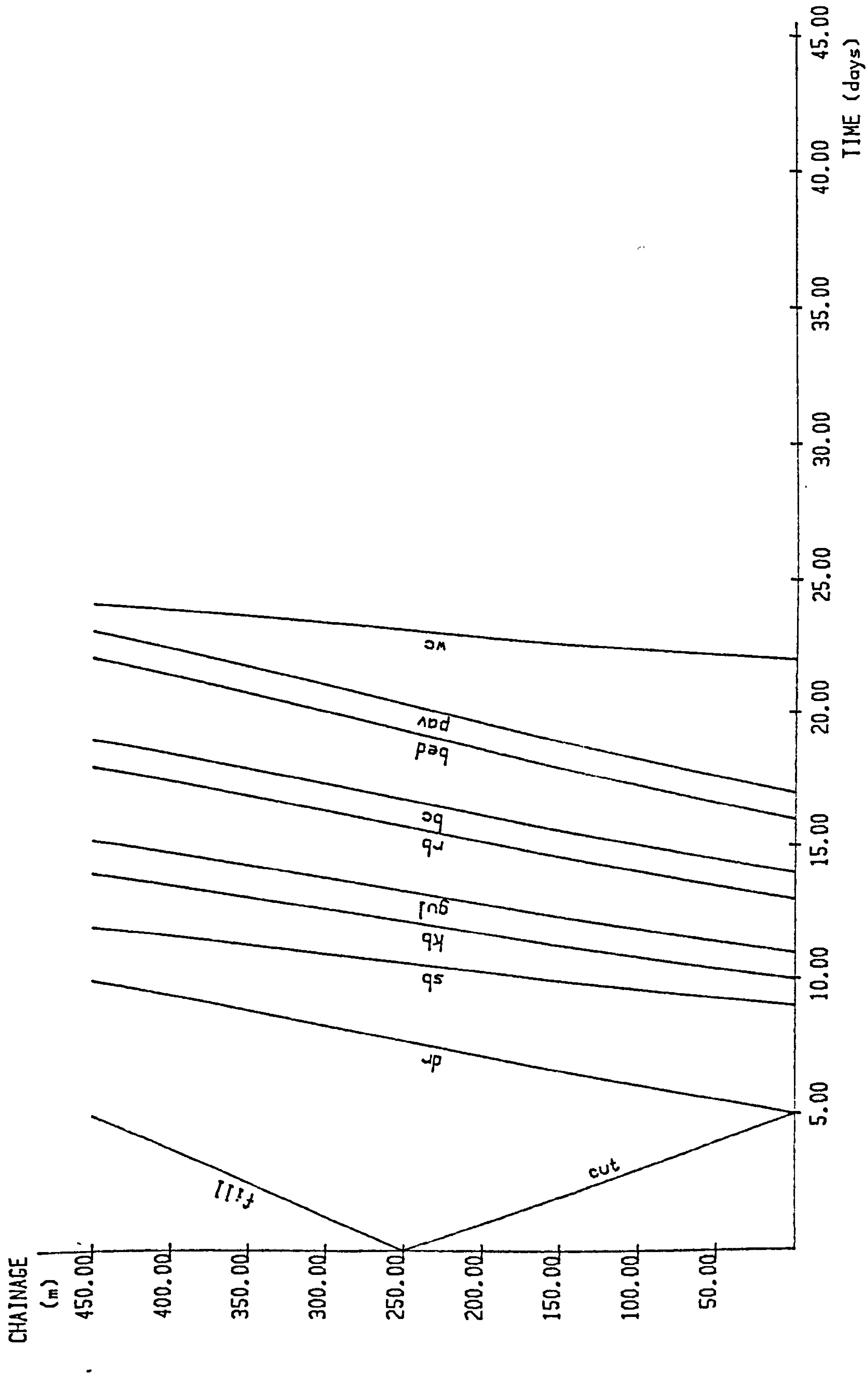


FIGURE NUMBER (9.3.1.2) CONTRACTOR No. 2 Road Plan

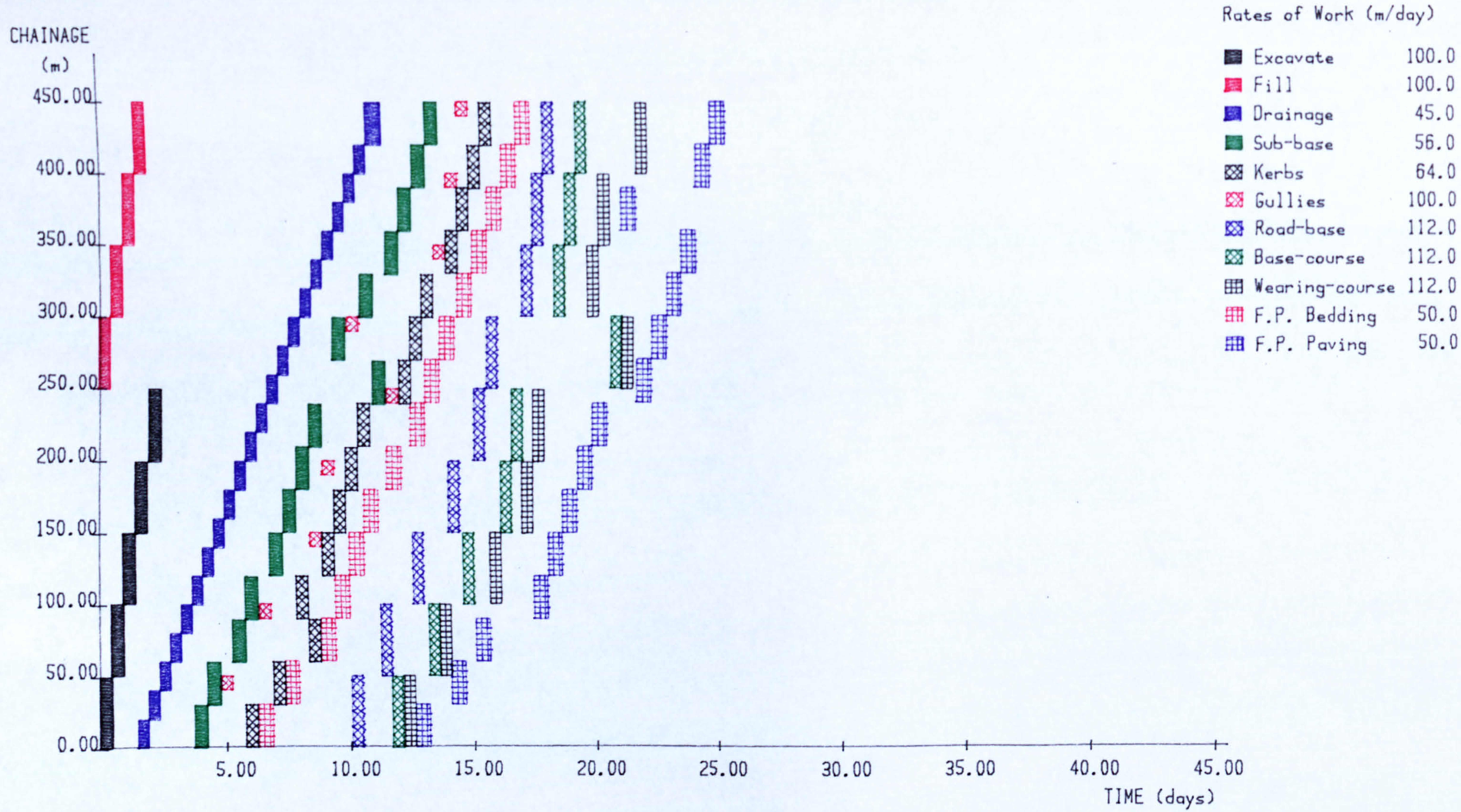


FIGURE NUMBER (9.3.2.1) ROAD TEST RUN

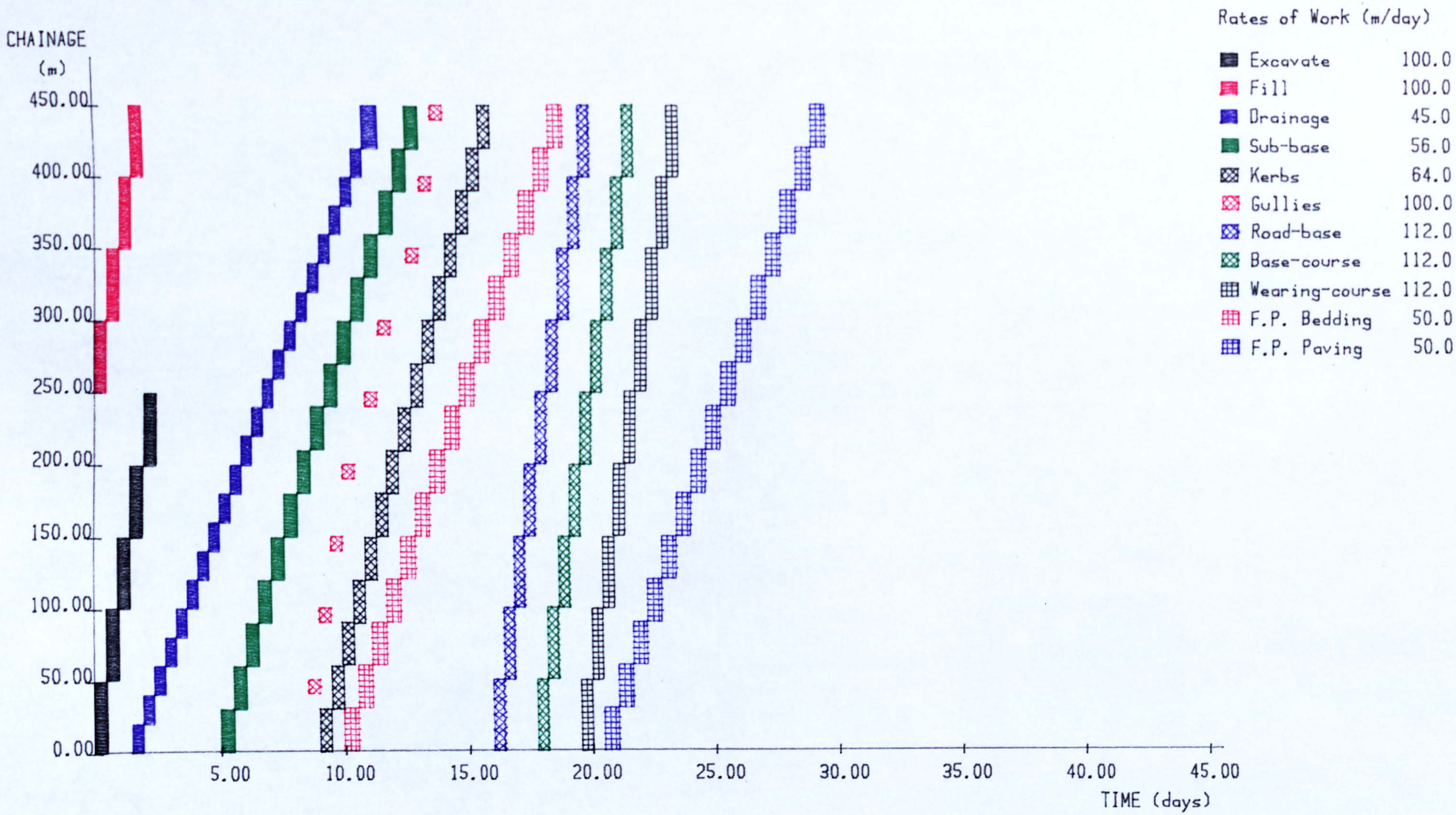


FIGURE NUMBER (9.3.2.2) ROAD TEST RUN

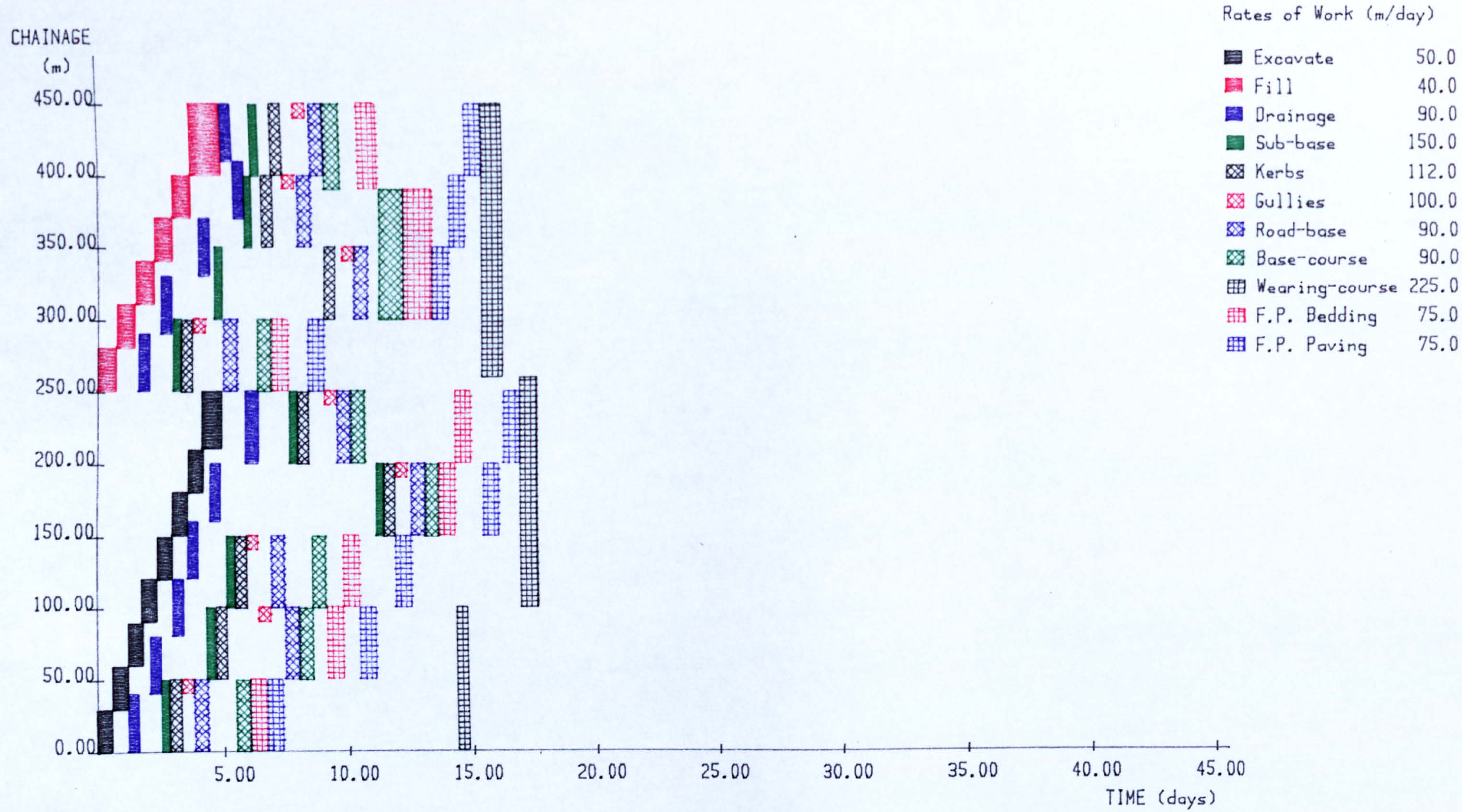


FIGURE NUMBER (9.3.2.3) ROAD TEST RUN

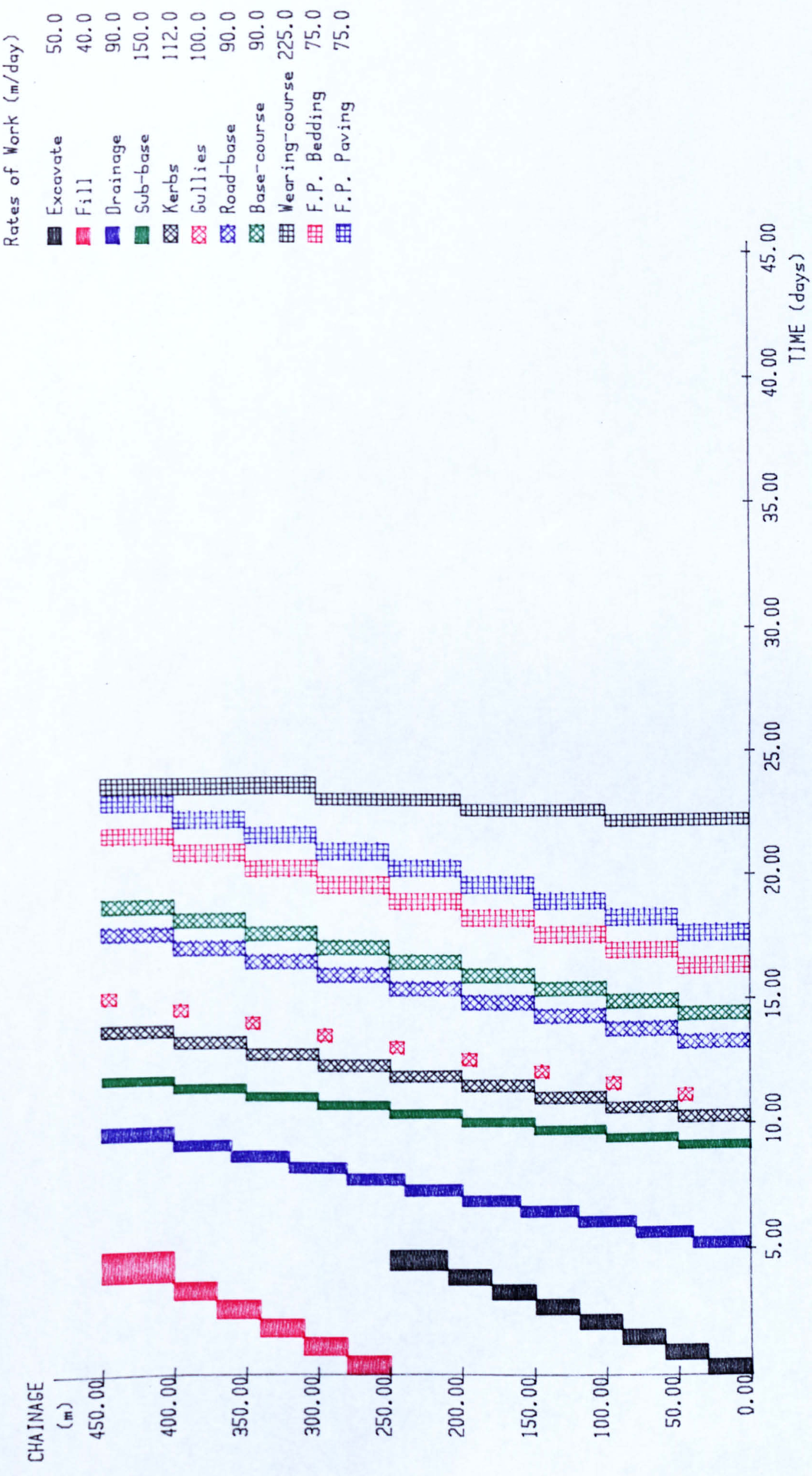


FIGURE NUMBER (9.3.2.4) ROAD TEST RUN

9.4 The Tank project

Plate (12) shows the information sheet the contractors used to plan the tank project. The project basically consists of a reinforced concrete tank of diameter 10m and depth 5m, with a pipe running from the centre of the tank for a length of 10m.

The contractors were required to produce barcharts using the following activities:

a) Excavate tank
b) Blinding
c) Steel to base
d) Formwork to base
f) Concrete to base
g) Steel to wall
h) Formwork to wall
i) Concrete to wall
j) Backfill tank
k) Bedding to trench
l) Lay pipe
m) Backfill trench

All the previous test runs have examined the "macro" site layout effects in planning. Macro site layout may be thought of as the positioning of the activities over large areas, and may be utilised in planning by influencing different resource movements and directions of work. In the tank project, all the work exists within a relatively small area. The value of this test run is in investigating the "micro" site layout within each individual grid square, and illustrating that the Level method of defining the sequence of work within the grid squares is successful.

9.4.1 The contractors' tank plans

Figures (9.4.1.1) and (9.4.1.2) show the plans produced by the contractors. They both have different rates of work and work methods. Figure (9.4.1.1) shows that the first contractor carried out most of the pipework before starting on the tank and then divided the tank into four segments. The second contractor, figure (9.4.1.2), completed the tank excavation and blinding concrete before starting the pipework. The project durations of each plan are around 32 days and 28 days respectively. These are tolerably close given that the individual activity durations and work methods are different.

In the wall concreting activities (i.e. formwork, steel, and concrete to walls), the first contractor seems to have applied some resource constraints. In this plan, the formwork may not be carried out whilst the pouring of concrete is occuring. This may be because the carpenter is required to supervise the pouring of the concrete. The steel fixing is also spread over more days than necessary. This may be to reduce the time that the steel is in place, to prevent damage. The second contractor, figure (9.4.1.2), carries out all the steel fixing and formwork to the wall in parallel and then pours the concrete in one.

9.4.2 The computer tank plans

Figures (9.4.2.1) and (9.4.2.2) show the computer plans for the two contractors' rates of work. The general sequencing of the tank activities adopted by the Level method placed the pipework activities after the tank excavation, and before the blinding concrete. This had the general effect of comparatively delaying the succeeding activities. The only other major difference between the computer plans and the contractors' plans is that the wall concreting activities are much more closely bunched.

The project durations of the two computerised plans are approximately 30 days and 33 days respectively. These are different from the contractors' durations but still reasonably close.

9.4.3 Conclusions to the Tank runs

The plans produced by the scheduler for the tank project were slightly different from the contractors plans. This is largely due to the different work methods adopted by the contractors and the scheduler. The scheduler plans, however, are no less reasonable or logical than the contractors' plans.

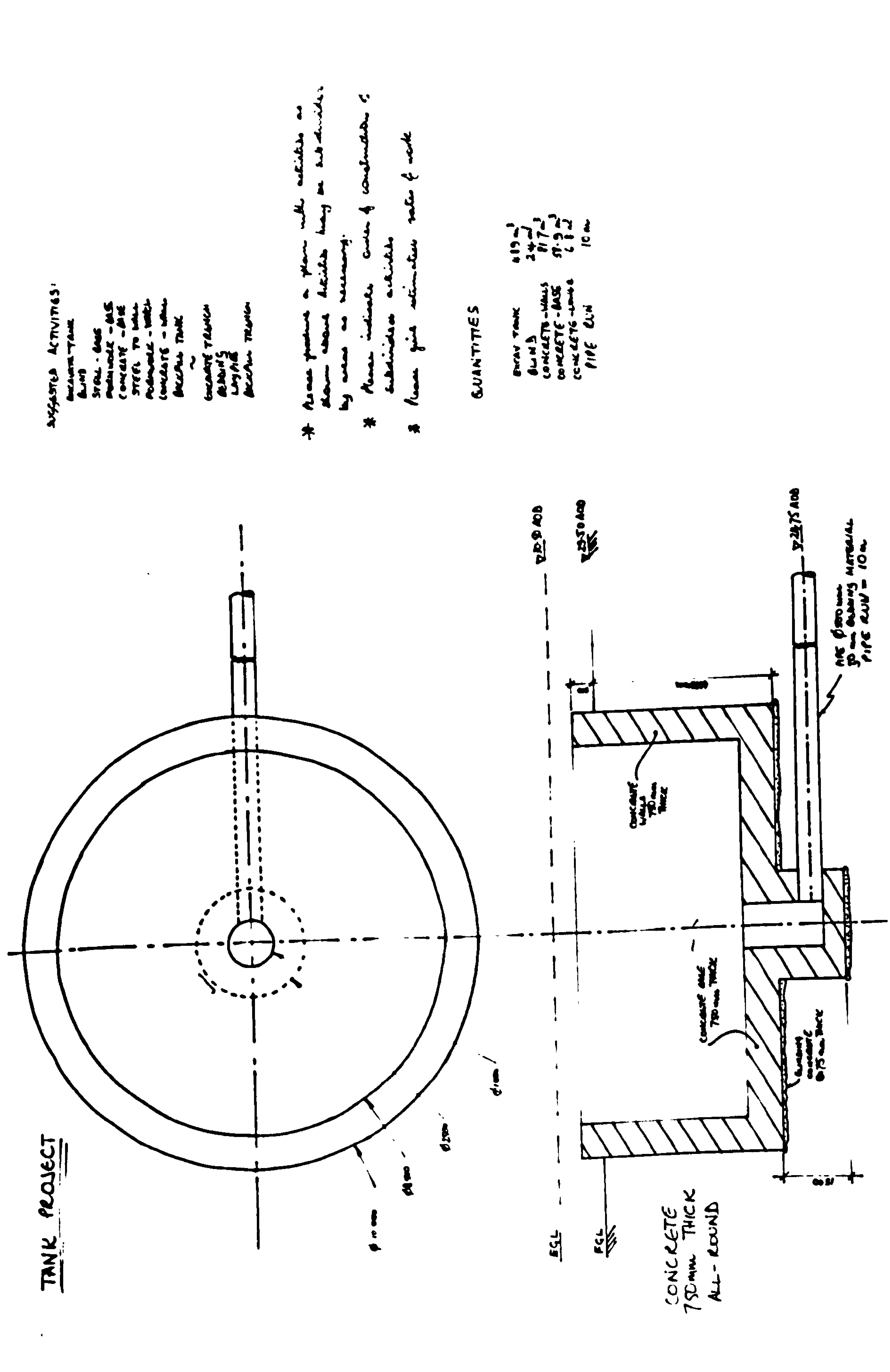


Plate 12 - Tank project information sheet

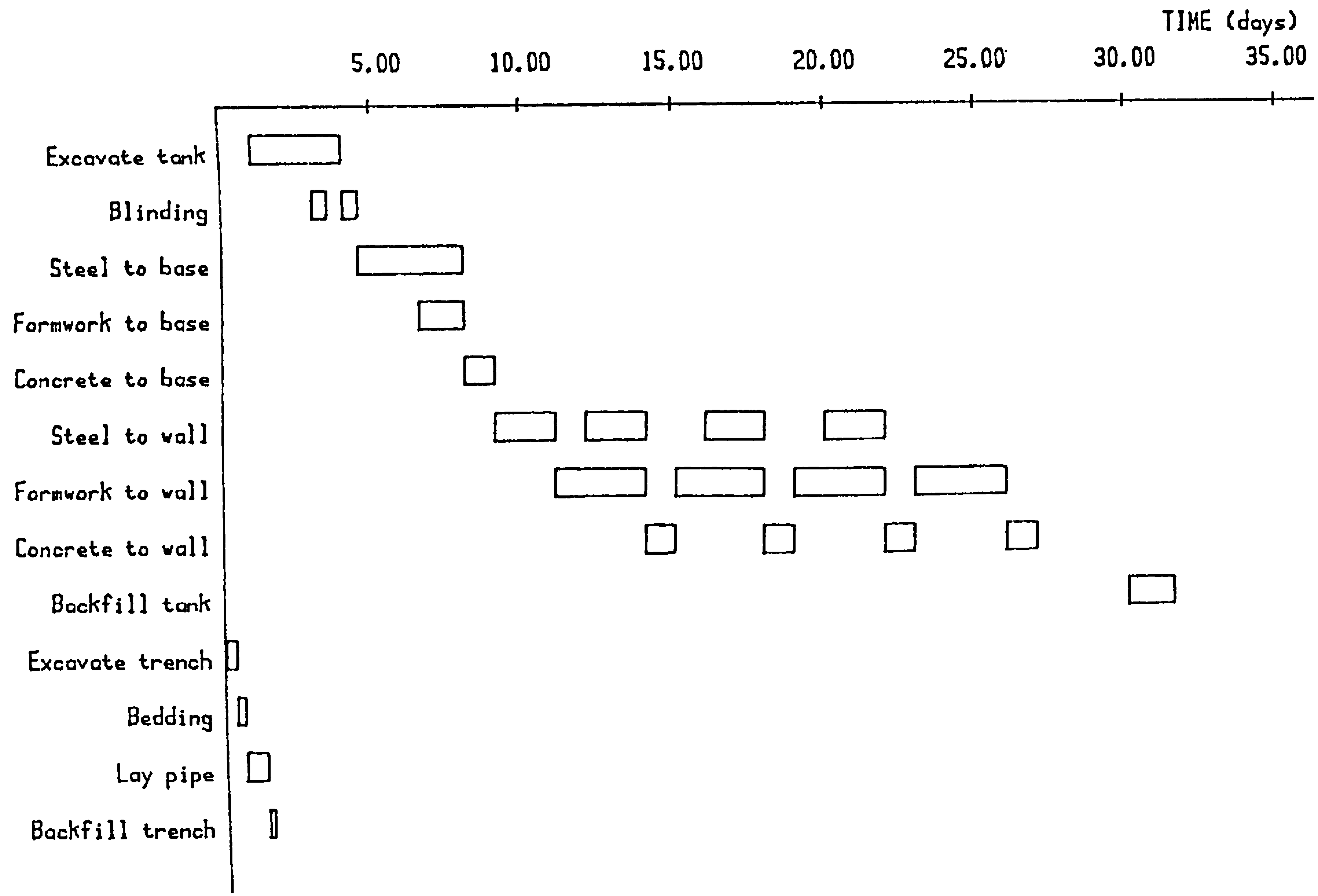


FIGURE NUMBER (9.4.1.1) Contractor No. 1 Tank Plan

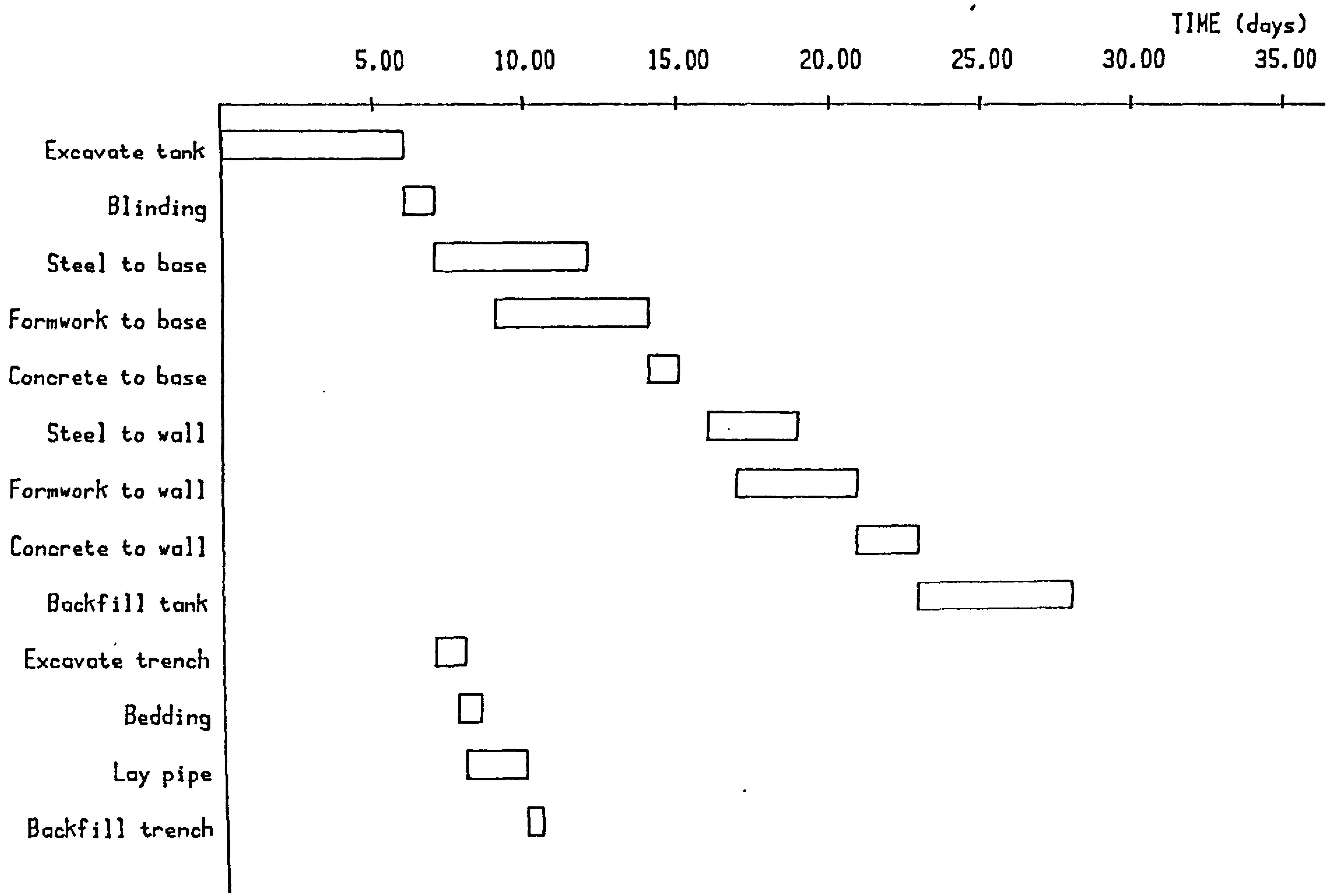


FIGURE NUMBER (9.4.1.2)   Contractor No. 2 Tank Plan

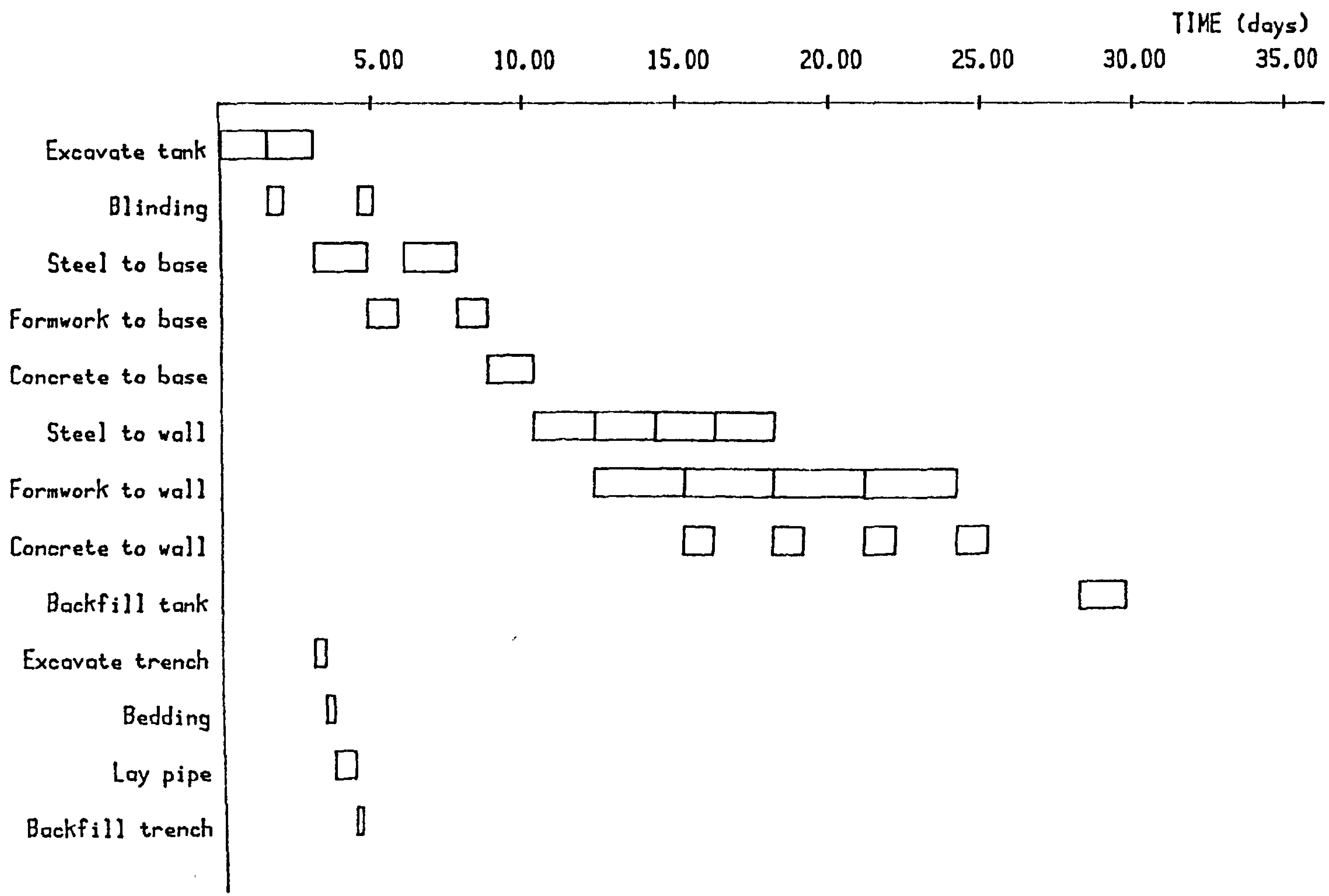


FIGURE NUMBER (9.4.2.1) TANK TEST RUN

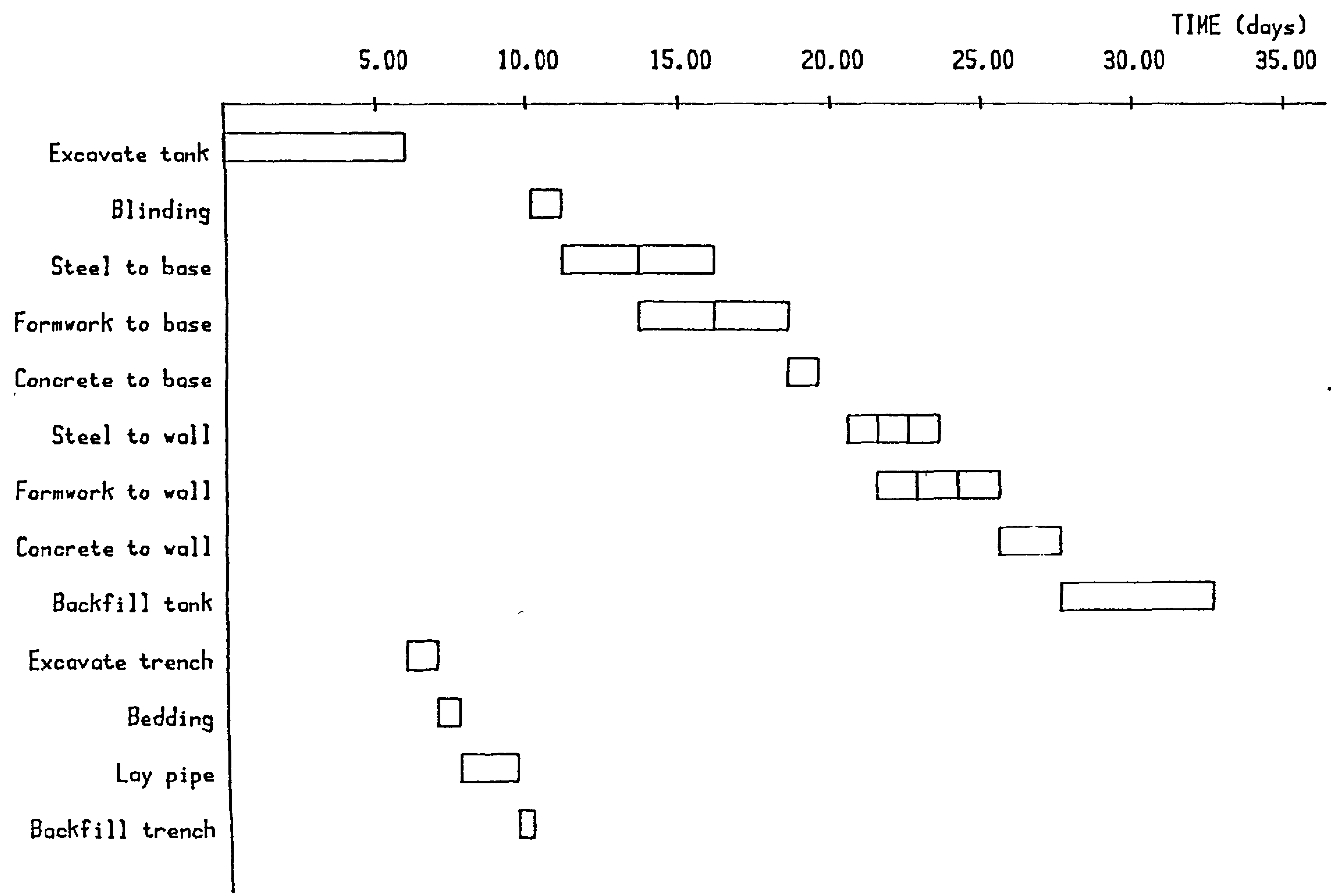


FIGURE NUMBER (9.4.2.2) TANK TEST RUN

9.5 Conclusions

The scheduler has successfully produced satisfactory plans for all the projects. In some cases, the plans were identical to the contractors' own plans. This is useful because it shows that the scheduler is a planning tool that may be used to reflect different contractors' work methods. This is important because some planning methods may require fundamental changes in planning techniques before they may successfully be used.

CHAPTER 10

DISCUSSION

10.1 General discussion of the model

The scheduler generally performed well in all the test runs. This success may be considered in two ways. Firstly, the road and culvert test run showed that the scheduler is able to produce different plans given different access points, resource numbers, allocation orders, and priority values. The second set of runs showed that the scheduler was able to produce plans that were comparable with those produced in industry.

The basic aim of the research was to develop a model that included site layout information in it's production of plans. The scheduler has surpassed those simple aims, and is now a model that utilises a sophisticated site and resource model to form plans semi-automatically from site layout data. The level of detail of the site and resource model is such that the plans are produced with efficient resource usage, resource buffers, area time lags (such as concrete curing), and resource transfer times. These are features that occur only singly (if at all) in other planning models. At some stage of the research, then, the aims changed to include the element of "realism" that has been strived for in many other models, as discussed in chapter 1.

The step towards automation of the logic production is valuble in two ways, Firstly, it eliminates much hard work on the part of the planner, and secondly will eventually lend itself to integration with a CAD drafting package. This integration is further discussed in section (10.5).

The test runs did illustrate some slight modifications that may be made to the model in order to improve it's performance. These are discussed in the sections below.

10.2 The map and logic formation

The map generally performed the tasks required of it throughout the test runs. The initial assumption that the grid size of the map should be small, say 0.5m x 0.5m, was not always necessary. This was illustrated in one set of the road and culvert test runs, which demonstrated that the size of the grid square only had to be as small as the lesser of:

a) the smallest minimum allocation area for the resources.
b) the minimum operating buffer for the resources.

This is useful because larger grid sizes would greatly reduce the size of the data and decrease the computational times.

The Level method of forming the logic within the individual grid squares also performed reasonably well. In circumstances where the level method was unable to form the logic, a secondary knowledge-based rule system was used. This knowledge system might typically be used to control the precedence of steel fixing, formwork, and concreting which all occur "within" one another. It is envisaged that the knowledge system would be a company-wide file of accepted construction practice. The general level of detail required in this file would not be high, and once formed would need little maintence or updating.

The single-path logic that was adopted for the scheduler has been shown to be slightly deficient in certain circumstances. The factory roof truss erection is one such example, where the single path logic is not able to incorporate logic links from the top of the columns to all the grid squares constituting the roof truss. The problem arises as a consequence of the prefabrication of the truss and may be modelled within the resource model, although care has to be shown to prevent the roof trusses being straddled over the top of one column. The roof truss problem does not occur in the case of an insitu concrete beam. This is because the beam may be constructed whilst supported on falsework, regardless of whether the columns are constructed or not.

The single path logic also prevents the planning of multi-storey buildings to be carried out satisfactorily. This is because the single-path logic restricts the number of work faces in any vertical column to only one. This is very limiting in high-rise construction where many trades may be working at different storeys in the building. It might be argued that the storeys may be planned in isolation and then a repetitive unit planning technique (such as the line of balance method) used to coordinate the storeys. This, however, is not in the true spirit of the scheduler, whose aims were to plan any project, regardless of form.

The examples above illustrate the need for multiple-path logic formation. Modifications to include this feature would require much rewriting of the computer program in terms of the map and logic formation, although is not technically difficult. The introduction of the multiple work faces within one vertical column of work would also require the introduction of vertical distance buffers, and this in turn may require the site map to be considered in terms of grid cubes rather than grid squares. A cubic site map would probably reduce the definition of the work within the vertical column, however, and may cause problems in the logic formation.

10.3 The resource model

The resource model forms a major part of the scheduler, and it is worth discussing some of it's component parts in order to illustrate any possible improvements that may be made.

10.3.1 Allocation areas

The allocation area for a resource indicates the quantity of work required by the resource before it may feasibly commence working in an area. The combination of optimum and minimum allocation areas operated well together in the test runs. The optimum work area was the allocation area that was allocated in most instances during the test runs, although in situations where there were only a limited number of available grid squares, the minimum allocation area was used. This two size system allowed almost full operation of resources on site. A similar method of resource utilisation occurs on site with resource rarely being left idle if some work is available.

10.3.2 Transfer speeds and times

The transfer speed of any resource is perhaps a slightly artificial value. This is because the transfer speed will depend on many site factors such as soil type, rainfall, availability of haul roads and relief (37,38). In future developments of the model these factors could feasibly be taken into account.

There are cases where there is a need for the inclusion of fixed time transfers. This situation may arise, for example, in the dismantling of a large tower crane which takes a fixed time regardless of the distance to be travelled.

The improvement of the transfer time would allow the positioning of temporary works facilities, such as batching plants, material stores, site offices and canteens to be evaluated. Time has prevented the development of temporary works layouts to be considered in this research, although the model is now in a position to facilitate this extra study.

10.3.3 Buffers

The resource buffers have generally worked well, however care must be taken in their use. This occurs because of the definition of the operating buffers in the model. In the line of balance method, for example, the buffers include a work element and a interference element. The scheduler buffers are only interference type buffers, with the work type being controlled by the allocation areas. The scheduler buffers are also additive buffers, so that the true buffer between two resources is the sum of the two individual buffers. This may not be a realistic situation in all situations, as operating room buffers may feasibly be shared by the two resources, for certain types of operations.

The present horizontal buffer system is satisfactory for most situations that may arise on a construction site, however, some situations do exist that are not. An example of this is where two work areas are horizontally very close, and consequently subject to buffers, but vertically displaced. In this situation the existing horizontal buffers are not suitable, as the work may feasibly be carried out at the two different levels. It may be worth, therefore, to consider the buffers as being "spherical", rather than the present "circular" type.

A previous section discussed the feasibility of three dimensional work maps and the corresponding requirement for vertical distance buffers. The new style spherical buffers would satisfactorily cover this eventuality.

10.3.4 Pure time lags

The pure time lags are applied to restricted areas on the construction site after the completion of certain operations. Concrete pouring is an example of this, where the newly poured concrete requires curing before further work may be carried out on it. The scheduler models the time lags as if there is a resource with zero operating buffers operating on the area. This not only prevents further work but also means that the area is unable to be included in another adjacent resource's operating buffer. This has benefits for certain resources and drawbacks for others. For concrete problem, for example, the area restriction should prevent plant rolling on and around the newly poured concrete, whereas overhead cranes should not be prevented from traversing over the concrete, as they would cause no damage.

It may be necessary therefore, to rethink the relationships between operating plant and restricted areas. These relationships would obviously depend not only on the nature of the work being carried out by the operating resources, but also of the restricted area.

10.4 Priorities

The priorities form an essential part of the resource allocation process. They are used to reflect the relative importance of the individual grid squares with respect to one another, and may be subdivided as follows:

a) Structure
b) Access
c) Resource

The main difficulty in using the three types of priority is in deciding the relative value of each. The road and culvert test runs showed that the priority balance between the the access and resource priorities produced different plans, and that it was essential to get the correct balance in order to achieve the "best" plan. The problem of finding this balance is compounded by the lack of common ground for the comparison of the three. The structure priority, for example, is formed by considering the cost of construction of any particular structure, whereas the access and resource priorities are formed by some notional distance measures. The distance measures for the access and resource priorities also cannot be used for direct comparison as it is difficult to reconcile the need and value of good access, which may occur at another area of the site, with that of transporting resources large distances to those areas.

This may not be a problem, however, as the priorities are intended to influence the flow of the resources around the site, and not immediately produce the best plan. The only means of achieving this plan is by using an iterative approach, as illustrated in the road and culvert test runs, and using a costing system that effectively and correctly models resource transfer costs. The scheduler would then be able to carry out all the interations, cost each plan, and present the lowest cost plan as being the best.

The access priority is one area in which the priority system may be improved. The road and culvert test runs illustrated two particular instances in which the access priority did model an infeasible site situation. The first of these was in the overlapping of activities (particularly excavate) as illustrated in figure (B73) in appendix B. In this test run, the third excavate team commenced work at chainage 75m even though no access was available there. Similar situations occured at chainages 225m and 375m on the same run. Technically, the access to these points would generally be provided by the continuous working of one of the excavate teams from a given access point.

The second occurance of the failure of the access priority is illustrated in figure (B46), and is similar to that described above. In figure (B46), excavation restarts at chainage 250m after a discontinuity caused by the culvert construction. In reality, the culvert construction would cut-off all access from the chainage 0m access point to areas in the region of chainages 200m to 400m.

The two illustrations above are cases in which the activities should have restricted access to other areas of the site. In order to model this, these restrictions have to be included in the access priority model, and would necessitate the recalculation of the access priorities after each resource allocation, as with the resource priorities.

10.5 Future work

Most of the initial future work in the development of the scheduler will probably be involved in improving the speed of the scheduling. As an indication of the speed of the present version of the scheduler, the factory erection project with a grid square size of 0.5m x 0.5m took about 4 hours to complete. In comparison, modern critical path calculations for a similar size project might take 30 seconds to complete. The turn-around-time for the scheduler is particularly unsatisfactory when one considers that many iterations may be required to produce reasonable plans.

The run time of the scheduler may be improved in two ways. Firstly, faster processing will improve the speed of the schedule, because the scheduling routines are almost entirely processor-bound. The increase of speed required for the scheduling would not be attained on any micro-computer presently available on the market, and consequently would involve the stepping up into the mini-computer range.

The second method of improving the speed is by the introduction of much larger reserves of computer memory (RAM). The present version of the scheduler is severely restricted by the size of the available RAM of the computer. Increases in the RAM would improve the speed of the scheduler in the following ways:

a) Storage of Work maps. The present version of the scheduler is required to form the maps of the available work whenever it considers the allocation of each resource. The availability of more RAM would mean that all the work maps for all the resources could permanently reside in memory. This would prevent the maps having to be reformed, by allowing a continual updating of each as the site situation altered. Keeping records of all the updating made during one allocation pass of the scheduler would also eliminate attempts to allocate resources in subsequent passes whose work availability has not changed. These two points would produce extremely significant time savings.

b) Disk information. Information that is stored on disk has a releatively long retrieval time in comparison to information stored in RAM. Although the quantity of disk information used during the schedule is small, some savings in time could be achieved by the storage of this information in RAM.

The combination of increased RAM and faster processing speeds may produce significant increases in the scheduling run time.

Another very time consuming task performed by the scheduler is the initial collection of the site information on which the schedule is based. It is envisaged that the future developments would include integration of the scheduler with a drafting package. This drafting package would supply all the information required for the formation of all the activities, site map and logic. The integration of the scheduler with a drafting package would allow the plans to be produced automatically from the engineering drawings supplied by the client.

Many of the points discussed in earlier sections of this chapter will also provide scope for further work. These are itemised below:

a) Multiple path logic
b) Site model improvements to include relief, soil type and weather effects.
c) Realistic transfer times and speeds
d) Costing system for plan evaluation
e) Dynamic resource priorities
f) Spherical and vertical buffers
g) Pure time lag relationships

CHAPTER 11

CONCLUSIONS

The construction industry has been aware of the influence that the layout of the construction site may have on the organisation of a project. Generally, however, most planning techniques that are commonly used in the construction industry, do not utilise any site layout information in the formulation of construction plans. Previous work on layouts has been largely limited to the Architectural and Production engineering fields in the design of building and process plants respectively. The development of layouts using these static methods was shown to have little relevance in the development of temporary works layouts for construction, as the requirements for temporary facilities changes thoughout the course of construction of the project.

Some construction planning techniques, such as the Line of balance method, allow the development of construction plans to be carried out with inclusion of site geography considerations. Application of these techniques, however, are limited to linear or repetitive-unit construction sites such as roads and housing estates, where the site geography may be simply defined in one dimension.

The main objective of this reseach was to develop a method that used layout information in the production of construction plans, regardless of the form of the construction site. The incorporation of this information took two forms. The first was the "macro" site layout, which may be defined as the relative positioning of structures on the site. This was utilised to influence the order of the construction of the structures and, consequently, the direction of the progression of work of the resource teams. The movement of the resources from one area of the site to another may thus be carried out in an efficient manner.

The second category of the site layout information was the "micro" site layout. This layout may be defined as the relative positioning of individual work types within a structure. This site layout information was utilised to define the sequencing of the various items of work.

The results of two sets of test runs of the model are discussed in chapters 8 and 9. The aim of the first set of test runs was to illustrate the working and various features of the model on a simple road and culvert project. The plans of work produced using the model were comparable to those produced using other methods (as discussed in chapter 4). The second set of test runs consisted of producing plans for three small projects. These projects were also planned by two contractors in industry. The plans produced by the model were very similar to those produced in industry.

The main drawback of the current version of the model is that it takes a very long time to produce plans. The future work section in chapter 10, discusses ways in which the performance of the model may be improved. The improvements basically involves the use of larger and faster computers, and would require the model to be developed on mini-computers. The model would also, in future developments, benefit from integration with a drafting package. This integration would allow the construction plans for a project to be developed automatically from the contract drawings. This automation would greatly reduce the time taken by the contractor's staff in producing plans.

REFERENCES

1. Calvert,R.E., "Introduction to Building Management", Butterworth, London, 1970

2. Broughton,H.F., "Economic site organisation and building supervision", Spon, London, 1970

3. Edmeades,D.H., "The Construction site (metric) : a study of site organisation and new concepts in operational control." Estates Gazette, London, 1972

4. Causey,E.D., "Productivity on Large Construction sites", Paper presented to MANPROD 70 Symposium Univ. of Manchester Inst. of Sci. and Tech. (1970)

5. Whitehead,B. and Eldars,M.Z., "The planning of single-storey layouts", Building Sci. Vol 1 (1965), pp 127-139

6. Agraa,O.M. and Whitehead,B., "A Study of Movement in a School Building", Building Sci. Vol 2 (1967), pp 279-289

7. Agraa,O.M. and Whitehead,B., "Nuisance restrictions in the planning of Single-storey Layouts", Building Sci. Vol 2 (1968), pp 291-302

8. Bernholtz,A. and Fosburg,S., "A Generalised program for transforming relationship values into plan layouts", Paper in Parslow and Green, "Advanced computer graphics", Plenium press, London and N.Y. (1971)

9. Lee,R.C. and Moore,J.M., "CORELAP - computerised relationship layout planning", Jour. Ind. Eng. Vol 18 (1967), pp195-200

10. Moore,J.M., "Computer program evaluates plant layout alternatives", Jour. Ind. Eng. Vol 3 (1971), pp19-25

11. Hafez,E.,Agraa,O.M. and Whitehead,B., "Automation of Data preparation in Computer program for the planning of single storey layouts", Build. Sci, Vol 2

12. Sekhon, G.S., "Dynamic programming interpretation of construction-type plant layout algorithms and some results", Computer-Aided Design, Vol 14 (1982), pp141-144

13. Buffa,E.S.,Armour,G.C. and Volman,T.E., " Allocating facilities with CRAFT", Harv. Bus. Rev. Vol 42 (1962), pp136-159

14. Armour,G.C. and Buffa,E.S., "A Heuristic Algorithm and simulative approach to relative location facilities", Man. Sci. Vol 9, No 2, Jan (1963)

15. Armour,G.C., "Computerised Relative Allocation of Facilities Technique (CRAFT)", Share Program Library, Sep (1965)

16. O'Brien,C. and Abdel Barr,S.E.Z., "An interative approach to Computer-Aided Facility Layout", Int. Jour. Prod. Res. Vol 18 (1980), pp201-211

17. Muther,R., "Systematic Layout Planning", Cahners Books (1973)

18. Rosenblatt,M.J., "The facilities layout problem: a multi-goal approach", Int. Jour. Prod. Res. Vol 17 (1979)

19. Dutta,K.N. and Sahu,S., "A multi-goal heuristic for facilities design problems: MUGHAL", Int. Jour. Prod. Res. Vol 20 (1982)

20. Fortenberry,J.C. and Cox,J.F., "Multiple criteria to the facilities layout problem", Int. Jour. Prod. Res. Vol 23 (1985)

21. Hammouche,A. and Webster,D.B., "Evaluation of an application of graph theory to the layout problem", Int. Jour. Prod. Res. Vol 23 (1985)

22. Lockyer,K.G., "An introduction to critical path analysis", The Pitman press, Bath. Third Edition (1974)

23. Simms,A.G. and Britten,J.R., "Project network analysis an critical path", Machinery Publishing Co. Ltd, Sussex (1969)

24. O'Brien,J.J., "CPM in construction management", McGraw-Hill Book Co., New York (1965)

25. Woodgate,H.S., "Planning by Network", Business Books Ltd, London (1967)

26. British Standards Institute, BS 4335, 1968

27. British Standards Institute, BS 4335, 1972

28. Elmaghaby,S.E., "Activity networks - project planning and control by network models", John Wiley & Sons Inc., USA (1977)

29. Battersby,A., "Network analysis for planning and scheduling", Macmillan, London, Third Edition (1970)

30. Lumsden,P., "The line of balance method", Pergammon Press Ltd, UK (1968)

31. National Building Agency, "Programming House Building by Line of Balance", N.B.A. (1968)

32. Johnston,D.W., "Linear scheduling method for Highway construction", Proc ASCE (Construction Div.), June 1981

33. O'Brien,J.J., "VPM scheduling for High rise Buildings", Proc ASCE (Construction Div.), Dec. 1975

34. Birrell,G.S., "Construction planning: beyond the critical path", Proc ASCE (Construction Div.), Sept 1980

35. Trimble,G., "Resource Orientated scheduling", Int. Jnl. of Project Management, May 1984

36. Scriver,B.A.A., "Planning linear projects on a micro-computer", BSc Thesis, Department of Civil Engineering, Univ. of Nott'm 1984

37. Stanyard,J.R., "An investigation into Site Layout", BSc Thesis, Department of Civil Engineering, Univ. of Nott'm 1976

38. Lindesay,D.F., "The effects of Site Layout on Project Cost", BSc Thesis, Department of Civil Engineering, Univ. of Nott'm 1983.

APPENDIX A - The Grimsby site survey

The Grimsby site was a 1km stretch of road, with all the temporary facilities for the site situated at it's mid-point.

An activity sampling technique was carried out on the labour-force over 5 days at irregular intervals. This was done so that there would be changes in the work types that were being carried out on the observation days. A total of 3200 observations of the labour-force were made on these days, which were sub-divided into the following categories:

a) Work
b) Assist
c) Discuss
d) Walk
e) Idle

The first and last of these categories are self-explanatory, however, the remaining categories may require some further discussion.

a) Assist - This category was used when a labourer was at the place of work and only prevented from working by the actions of another member of his gang. An example of this might occur when two labourers are digging a hole, one with a pick axe and the other with a shovel. In this situation, both of the labourers may not work at the same time, as one depends on the other.

b) Discuss - This category was used in situations when then labour-force was discussing the work. Normally this occured between the foreman and the ganger, or the ganger and the labourers.

c) Walk - This category was used when the labourers were observed walking across the site. This category was sub-divided into two sub-categories of:

i) Loaded

ii) Unloaded

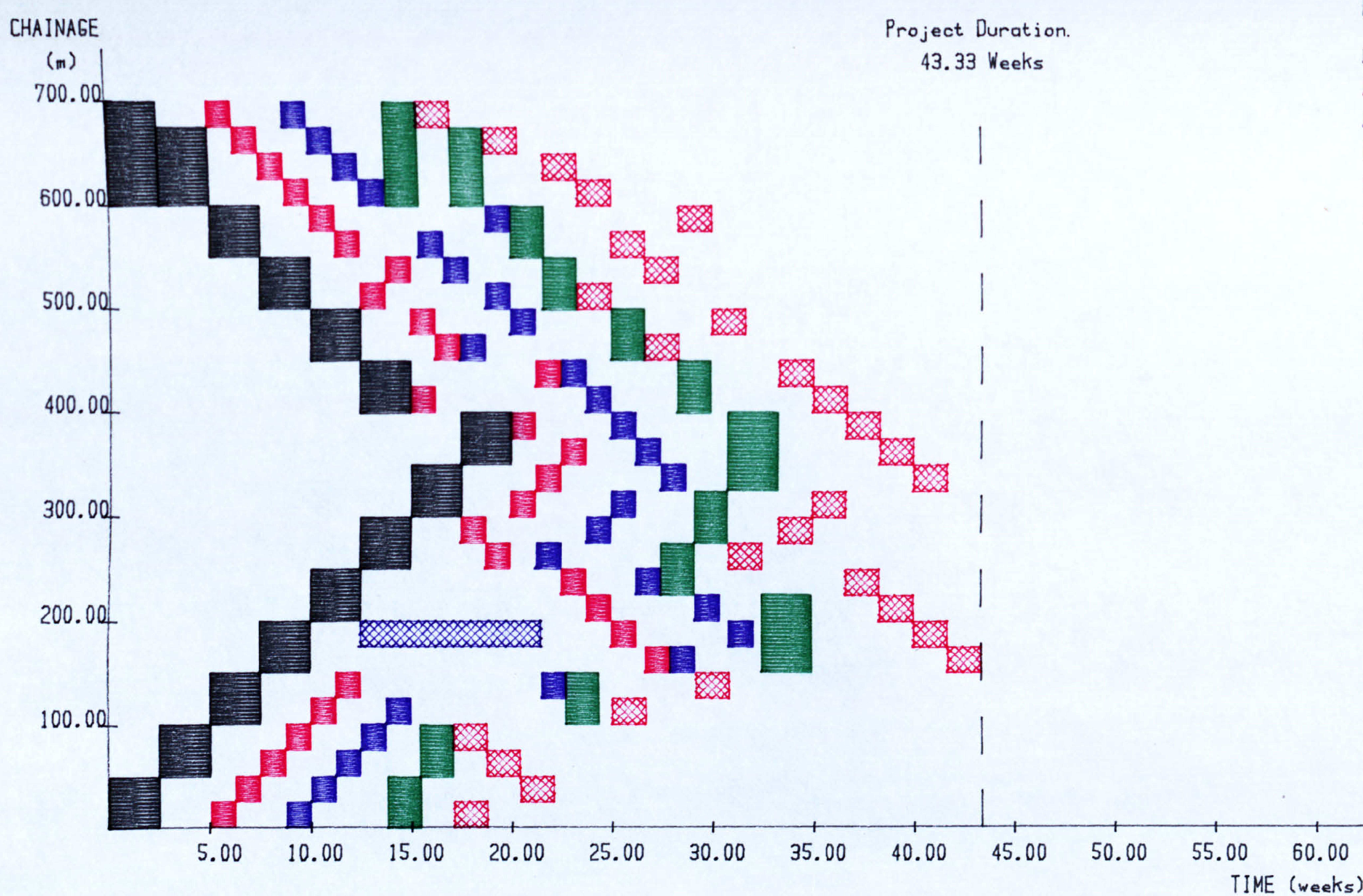
In the first of these the labourer was carrying some equipment or materials, and the second he was empty-handed.

The results for the Grimsby site observations are given below under the categories described above.

Work -	47 %
Assist -	5 %
Discuss -	9 %
Walk (L) -	4 %
Walk (U) -	13 %
Idle -	22 %

APPENDIX B - Road and Culvert test runs

This appendix contains all the time chainage charts for the road and culvert test runs, which are discussed in detail in chapter 8.



Minimum Distances (m)

Excavate	50.0
Sub-base	25.0
Road-base	25.0
Surface	50.0
Finishes	25.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.010
Resource	0.990

Resource Utilisation (%)

Excavate	100.00
Sub-base	84.00
Road-base	80.00
Surface	57.14
Finishes	88.89
Culvert	100.00

FIGURE NUMBER (B1) ROAD AND CULVERT TEST RUN NUMBER 1

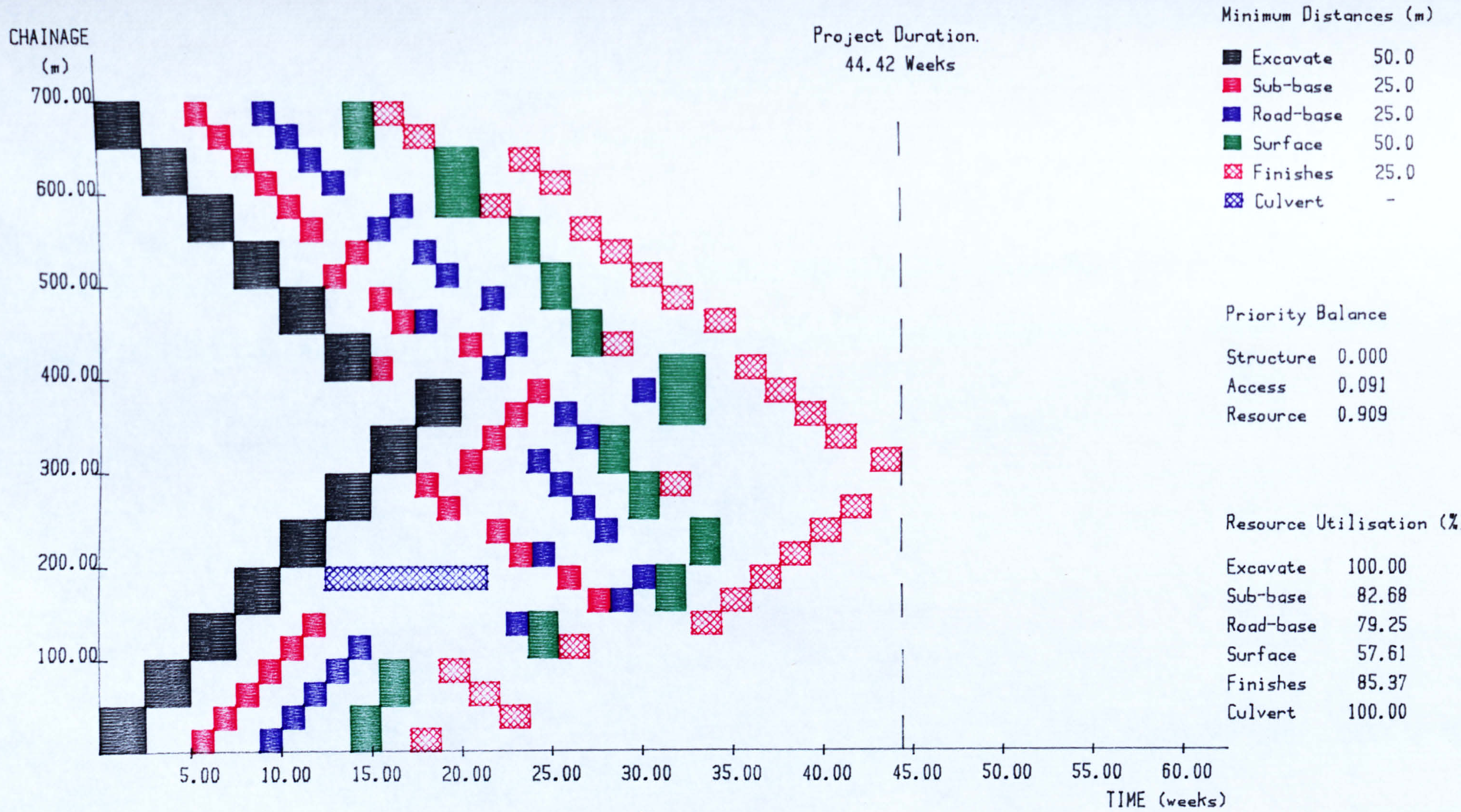


FIGURE NUMBER (B2) ROAD AND CULVERT TEST RUN NUMBER 2

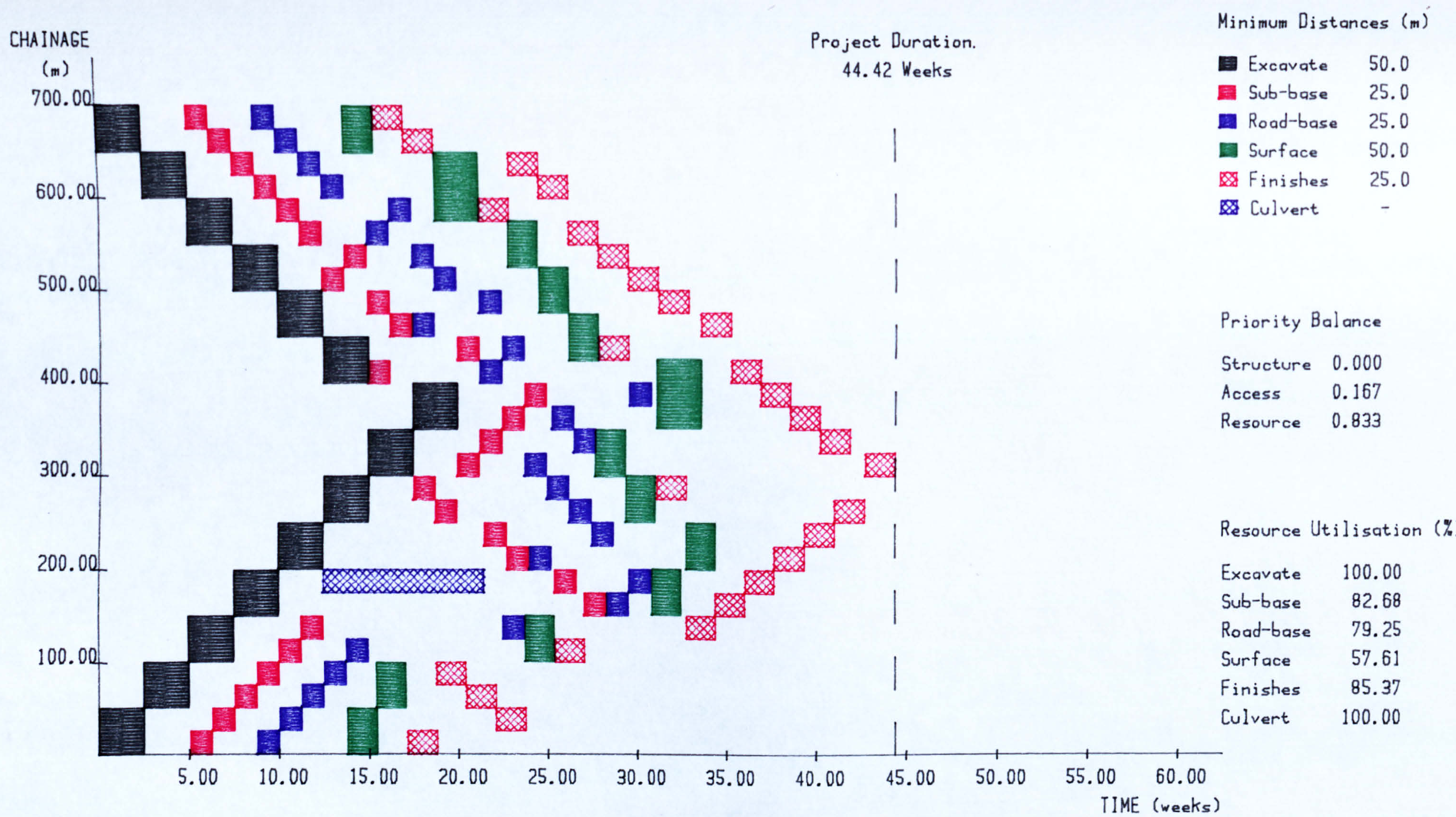


FIGURE NUMBER (B3) ROAD AND CULVERT TEST RUN NUMBER 3

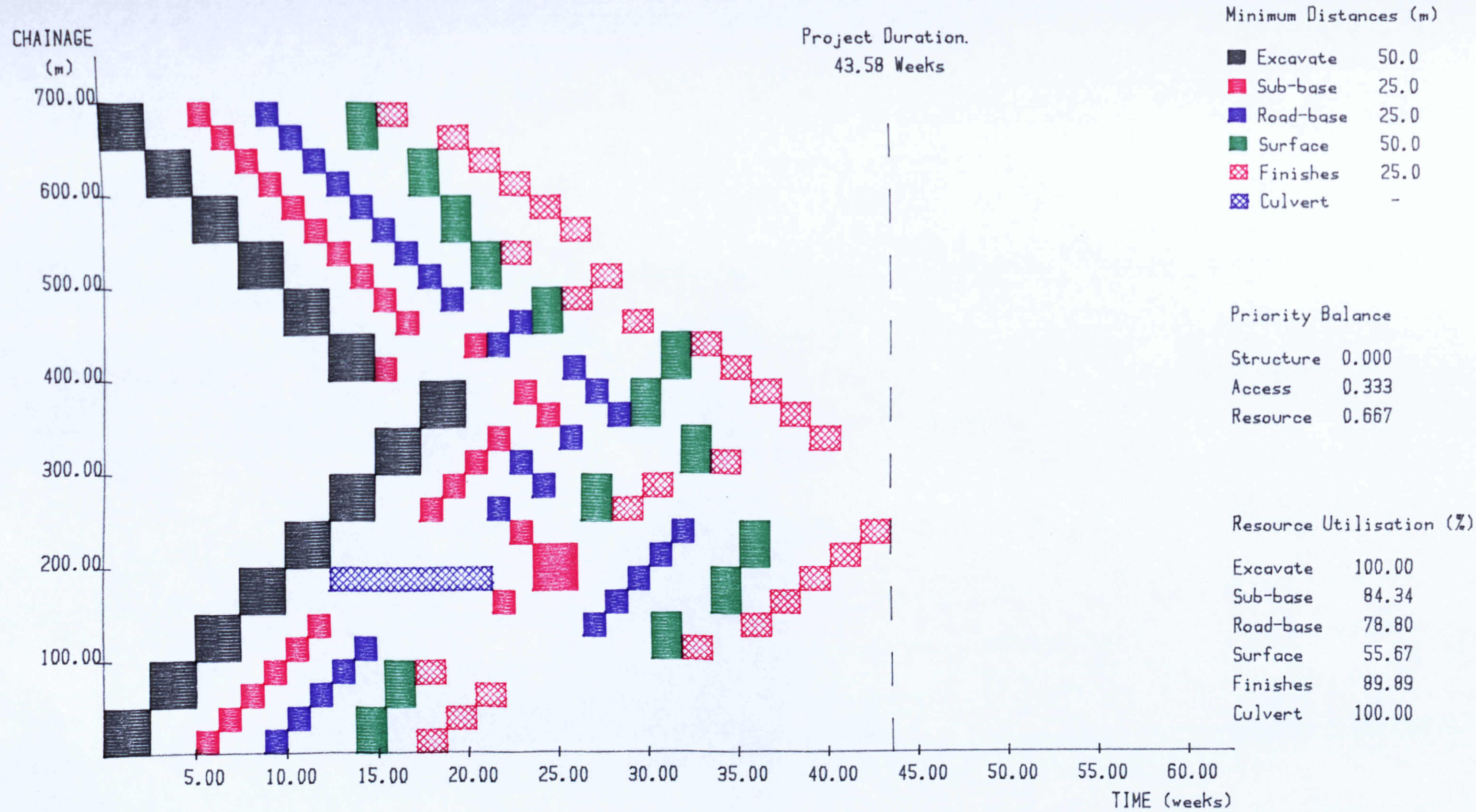


FIGURE NUMBER (B4) ROAD AND CULVERT TEST RUN NUMBER 4

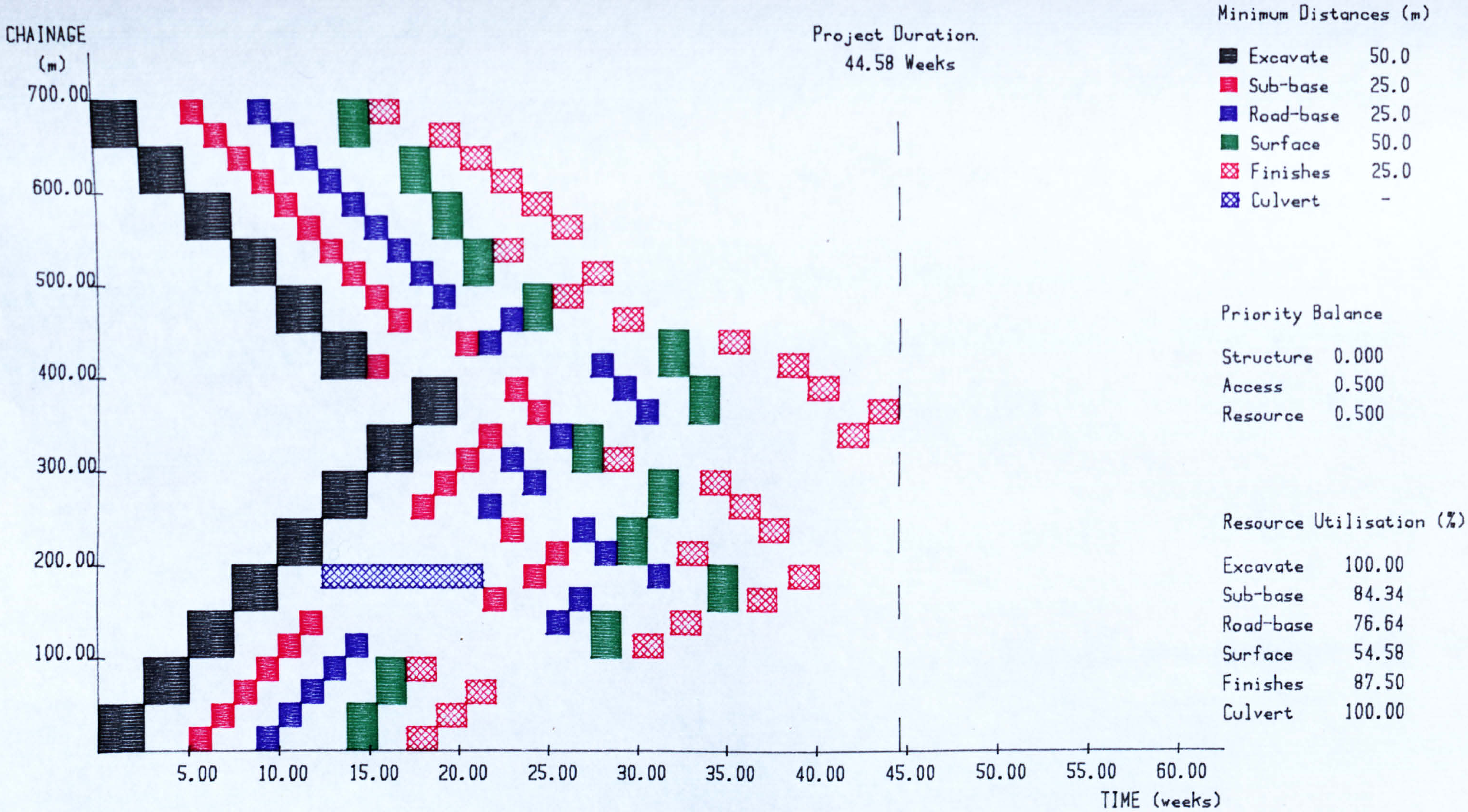


FIGURE NUMBER (B5) ROAD AND CULVERT TEST RUN NUMBER 5

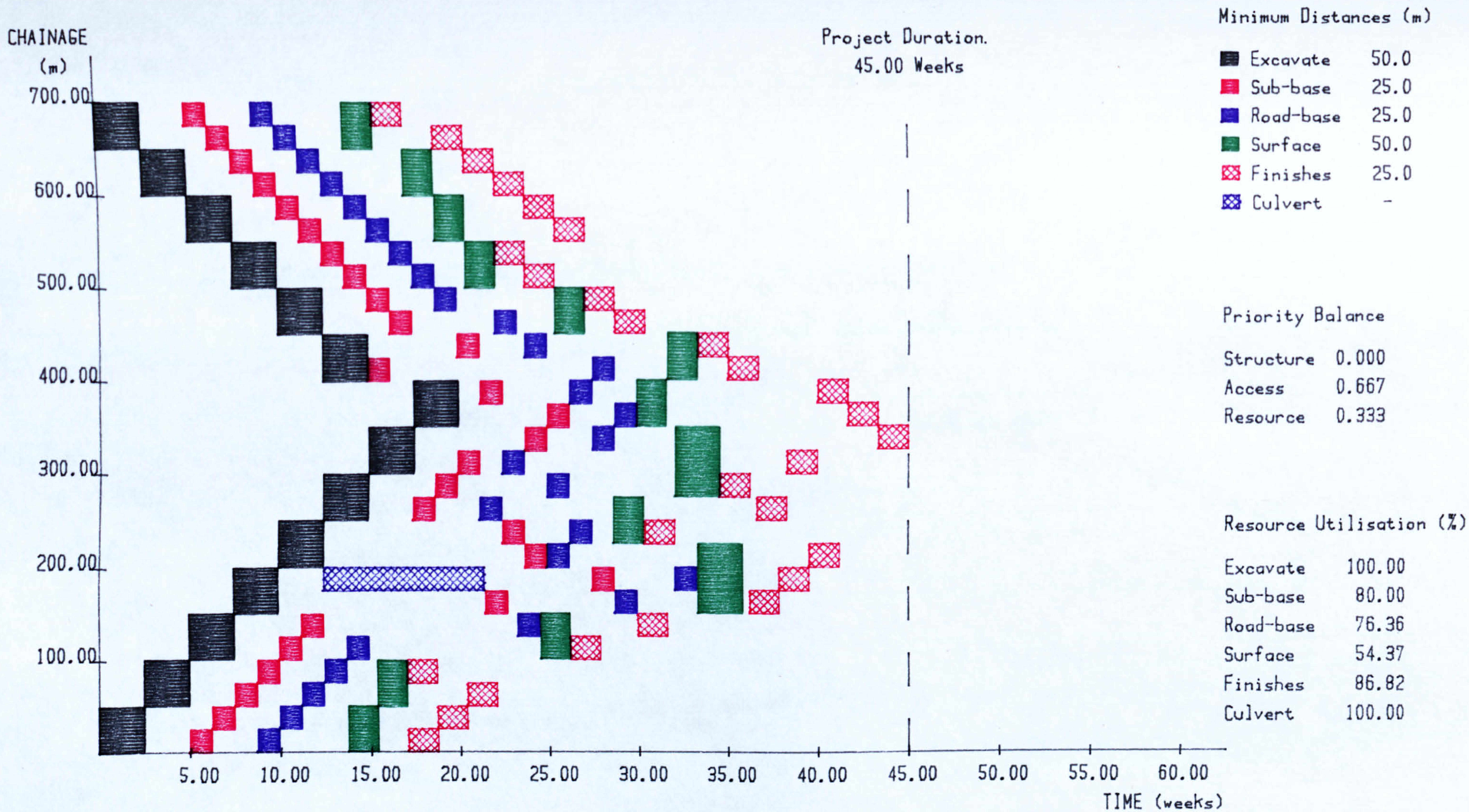


FIGURE NUMBER (B6) ROAD AND CULVERT TEST RUN NUMBER 6

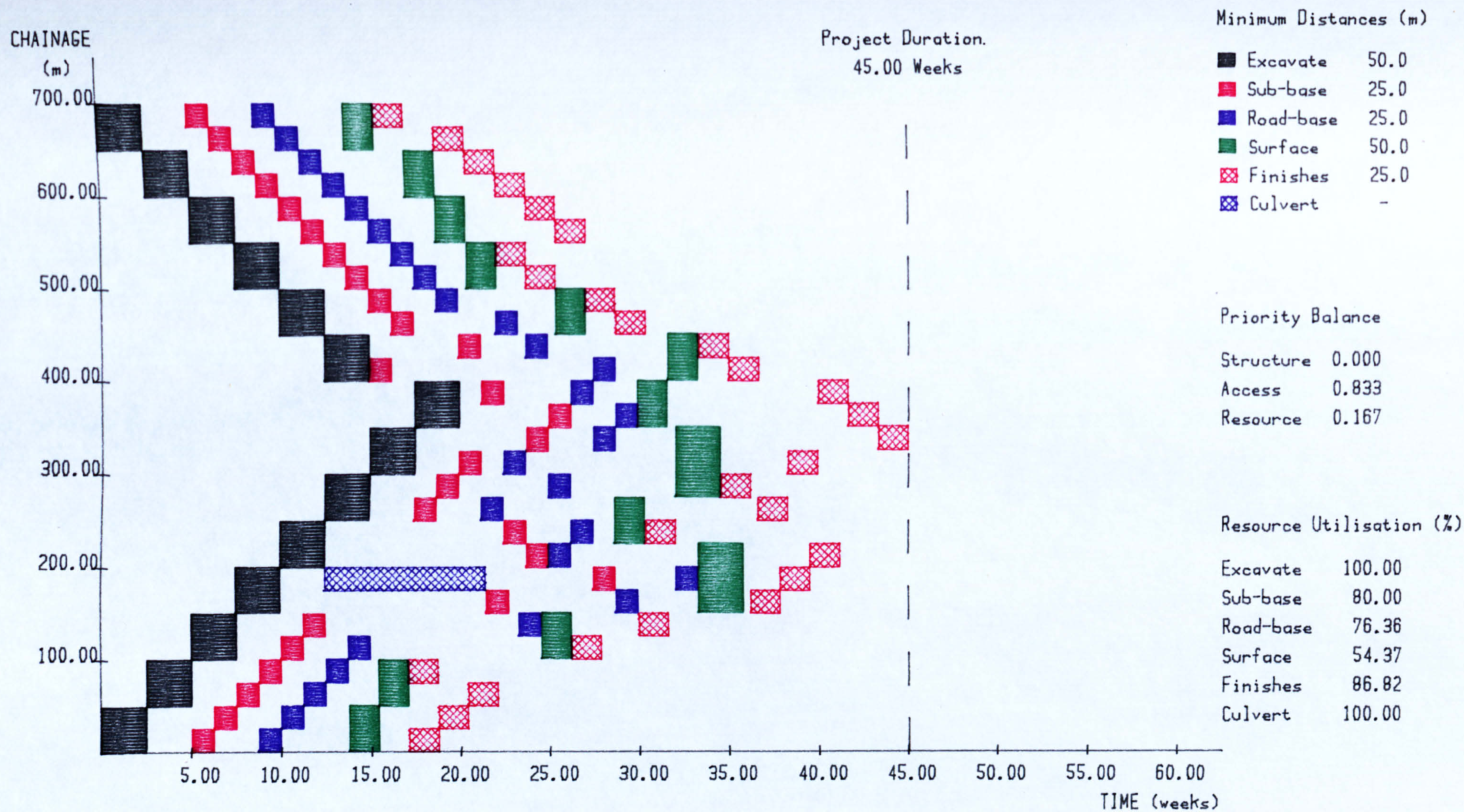


FIGURE NUMBER (B7) ROAD AND CULVERT TEST RUN NUMBER 7

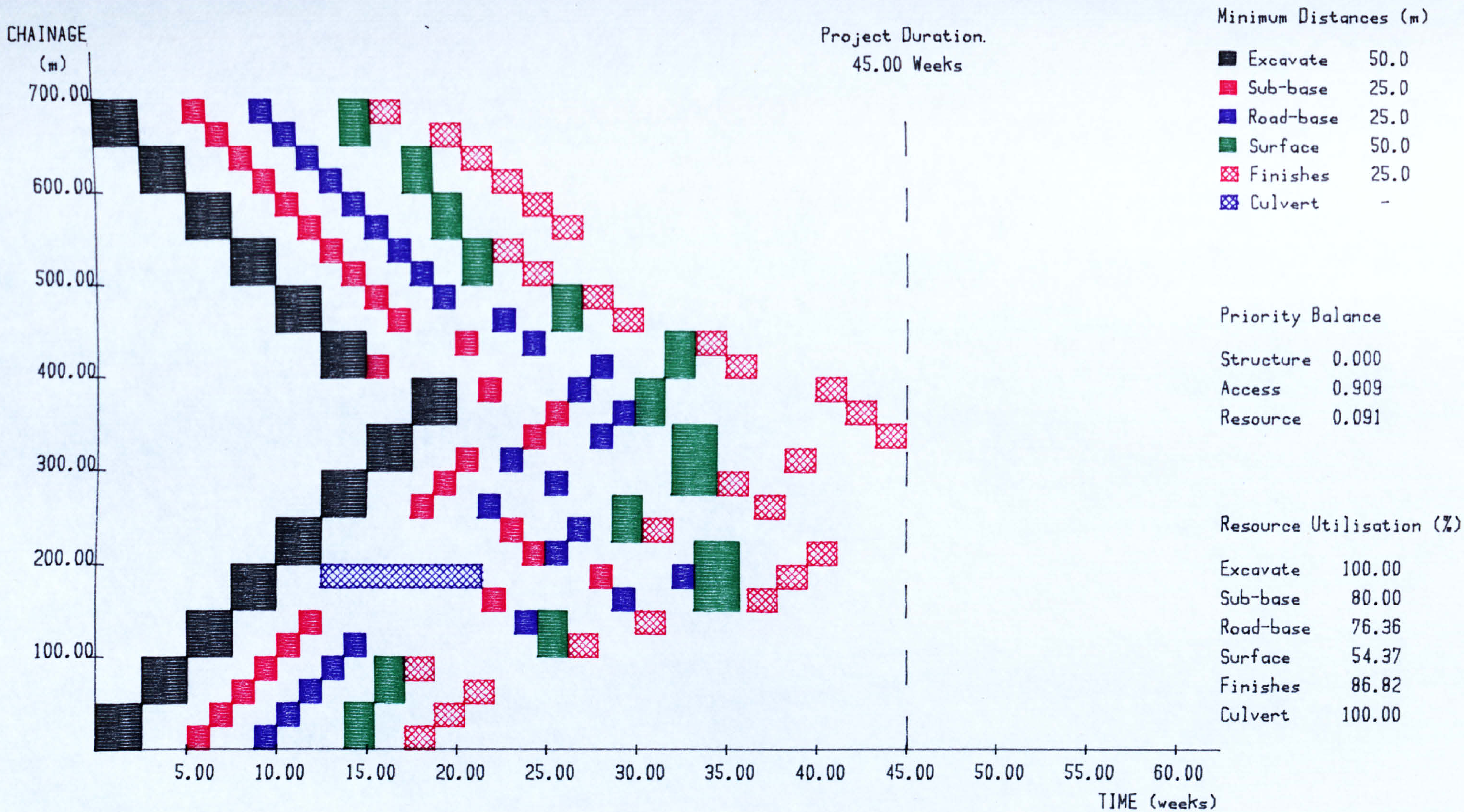


FIGURE NUMBER (B8)   ROAD AND CULVERT TEST RUN NUMBER 8

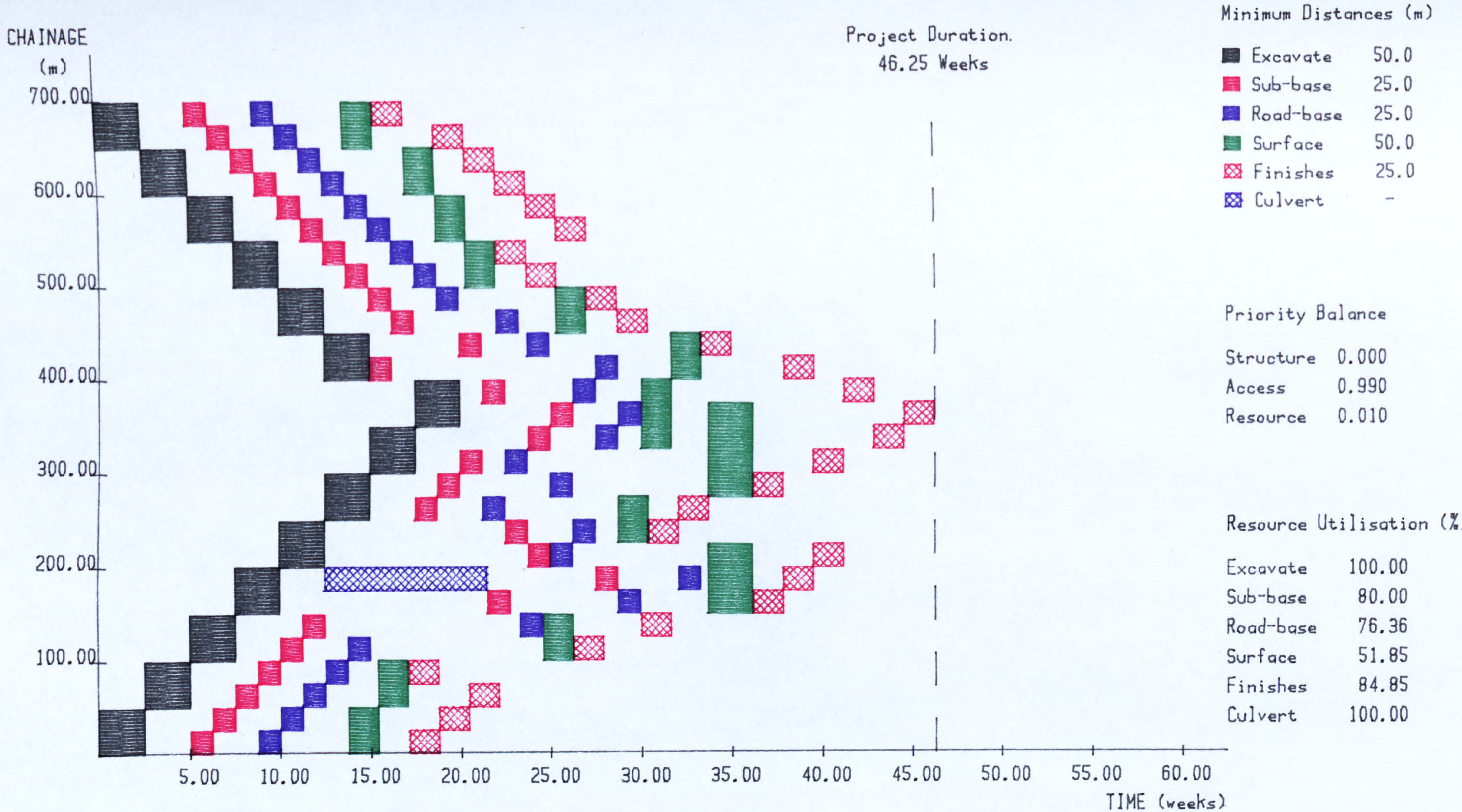


FIGURE NUMBER (B9) ROAD AND CULVERT TEST RUN NUMBER 9

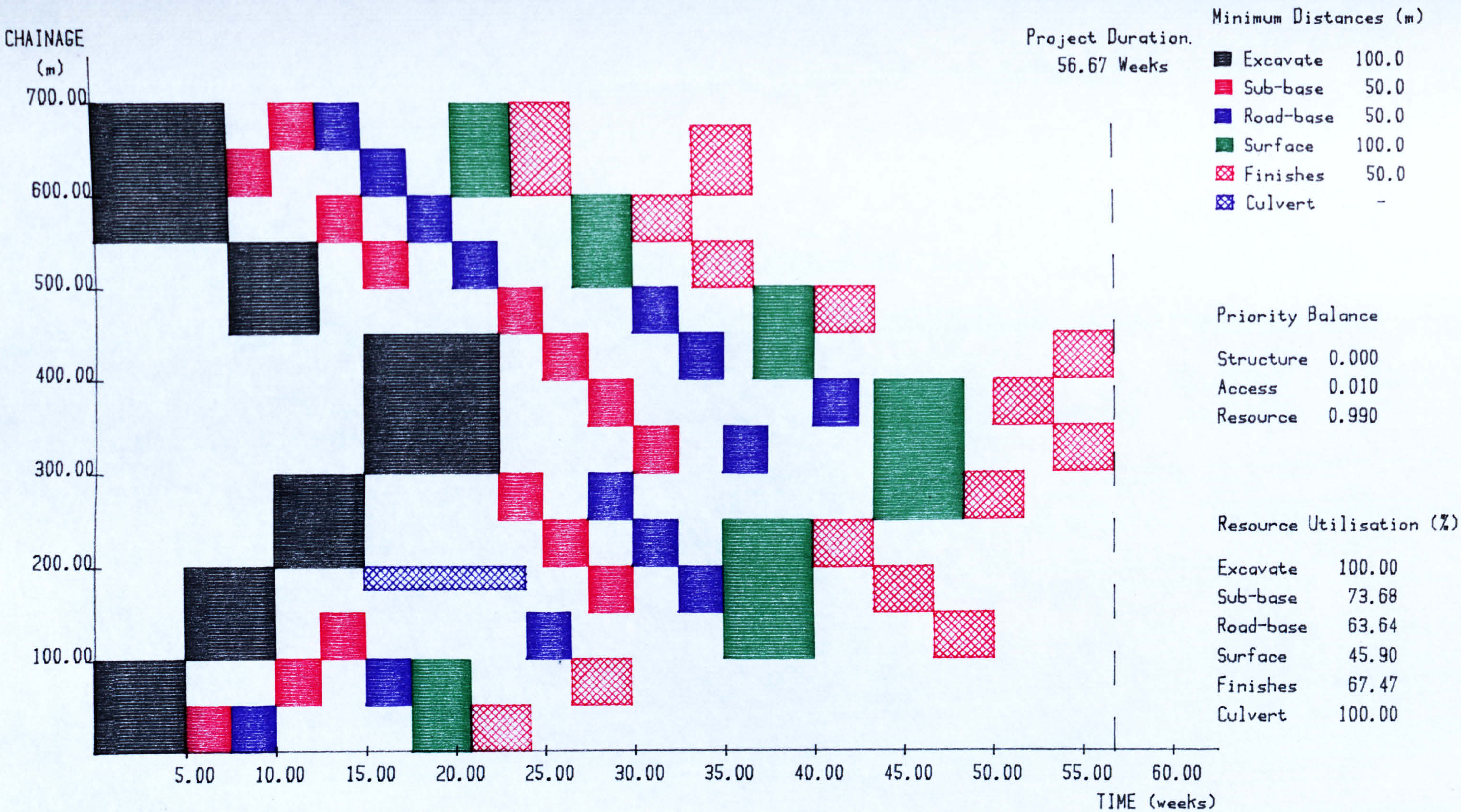


FIGURE NUMBER (B10) ROAD AND CULVERT TEST RUN NUMBER 10

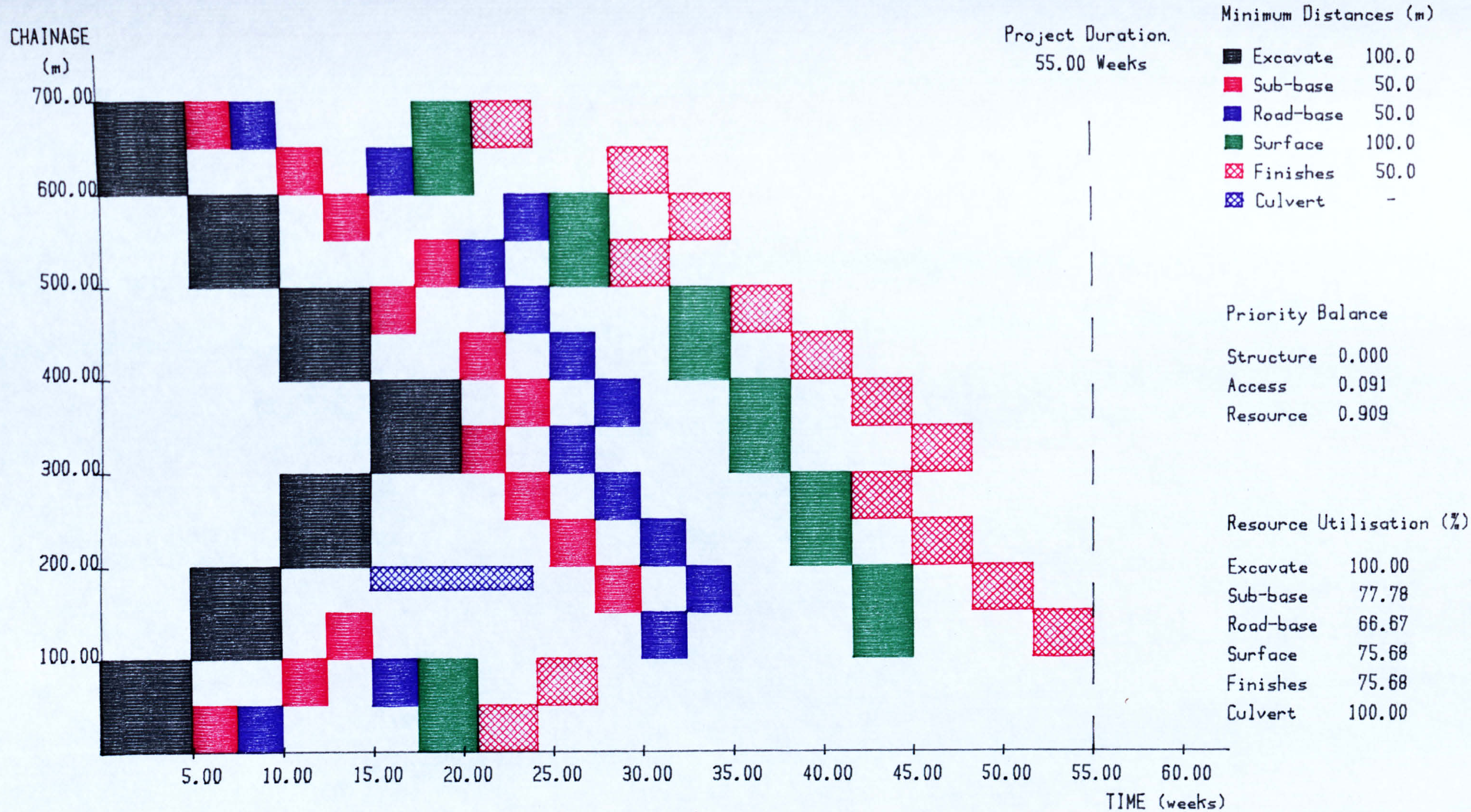


FIGURE NUMBER (B11) ROAD AND CULVERT TEST RUN NUMBER 11

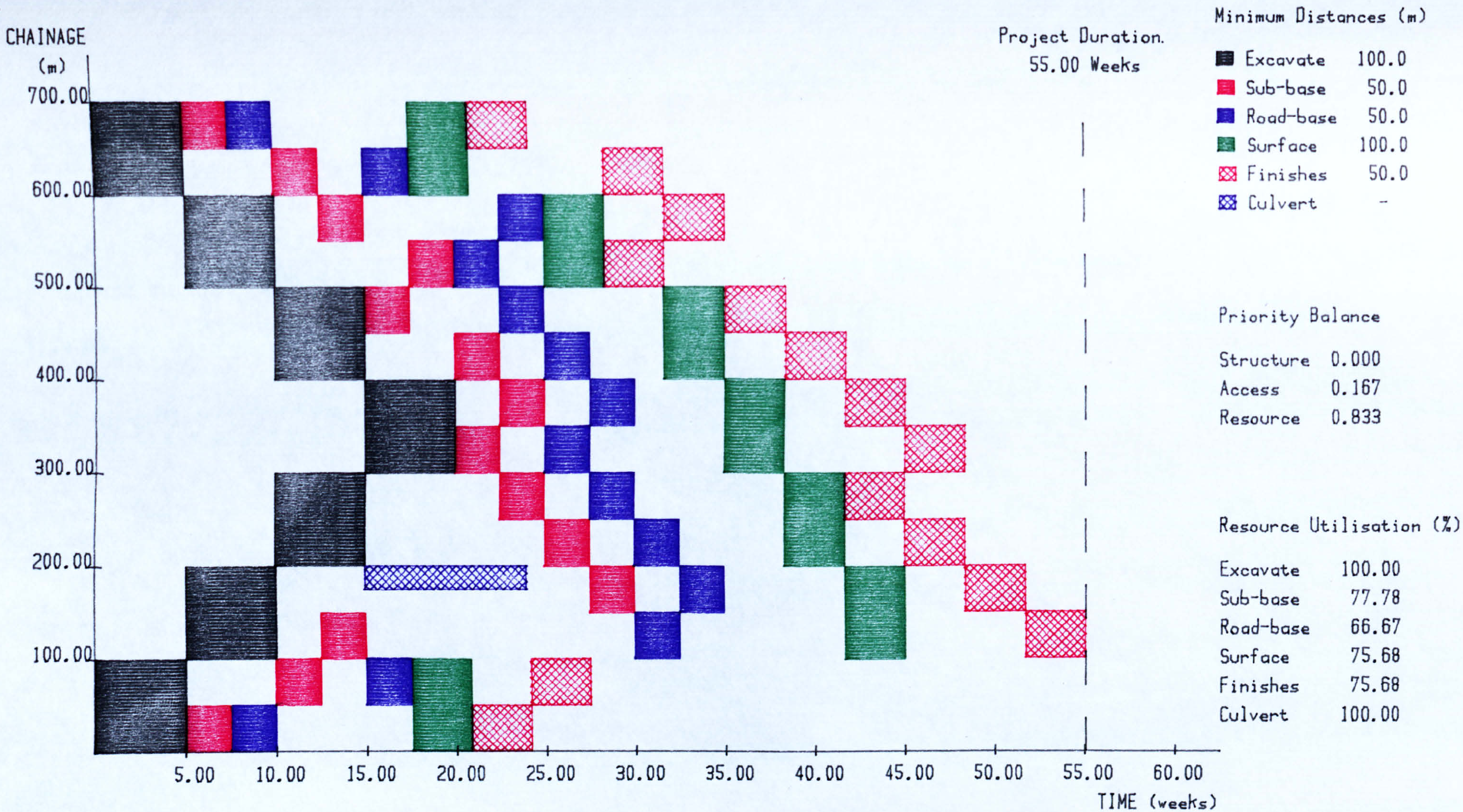


FIGURE NUMBER (B12) ROAD AND CULVERT TEST RUN NUMBER 12

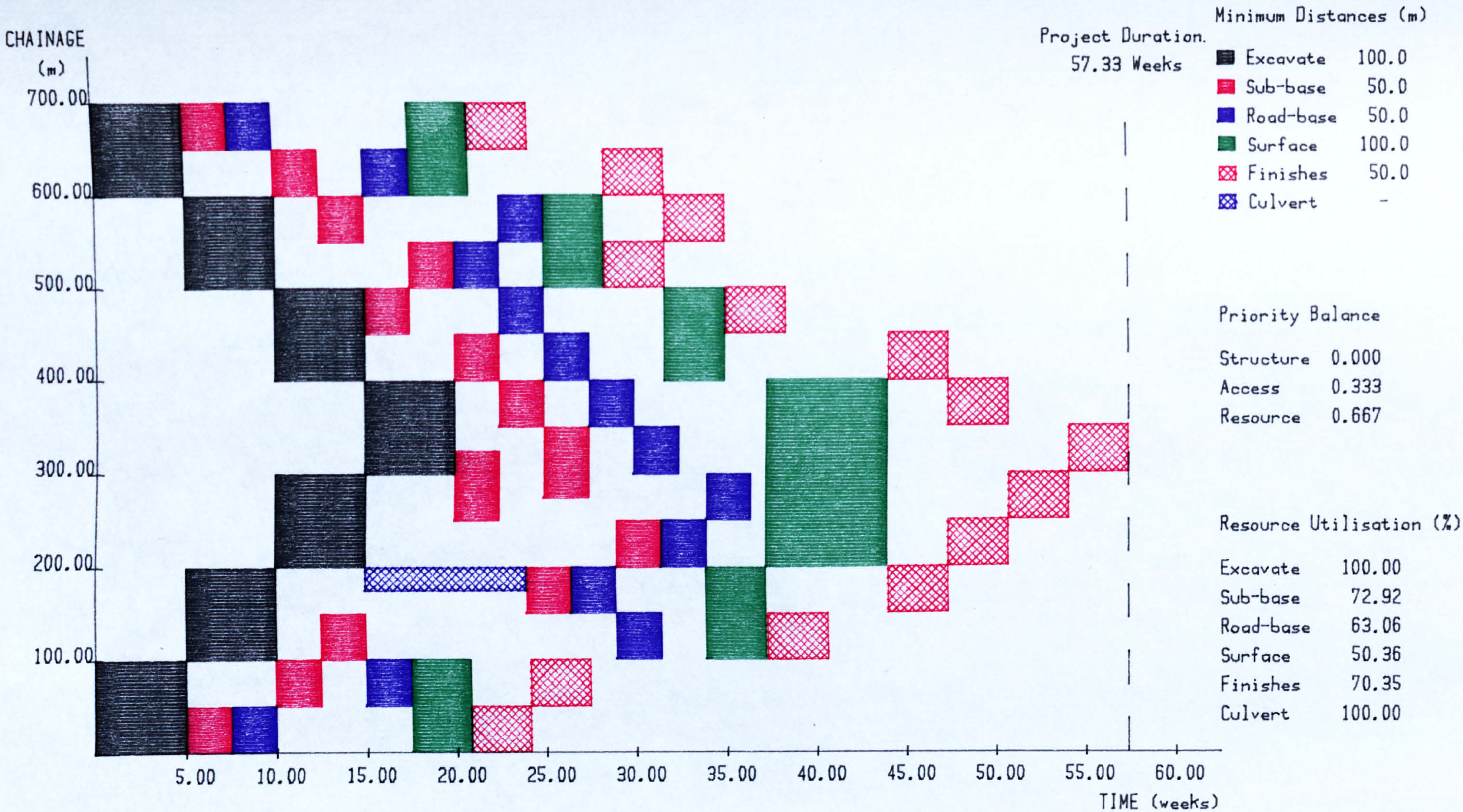


FIGURE NUMBER (B13) ROAD AND CULVERT TEST RUN NUMBER 13

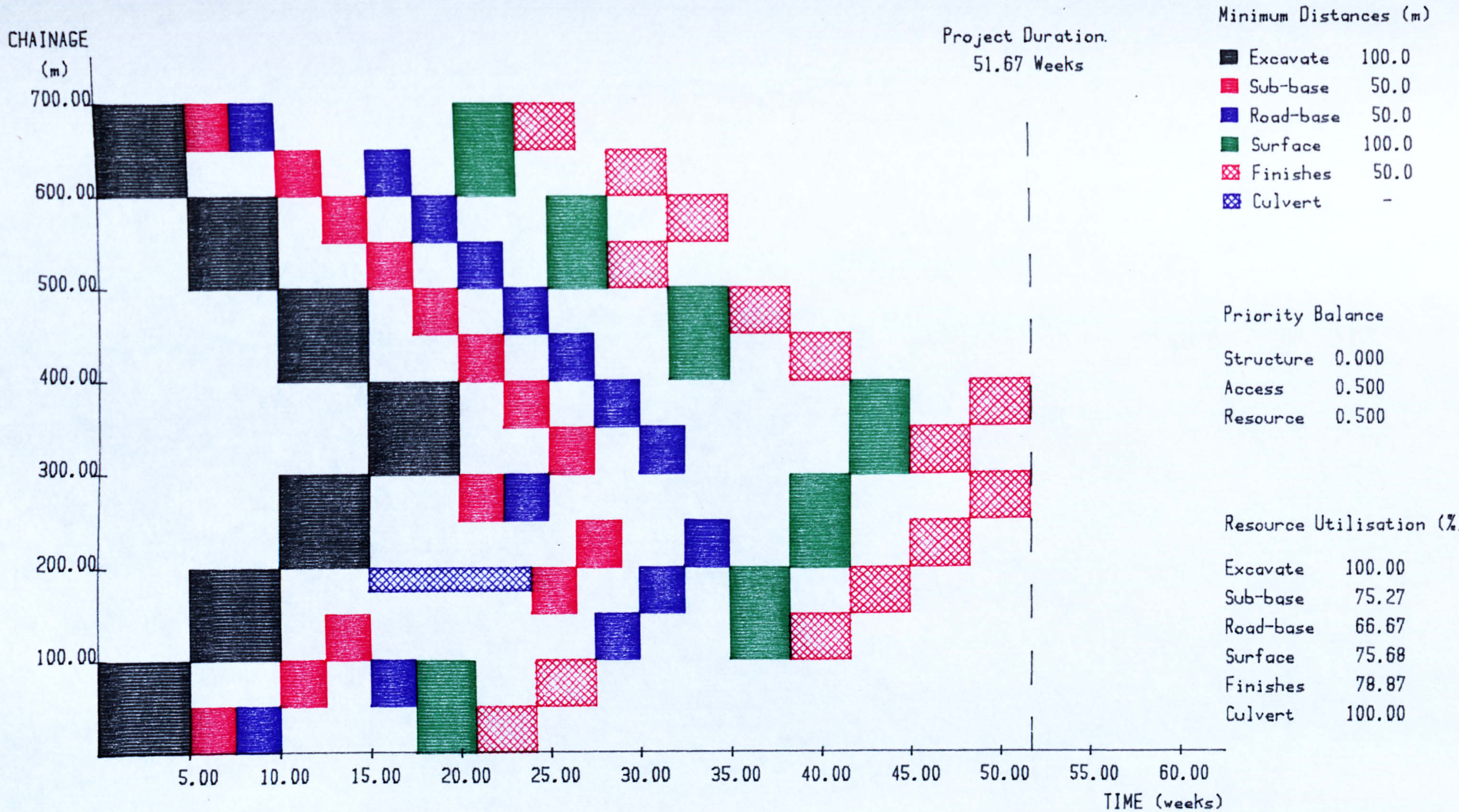


FIGURE NUMBER (B14) ROAD AND CULVERT TEST RUN NUMBER 14

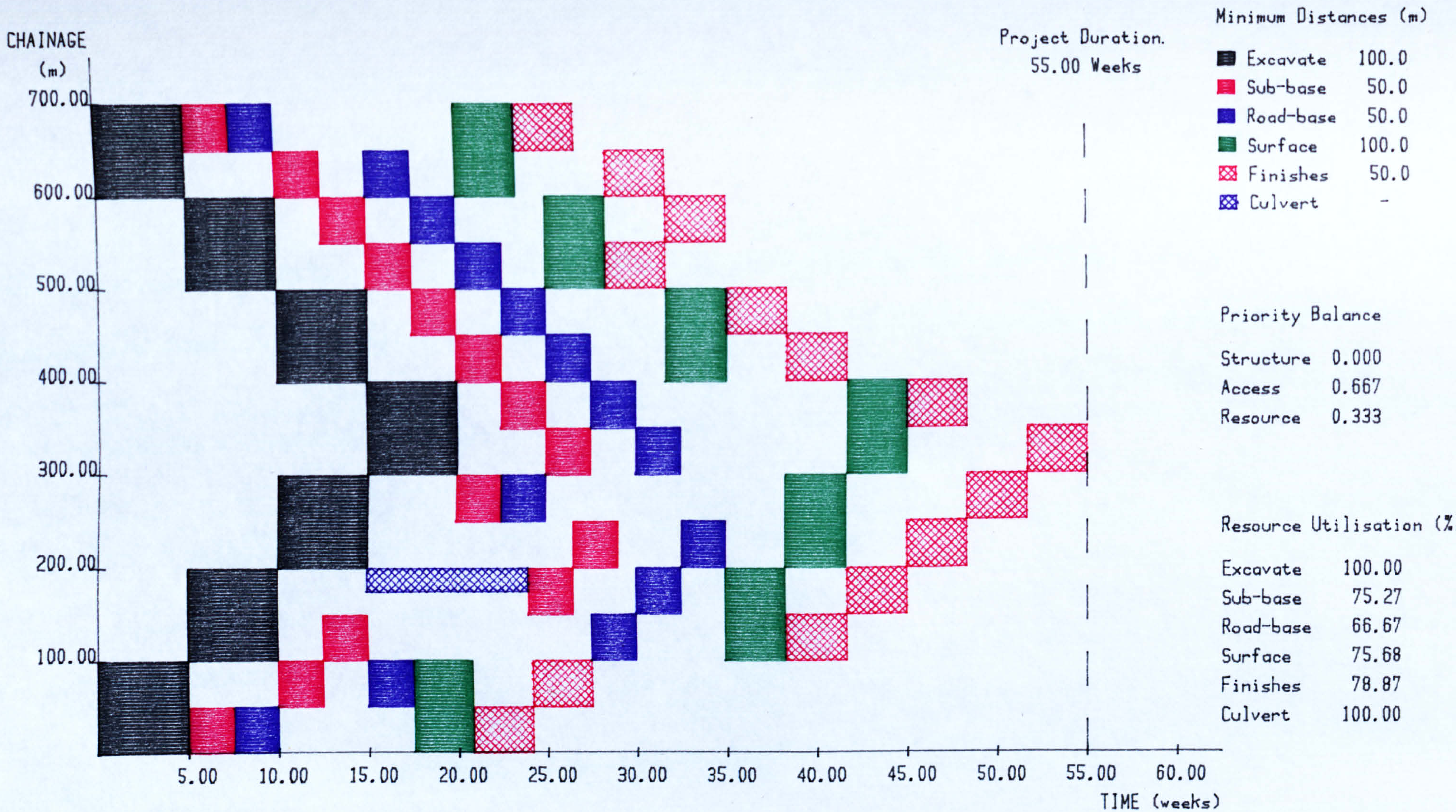
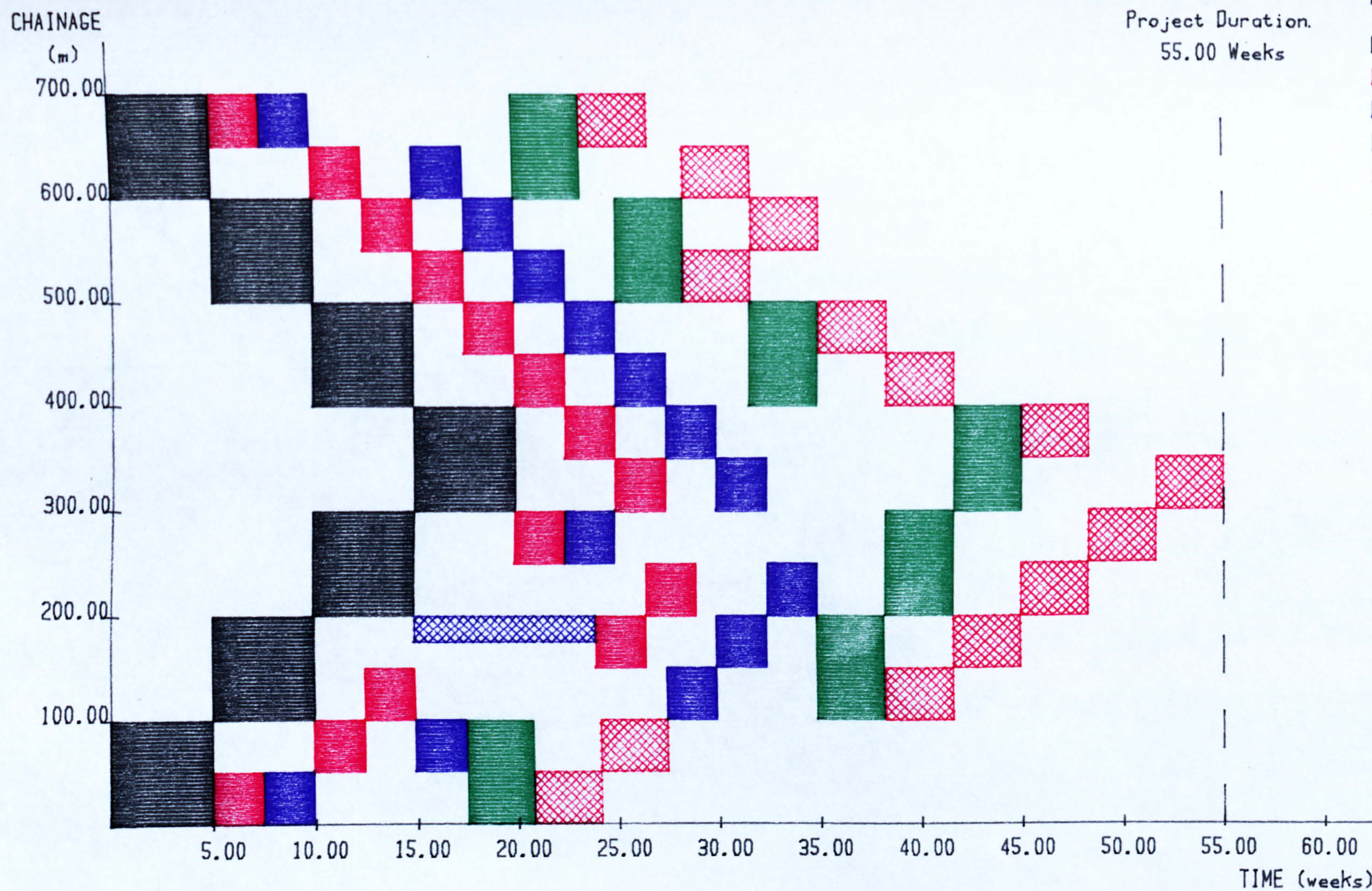


FIGURE NUMBER (B15) ROAD AND CULVERT TEST RUN NUMBER 15



Minimum Distances (m)

Excavate	100.0
Sub-base	50.0
Road-base	50.0
Surface	100.0
Finishes	50.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.833
Resource	0.167

Resource Utilisation (%)

Excavate	100.00
Sub-base	75.27
Road-base	66.67
Surface	75.68
Finishes	78.87
Culvert	100.00

FIGURE NUMBER (B16) ROAD AND CULVERT TEST RUN NUMBER 16

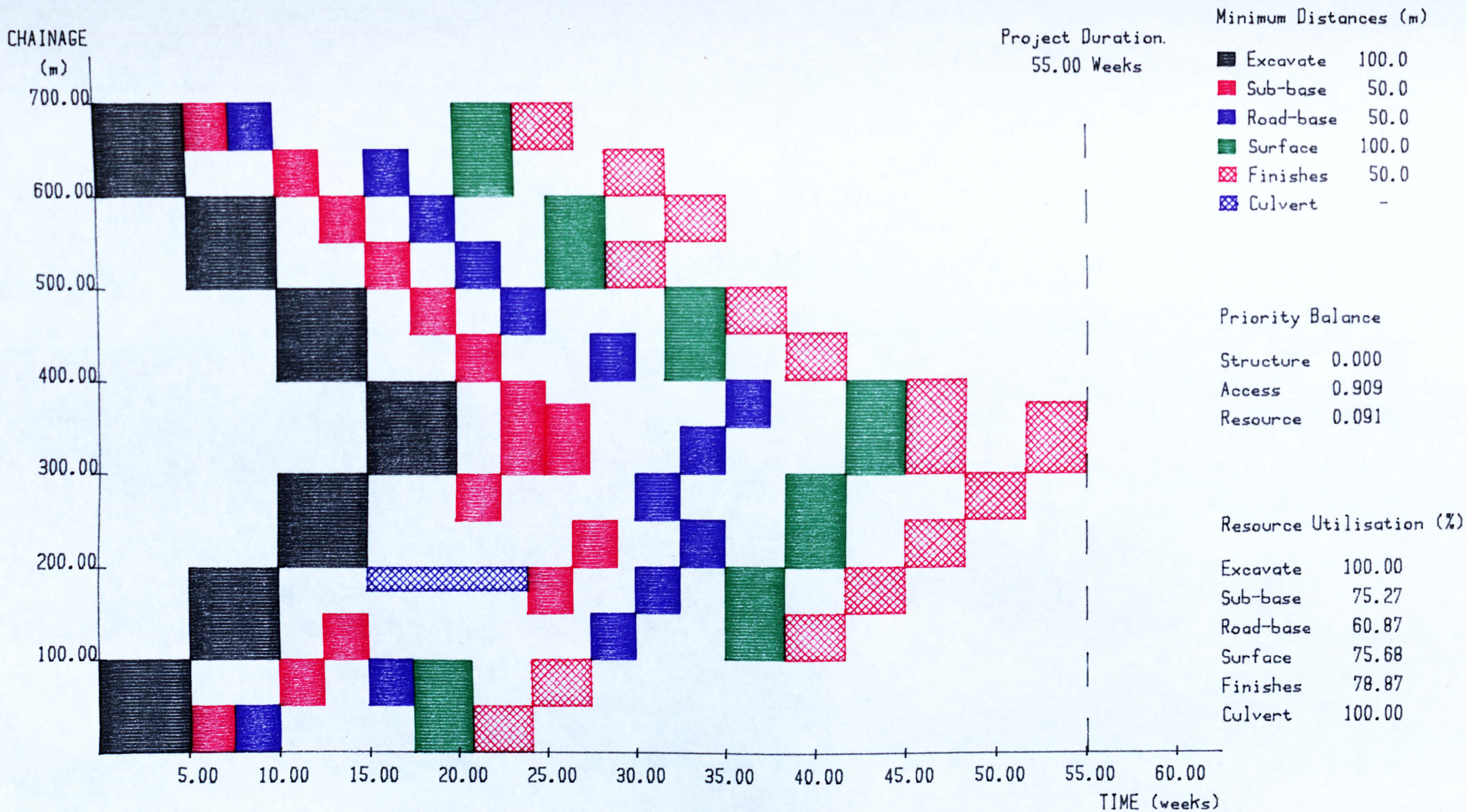


FIGURE NUMBER (B17) ROAD AND CULVERT TEST RUN NUMBER 17

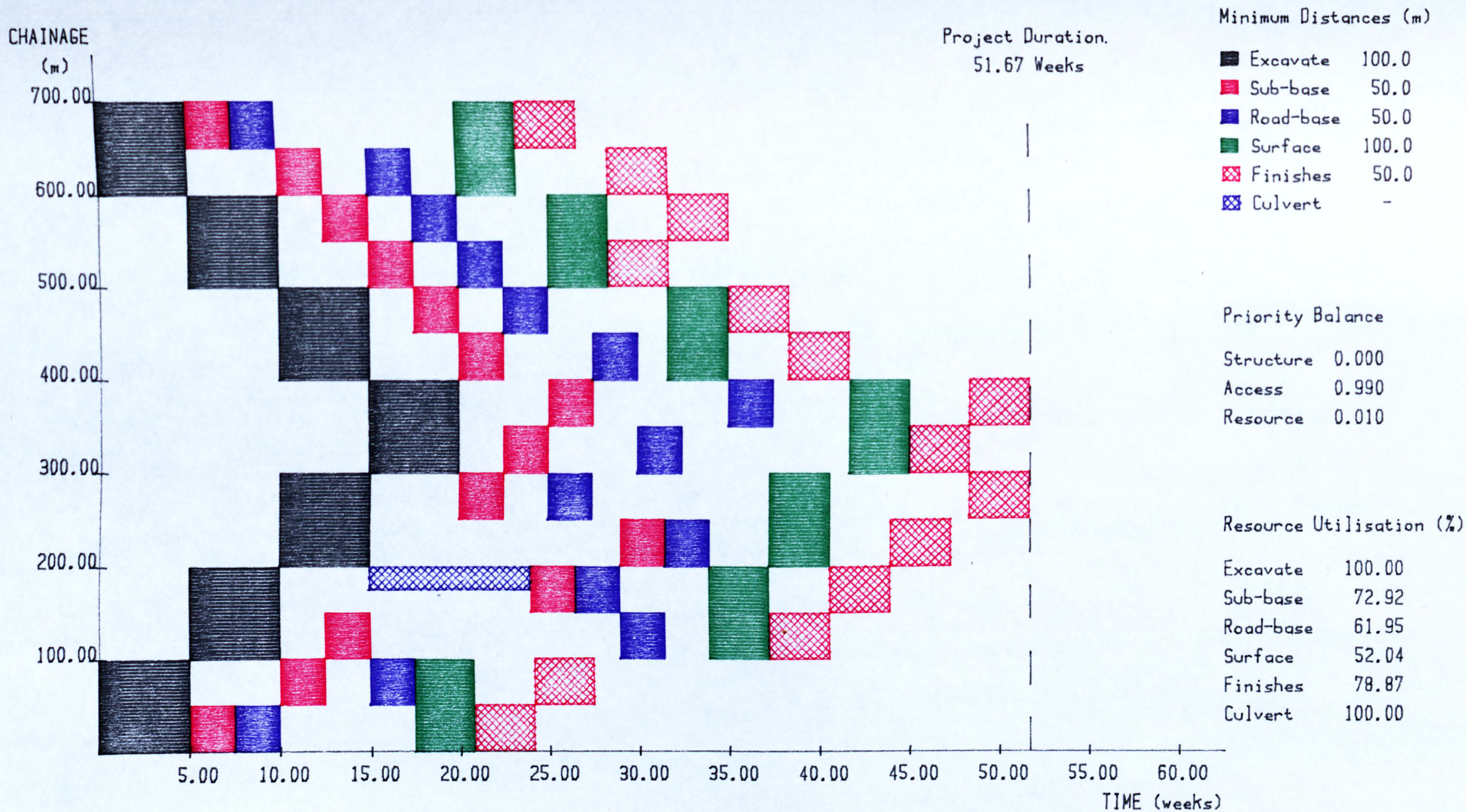


FIGURE NUMBER (B18) ROAD AND CULVERT TEST RUN NUMBER 18

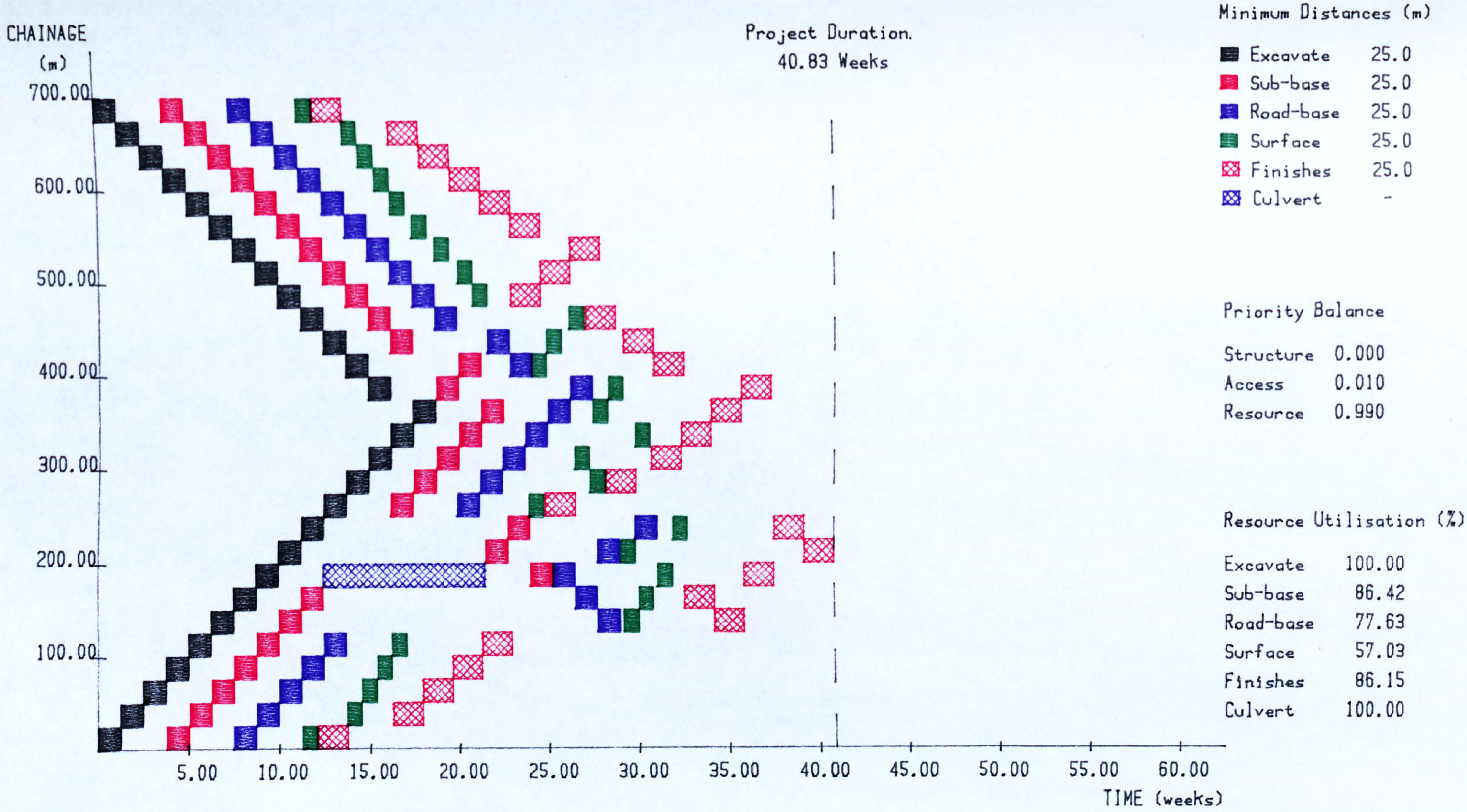
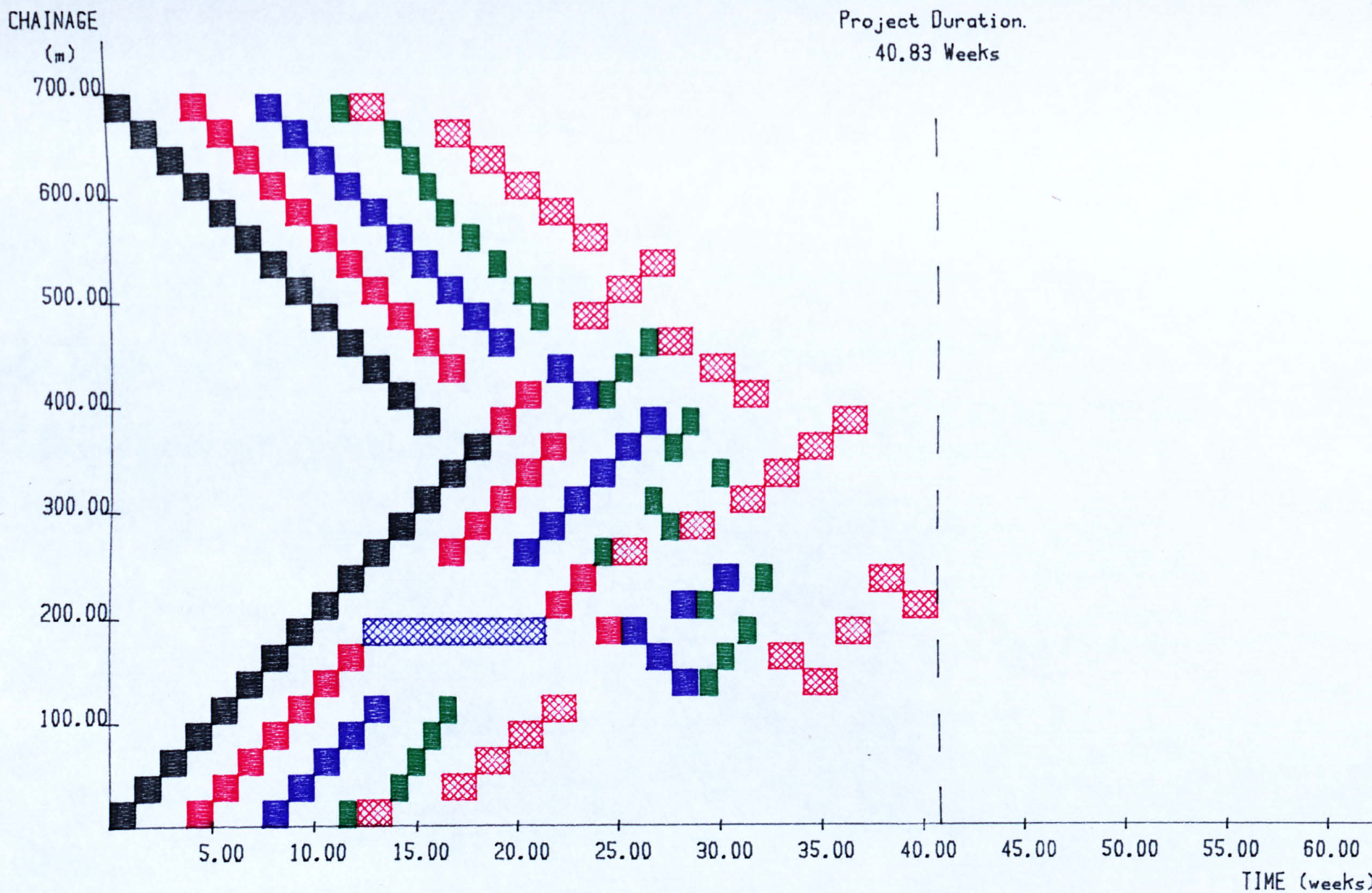


FIGURE NUMBER (B19) ROAD AND CULVERT TEST RUN NUMBER 19



Minimum Distances (m)

Excavate	25.0
Sub-base	25.0
Road-base	25.0
Surface	25.0
Finishes	25.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.091
Resource	0.909

Resource Utilisation (%)

Excavate	100.00
Sub-base	86.42
Road-base	77.63
Surface	57.03
Finishes	86.15
Culvert	100.00

FIGURE NUMBER (B20) ROAD AND CULVERT TEST RUN NUMBER 20

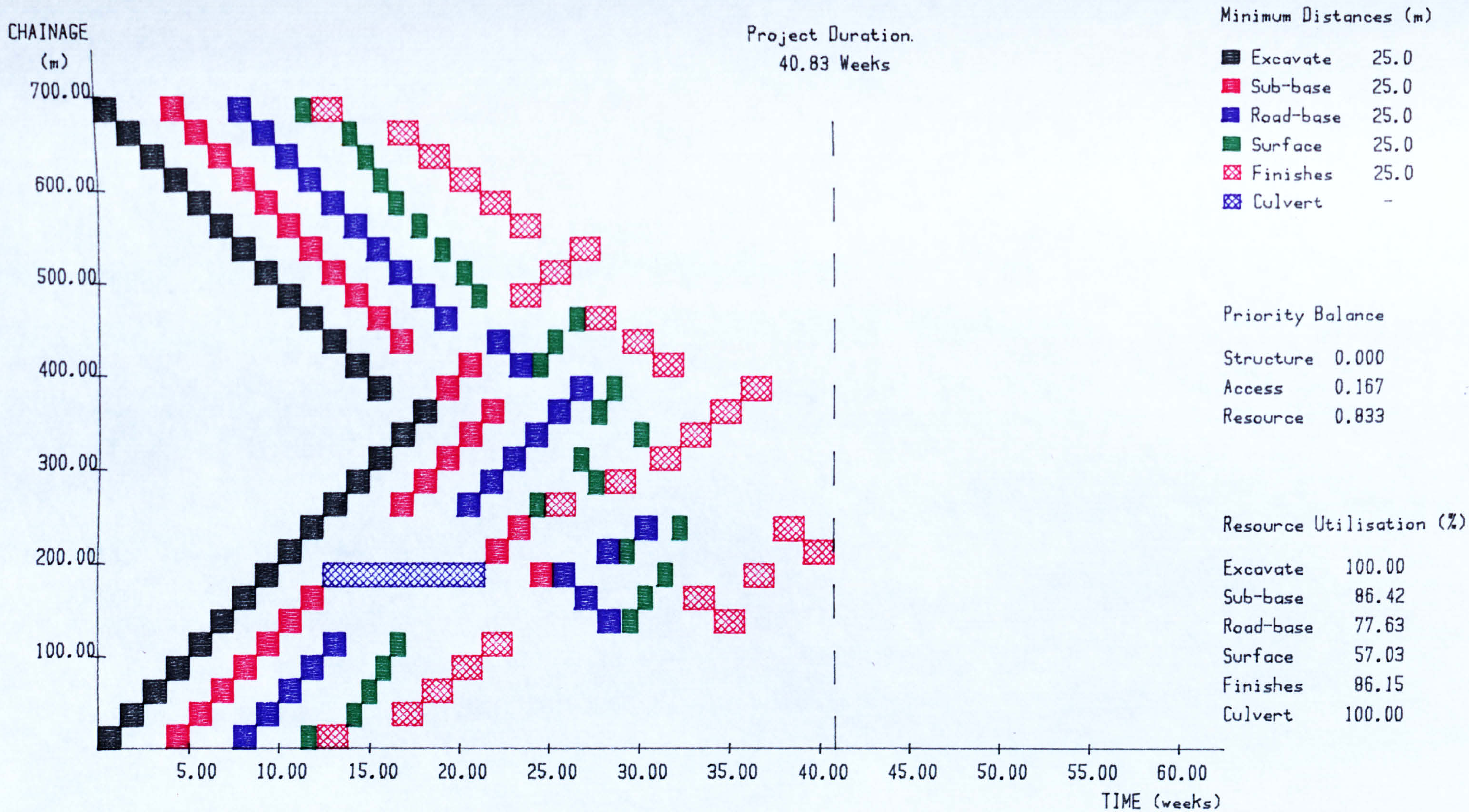


FIGURE NUMBER (B21) ROAD AND CULVERT TEST RUN NUMBER 21

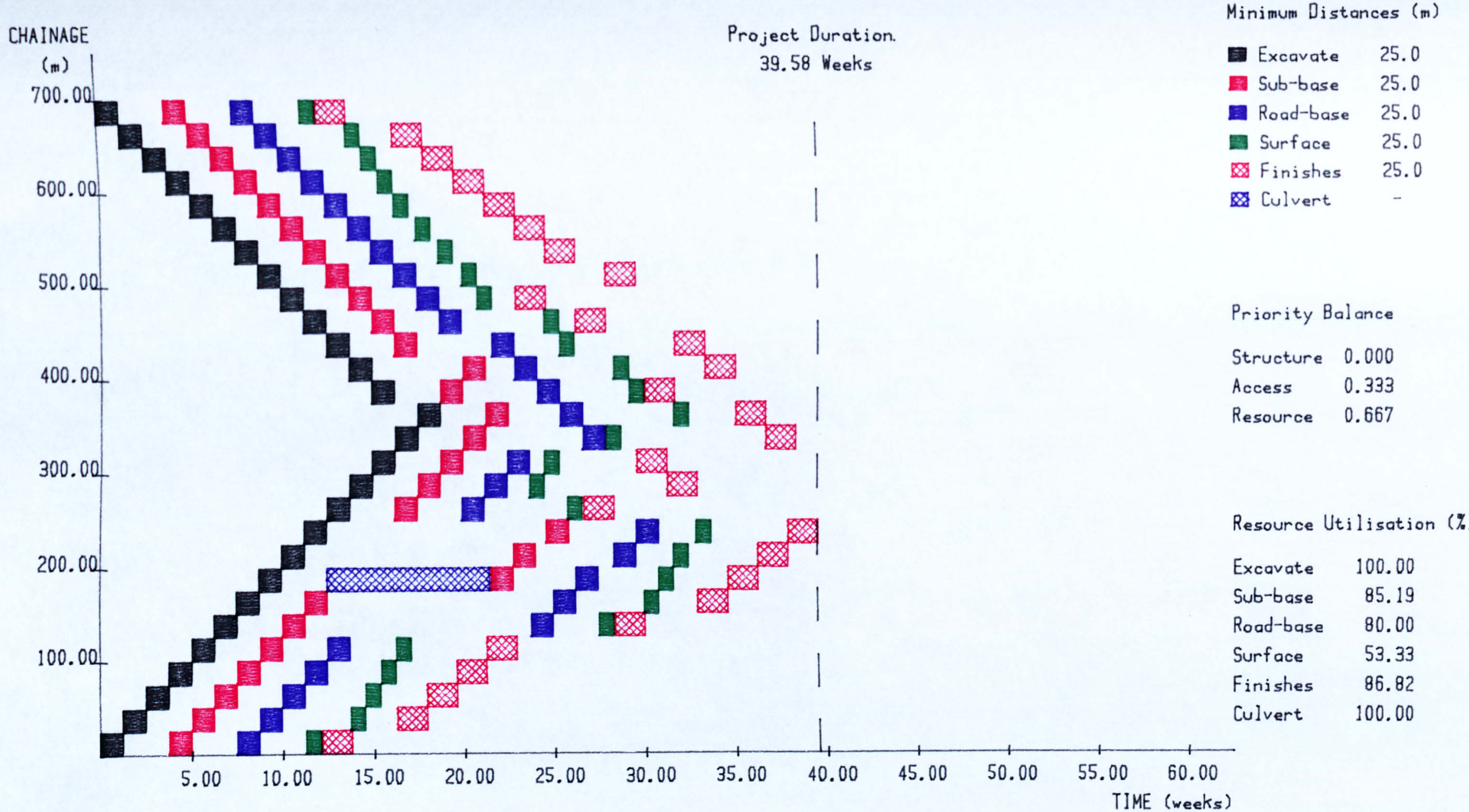


FIGURE NUMBER (B22) ROAD AND CULVERT TEST RUN NUMBER 22

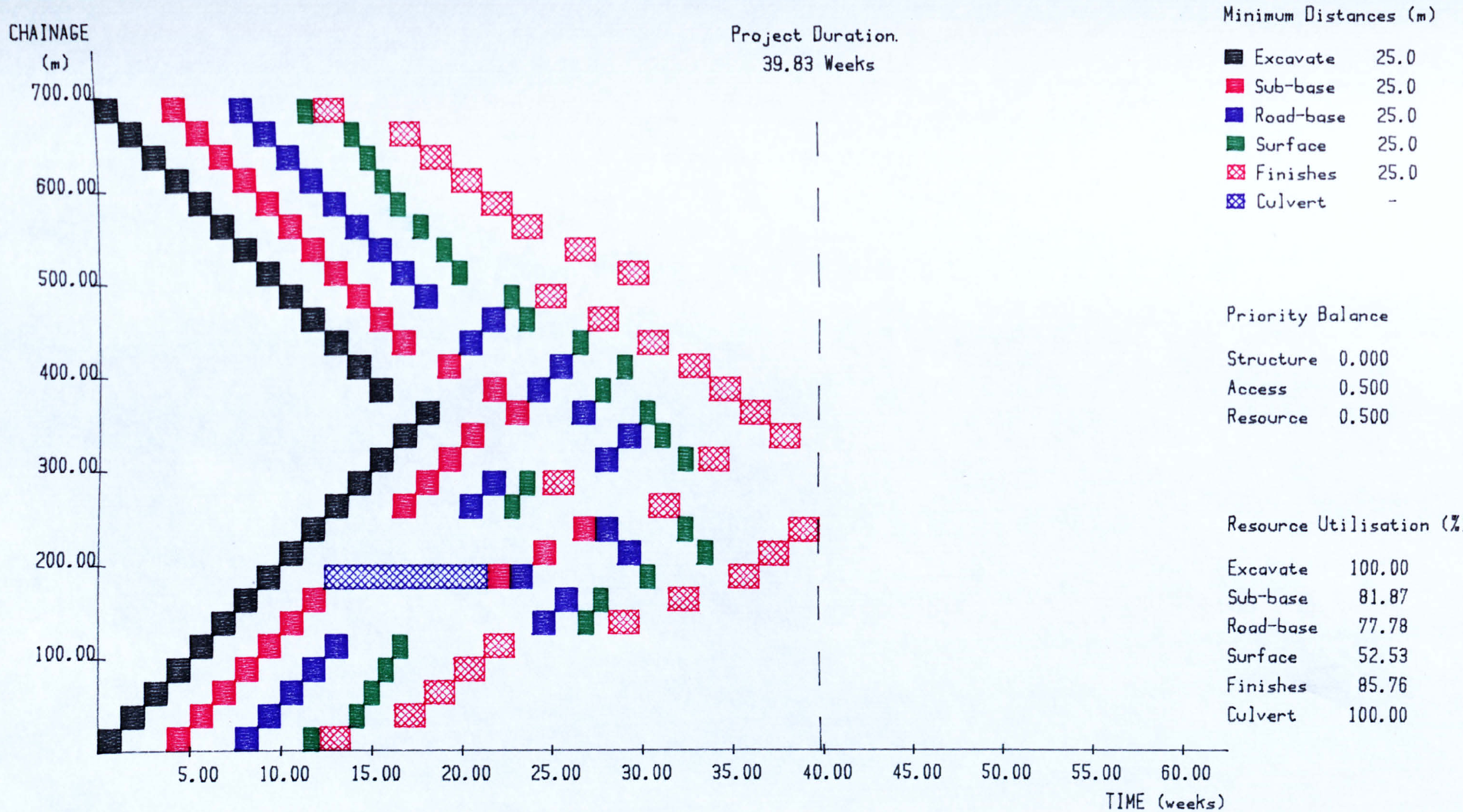
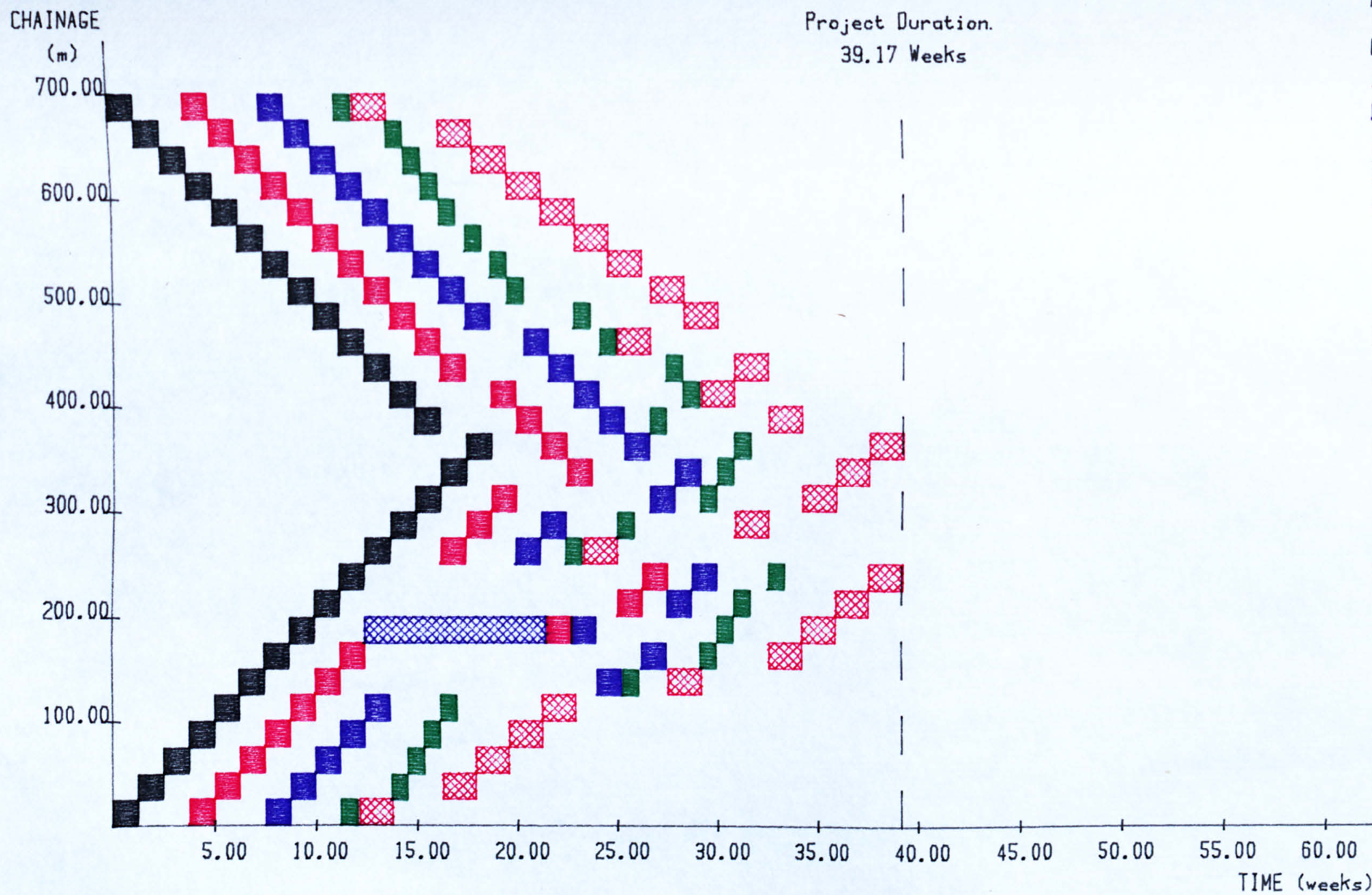


FIGURE NUMBER (B23) ROAD AND CULVERT TEST RUN NUMBER 23



Minimum Distances (m)

Excavate	25.0
Sub-base	25.0
Road-base	25.0
Surface	25.0
Finishes	25.0
Culvert	-

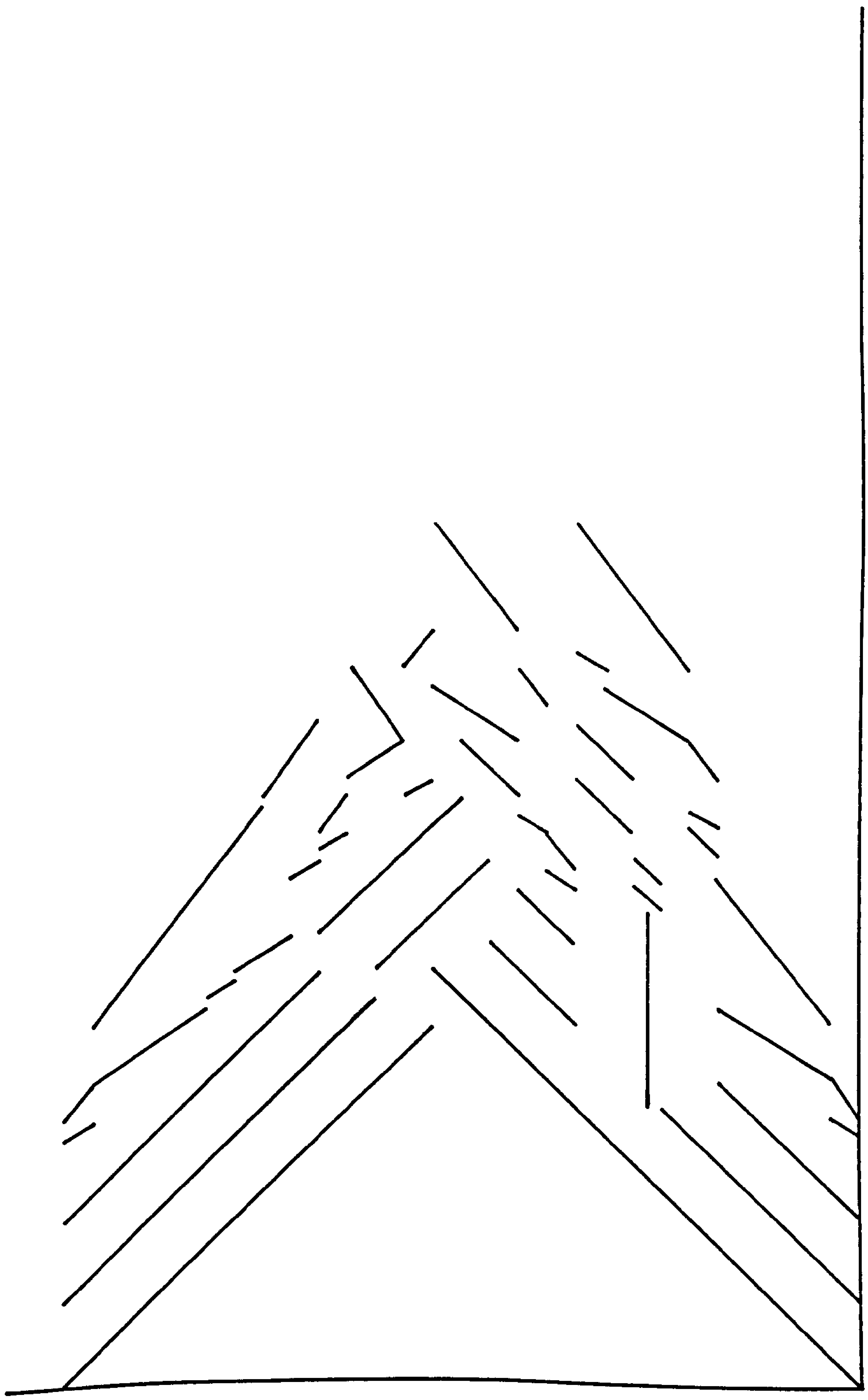
Priority Balance

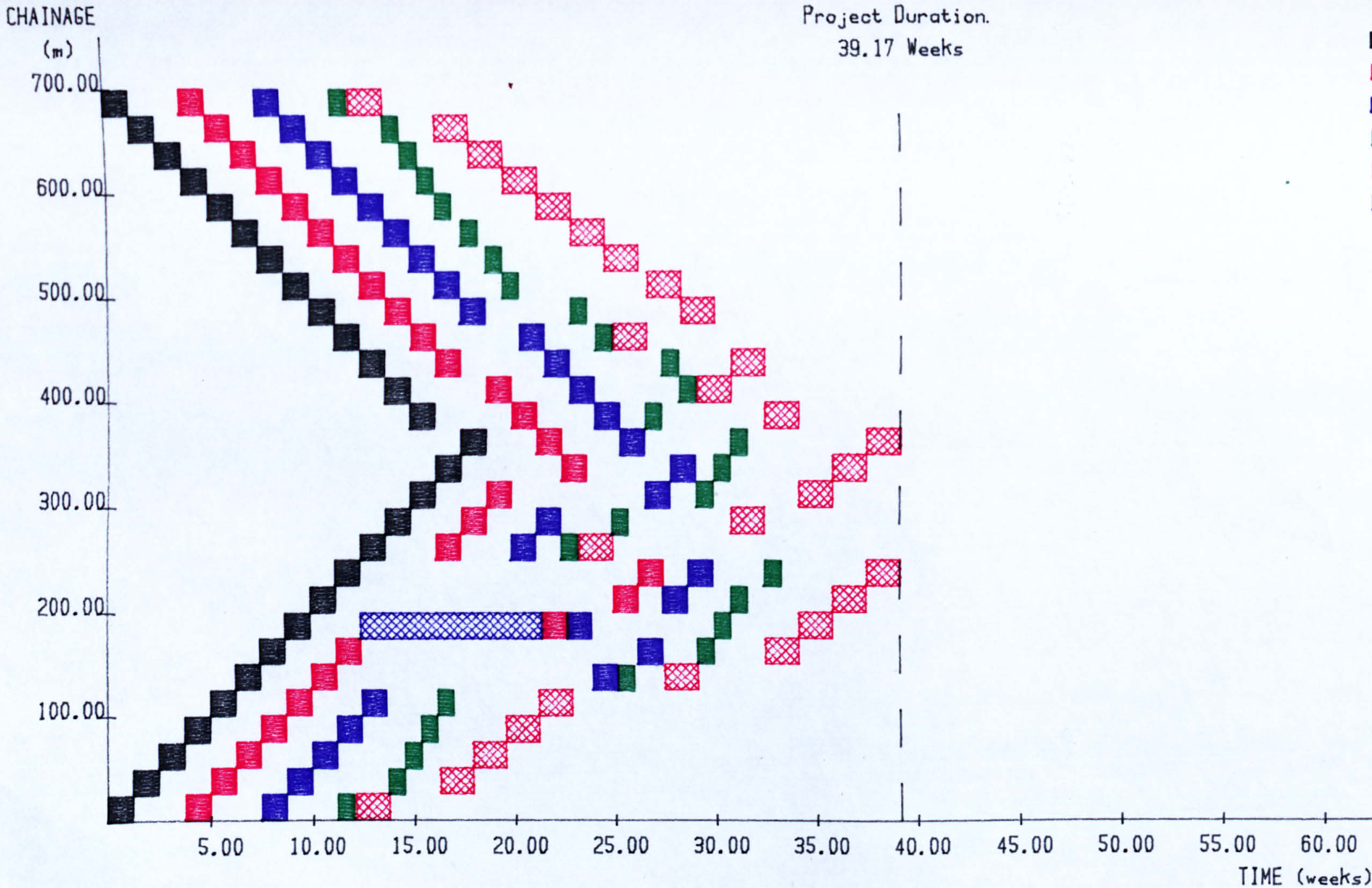
Structure	0.000
Access	0.667
Resource	0.333

Resource Utilisation (%)

Excavate	100.00
Sub-base	81.87
Road-base	79.25
Surface	54.90
Finishes	86.15
Culvert	100.00

FIGURE NUMBER (B24) ROAD AND CULVERT TEST RUN NUMBER 24





Minimum Distances (m)

Excavate	25.0
Sub-base	25.0
Road-base	25.0
Surface	25.0
Finishes	25.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.833
Resource	0.167

Resource Utilisation (%)

Excavate	100.00
Sub-base	81.87
Road-base	79.25
Surface	54.90
Finishes	86.15
Culvert	100.00

FIGURE NUMBER (B25) ROAD AND CULVERT TEST RUN NUMBER 25

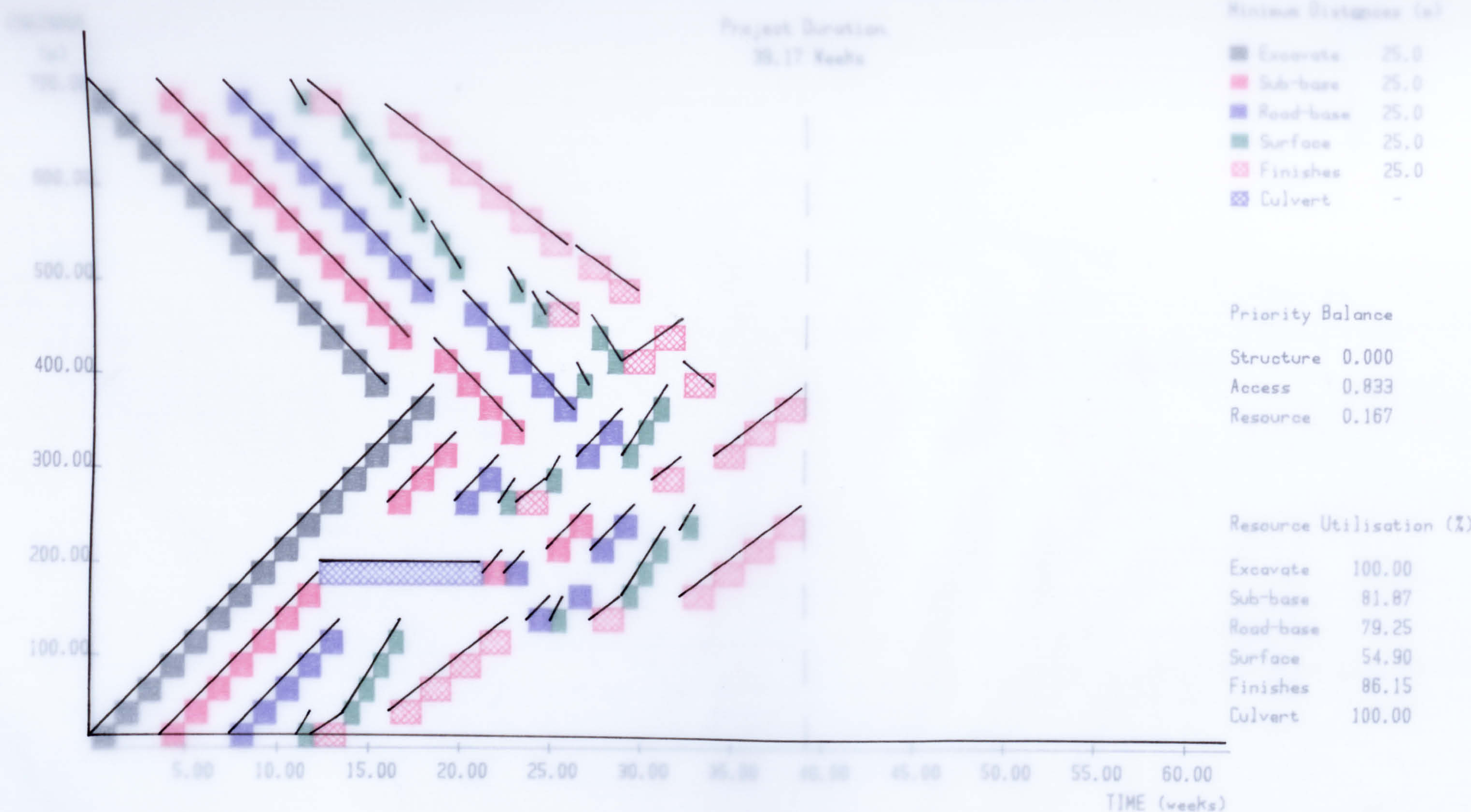


FIGURE NUMBER (B25) ROAD AND CULVERT TEST RUN NUMBER 25

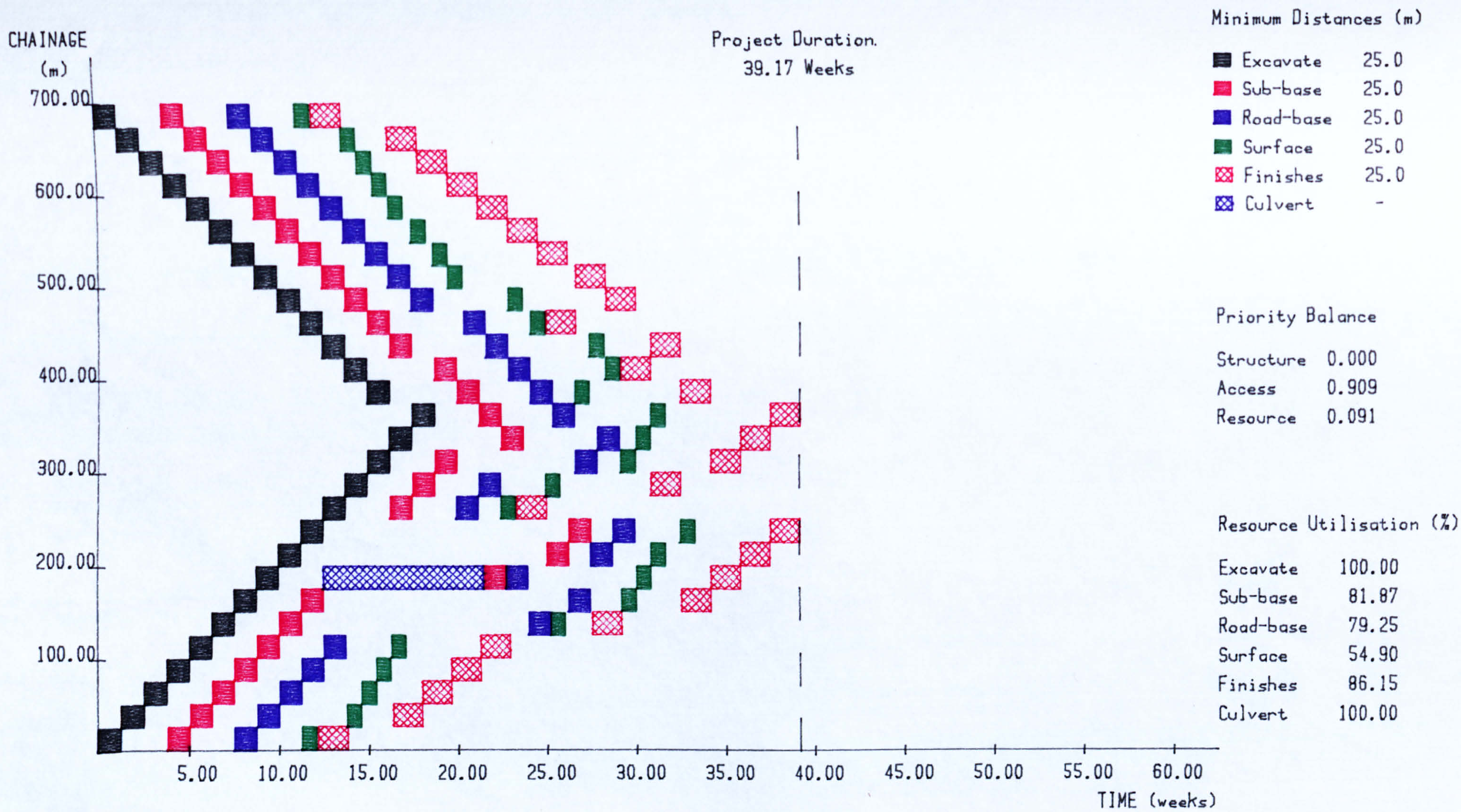


FIGURE NUMBER (B26) ROAD AND CULVERT TEST RUN NUMBER 26

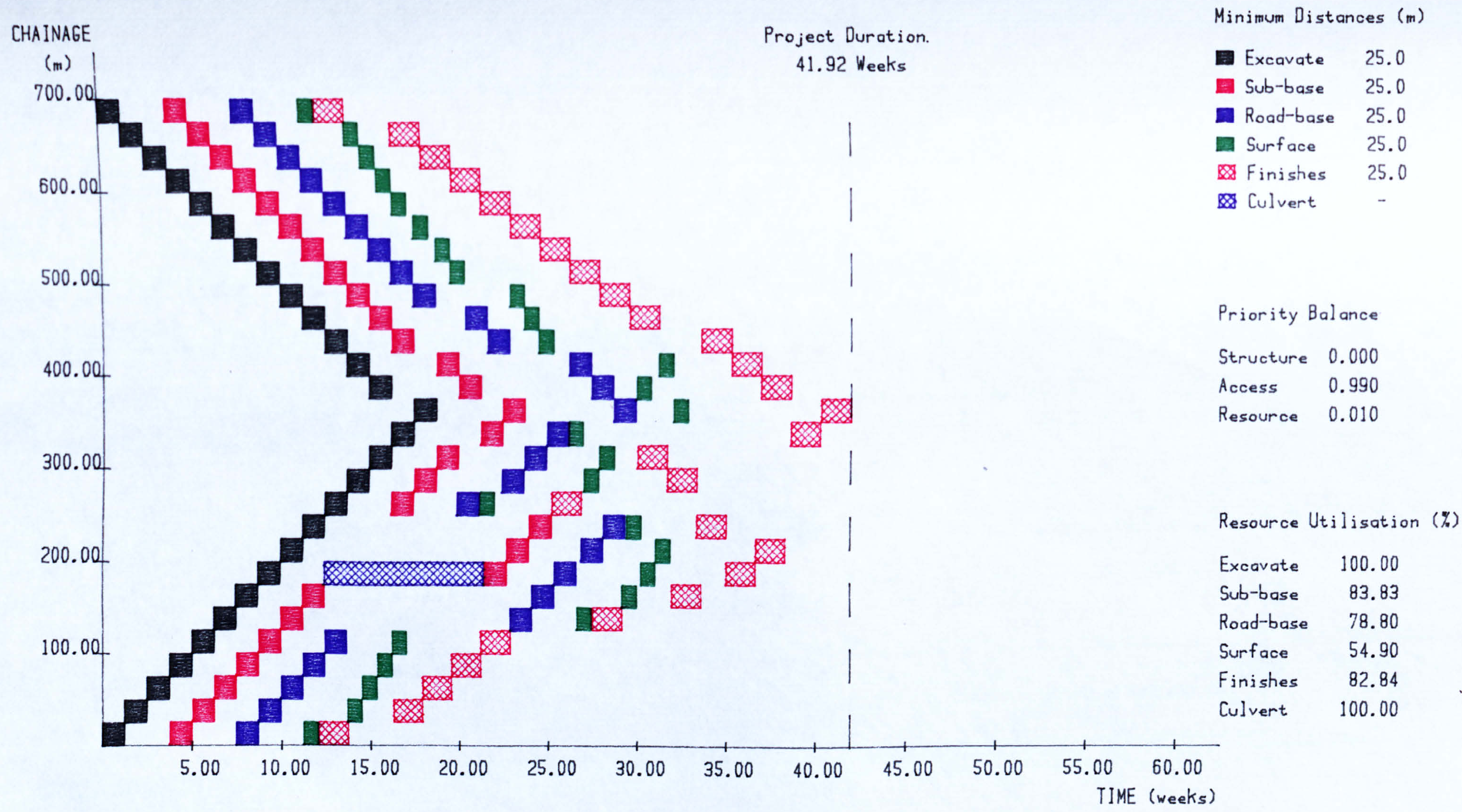


FIGURE NUMBER (B27) ROAD AND CULVERT TEST RUN NUMBER 27

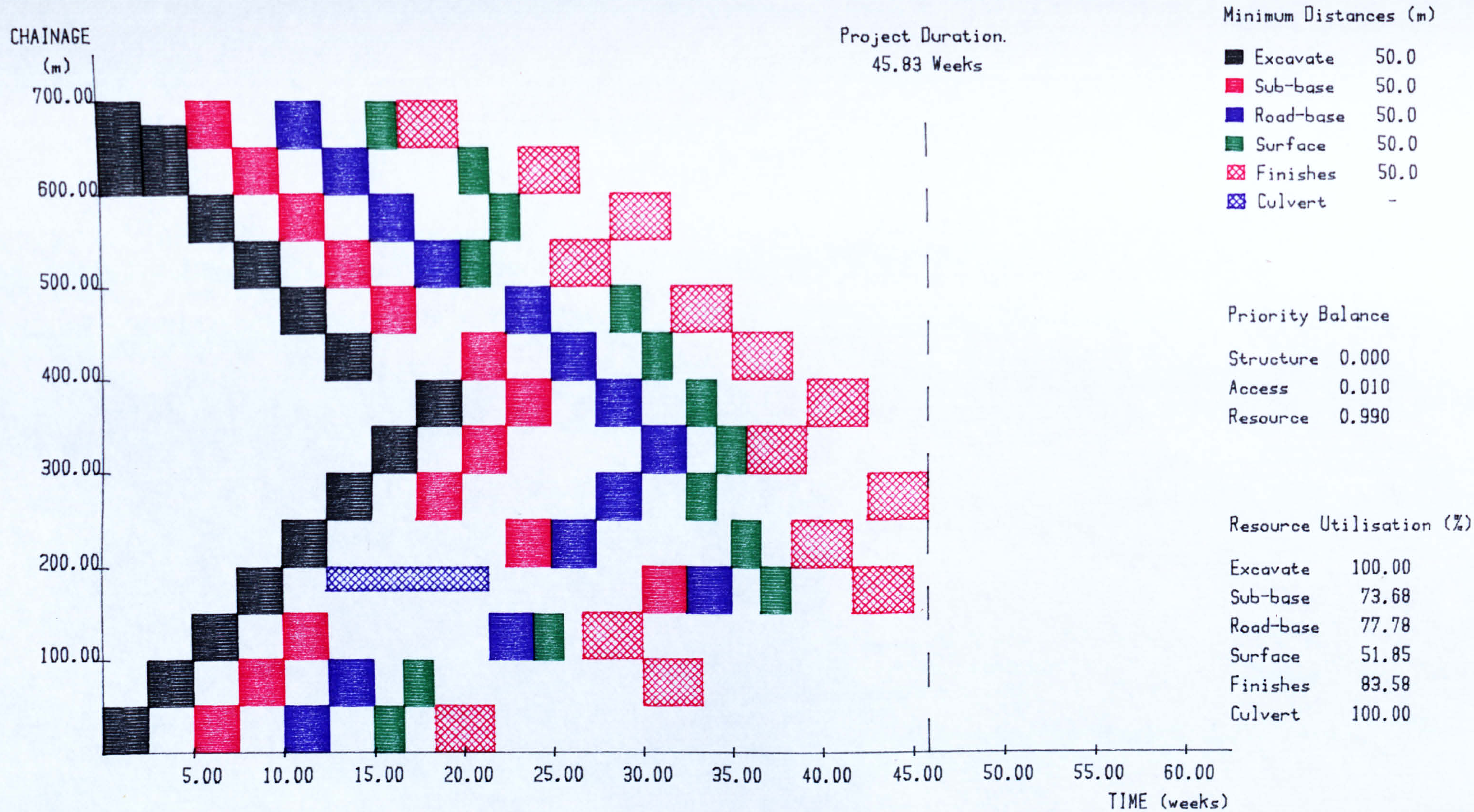


FIGURE NUMBER (B28) ROAD AND CULVERT TEST RUN NUMBER 28

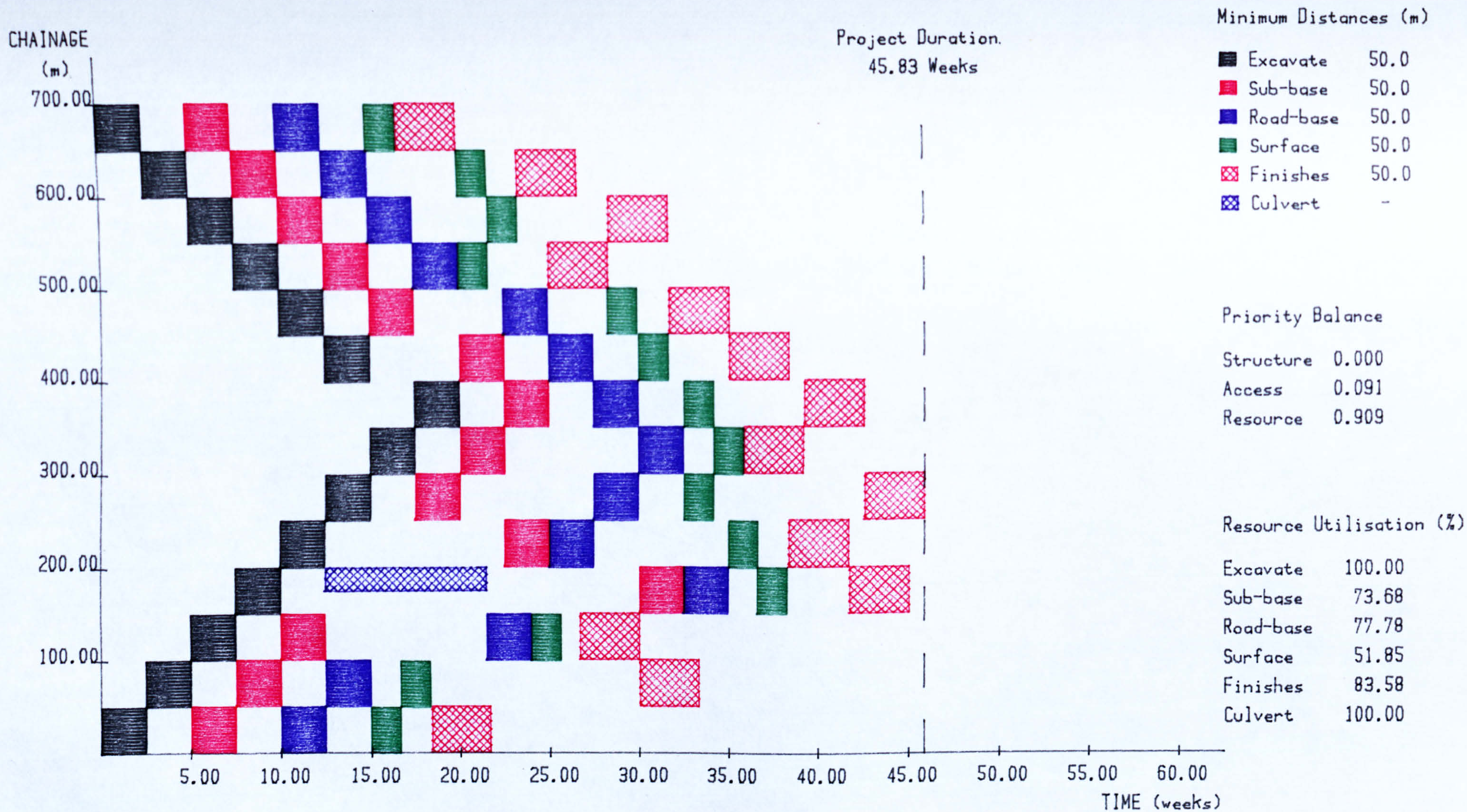


FIGURE NUMBER (B29) ROAD AND CULVERT TEST RUN NUMBER 29

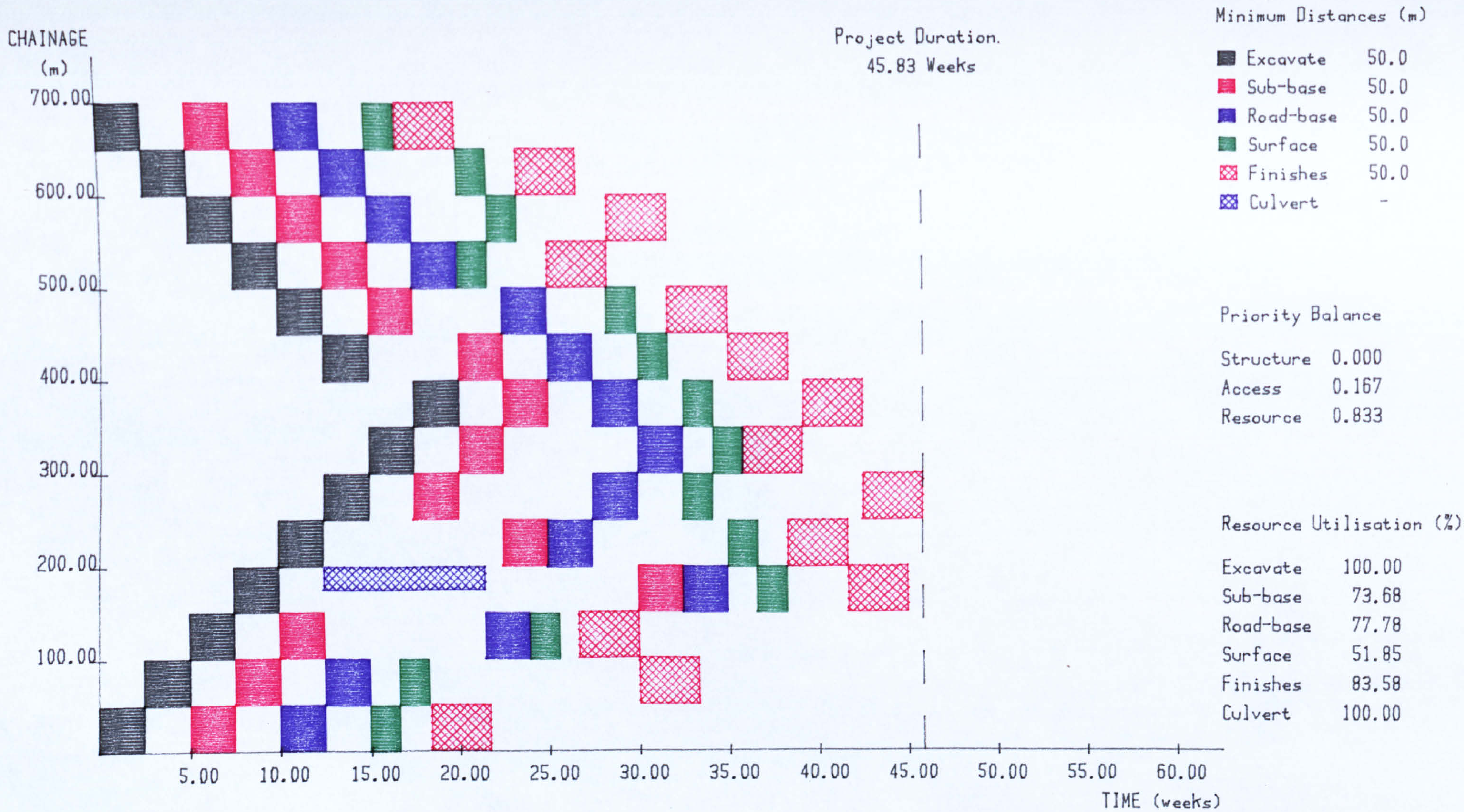


FIGURE NUMBER (B30) ROAD AND CULVERT TEST RUN NUMBER 30

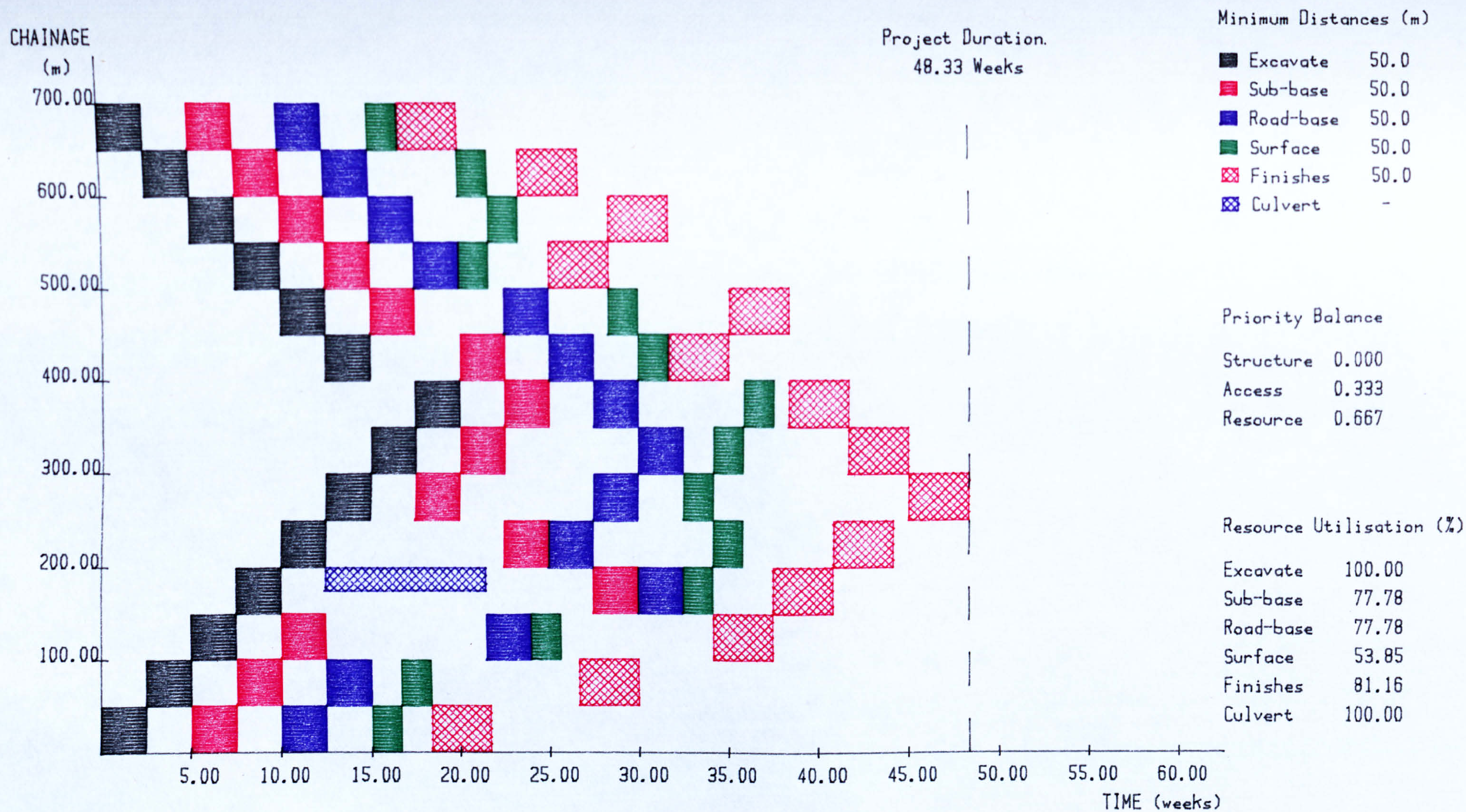


FIGURE NUMBER (B31) ROAD AND CULVERT TEST RUN NUMBER 31

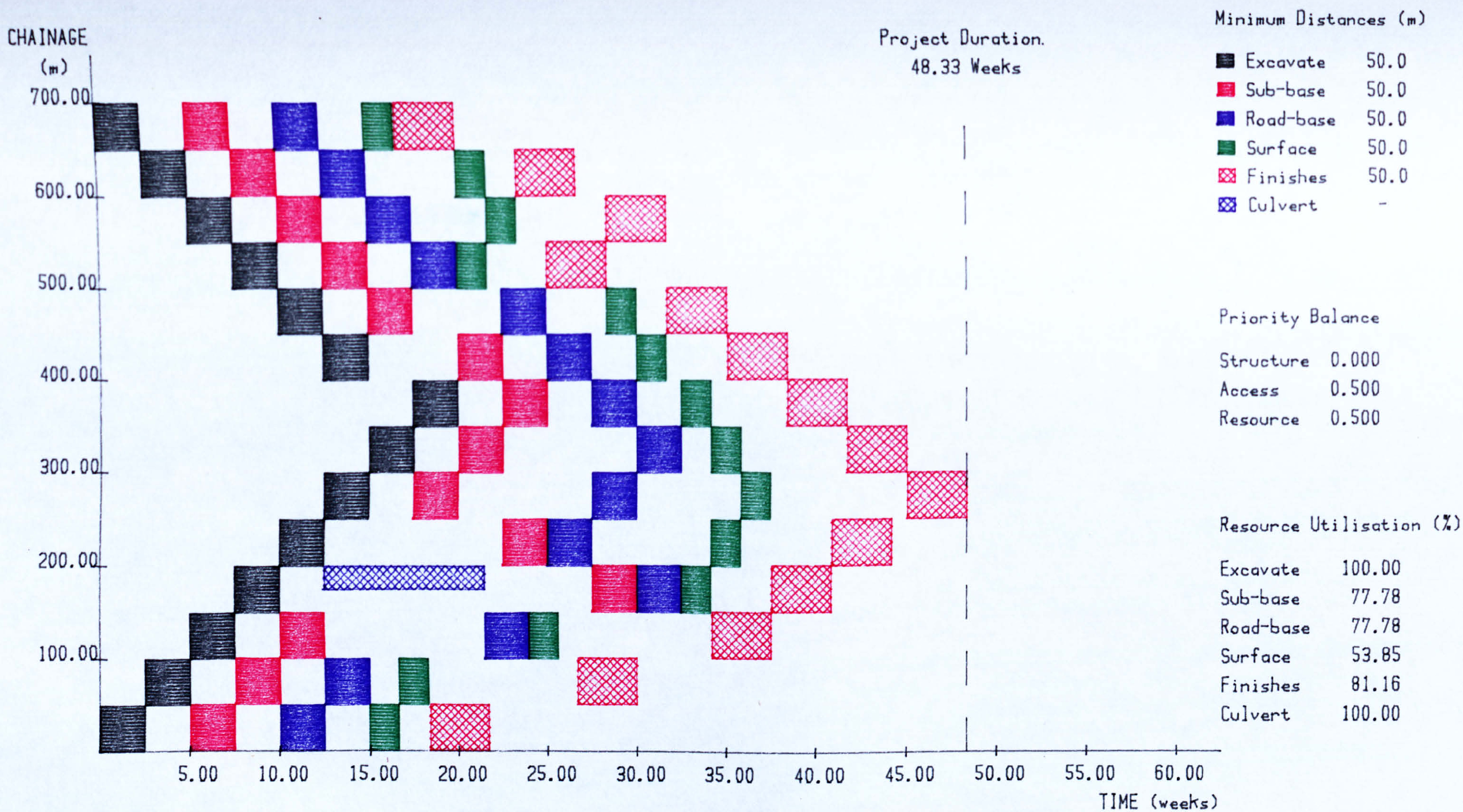


FIGURE NUMBER (B32) ROAD AND CULVERT TEST RUN NUMBER 32

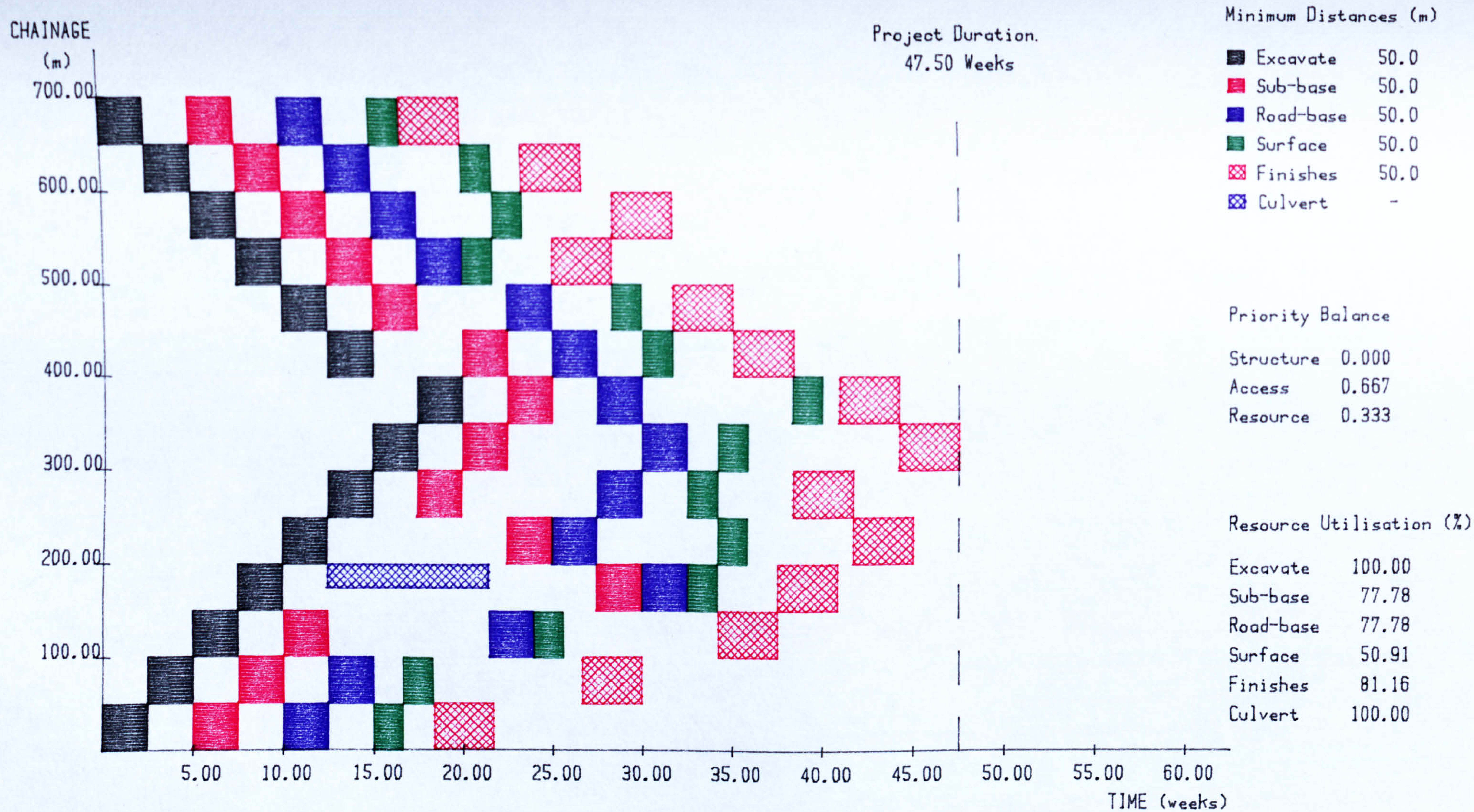


FIGURE NUMBER (B33) ROAD AND CULVERT TEST RUN NUMBER 33

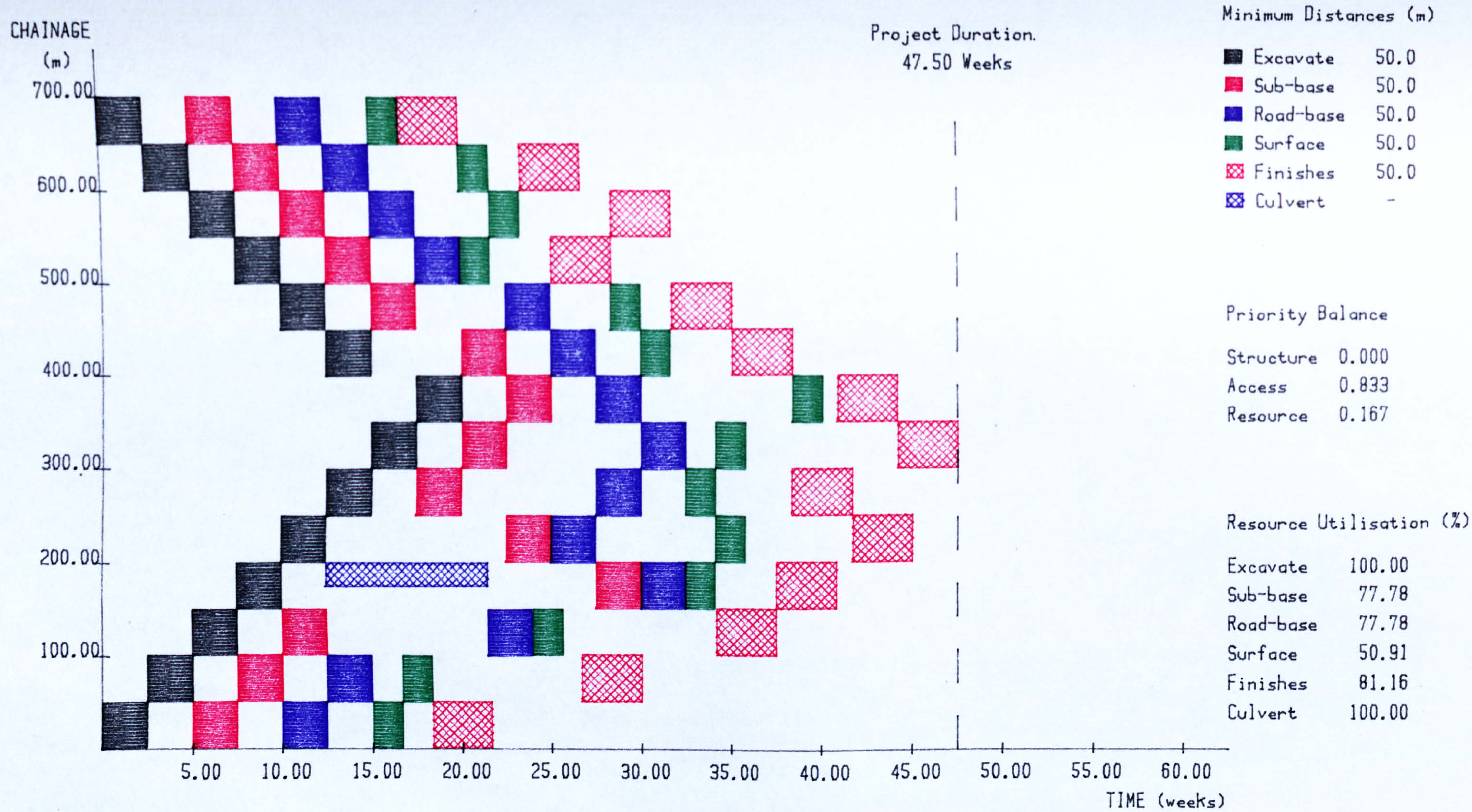


FIGURE NUMBER (B34) ROAD AND CULVERT TEST RUN NUMBER 34

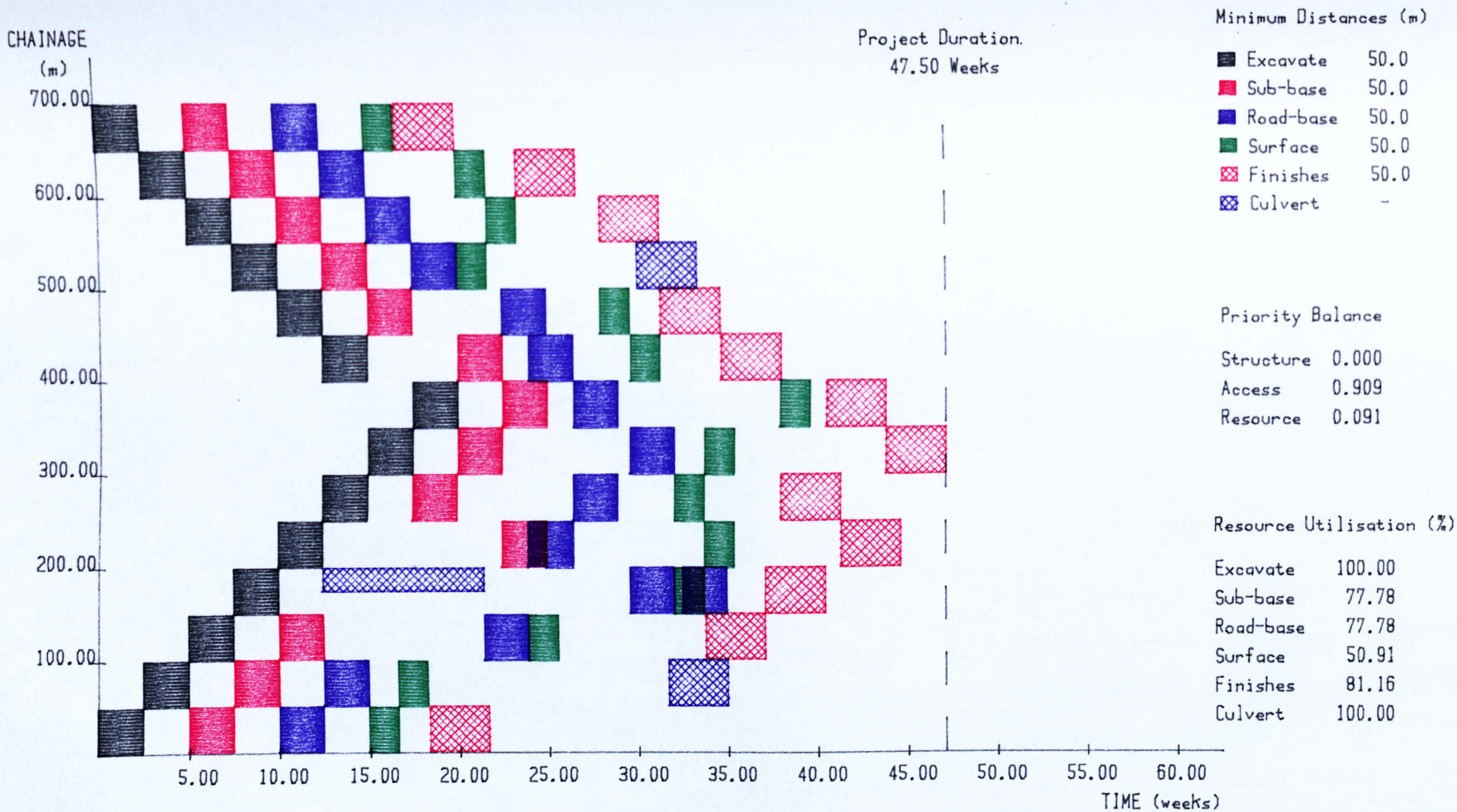


FIGURE NUMBER (B35) ROAD AND CULVERT TEST RUN NUMBER 35

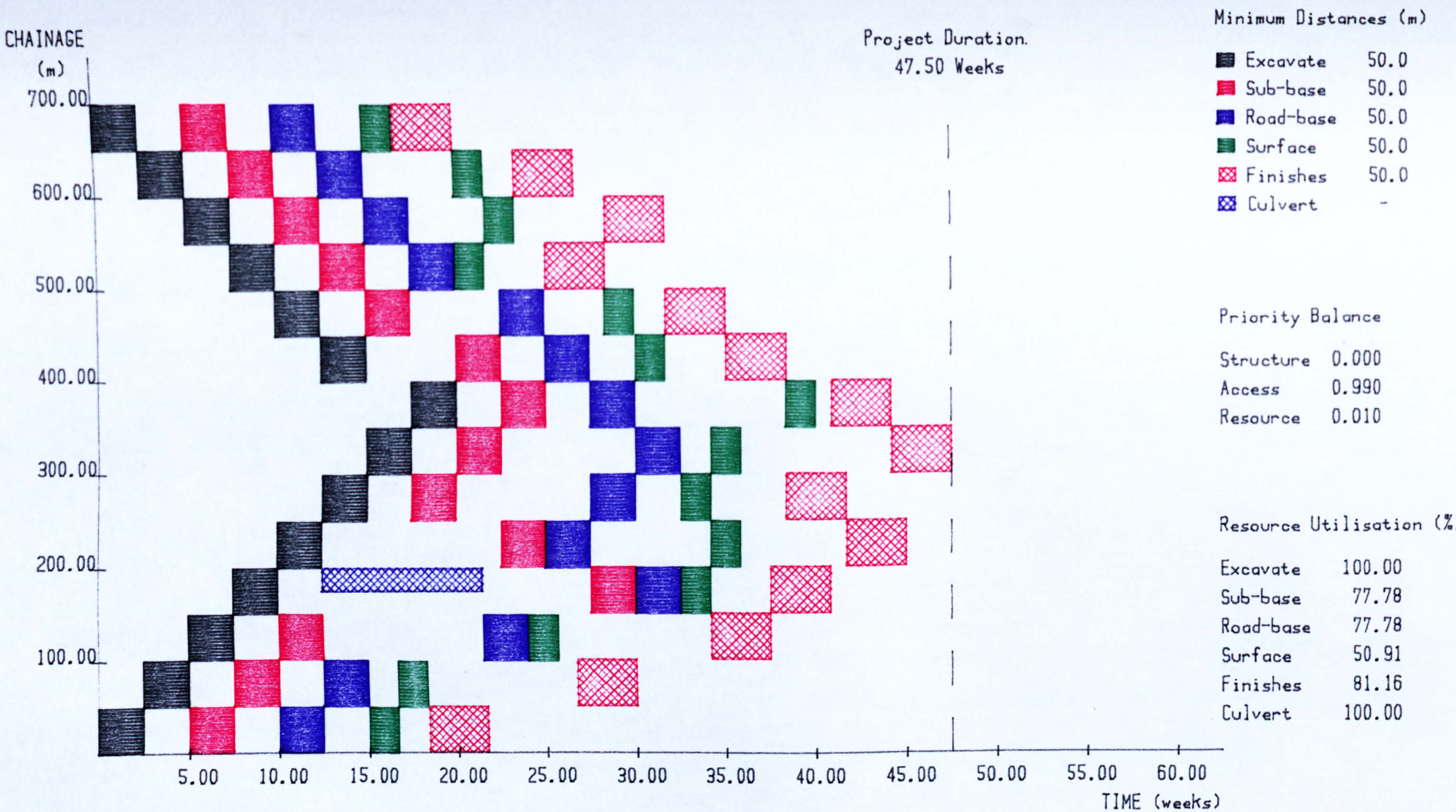


FIGURE NUMBER (B36) ROAD AND CULVERT TEST RUN NUMBER 36

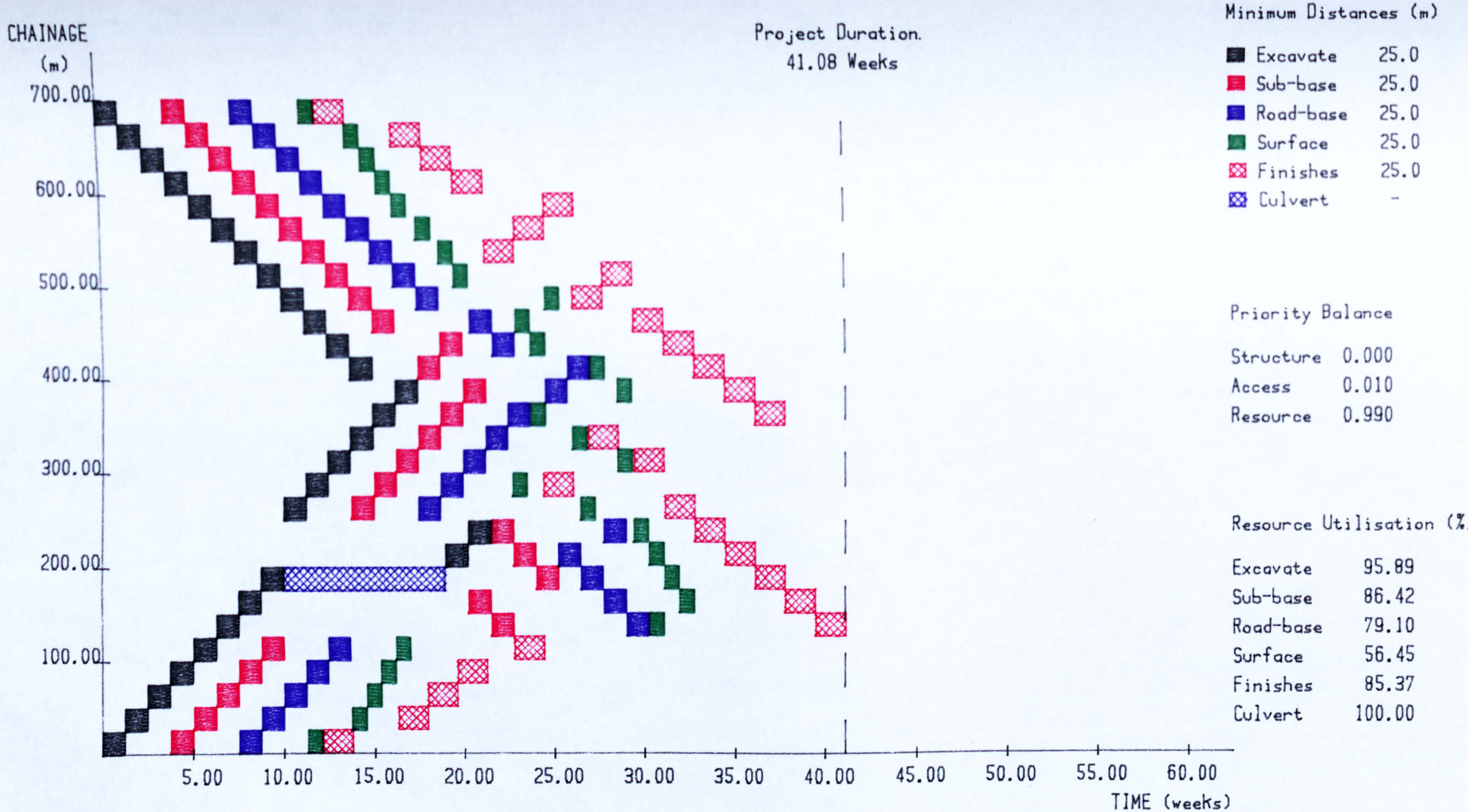


FIGURE NUMBER (B46) ROAD AND CULVERT TEST RUN NUMBER 46

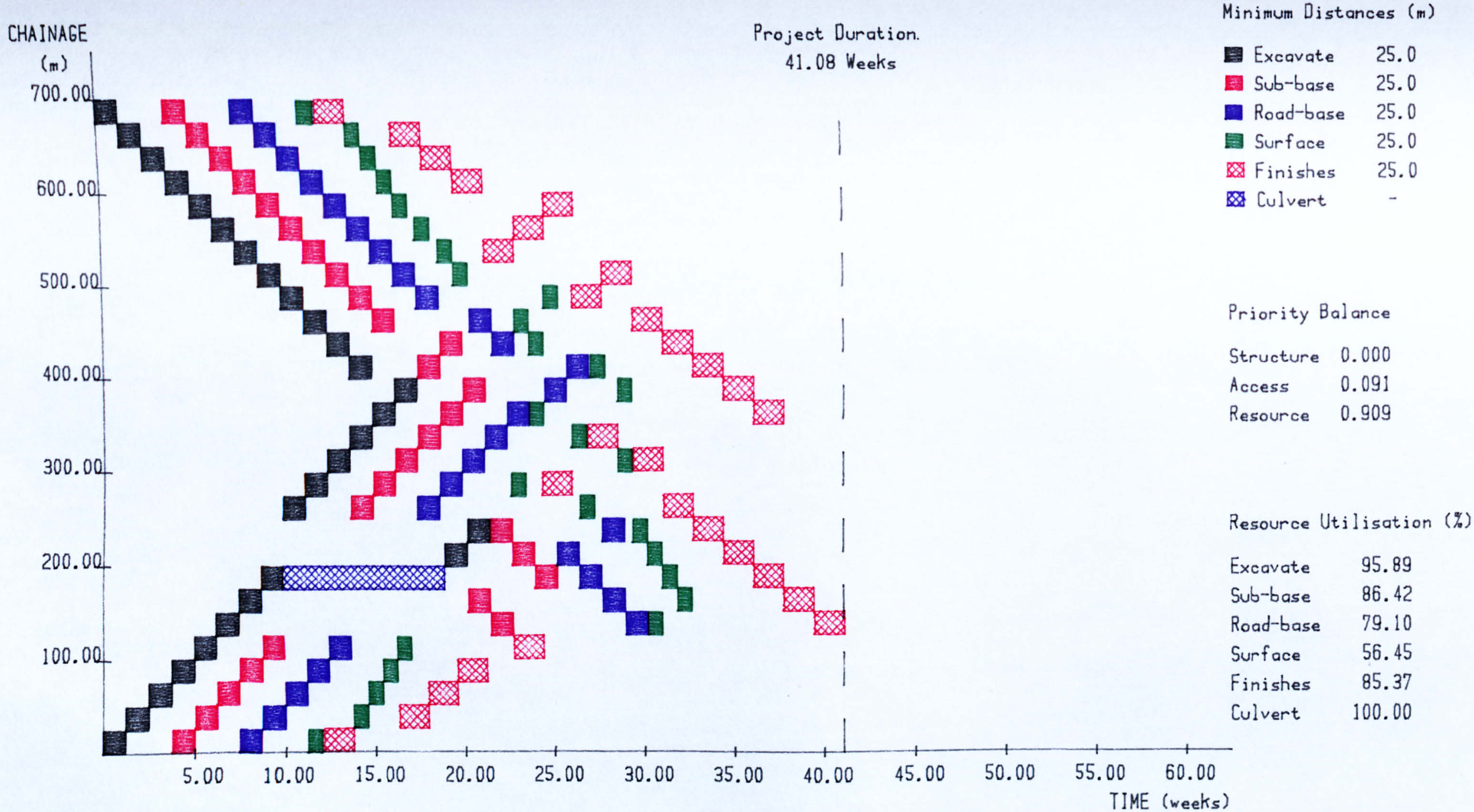


FIGURE NUMBER (B47) ROAD AND CULVERT TEST RUN NUMBER 47

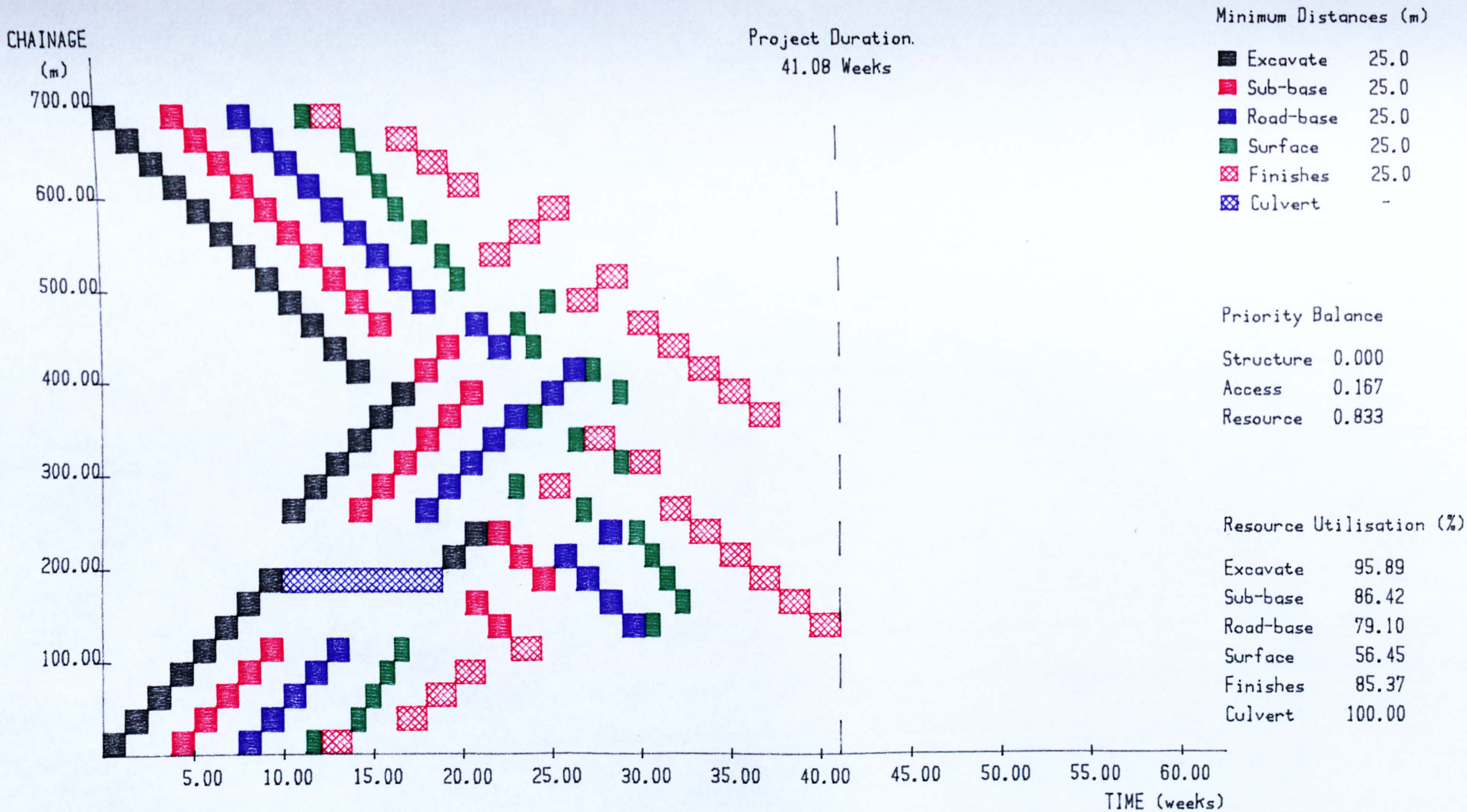


FIGURE NUMBER (B48) ROAD AND CULVERT TEST RUN NUMBER 48

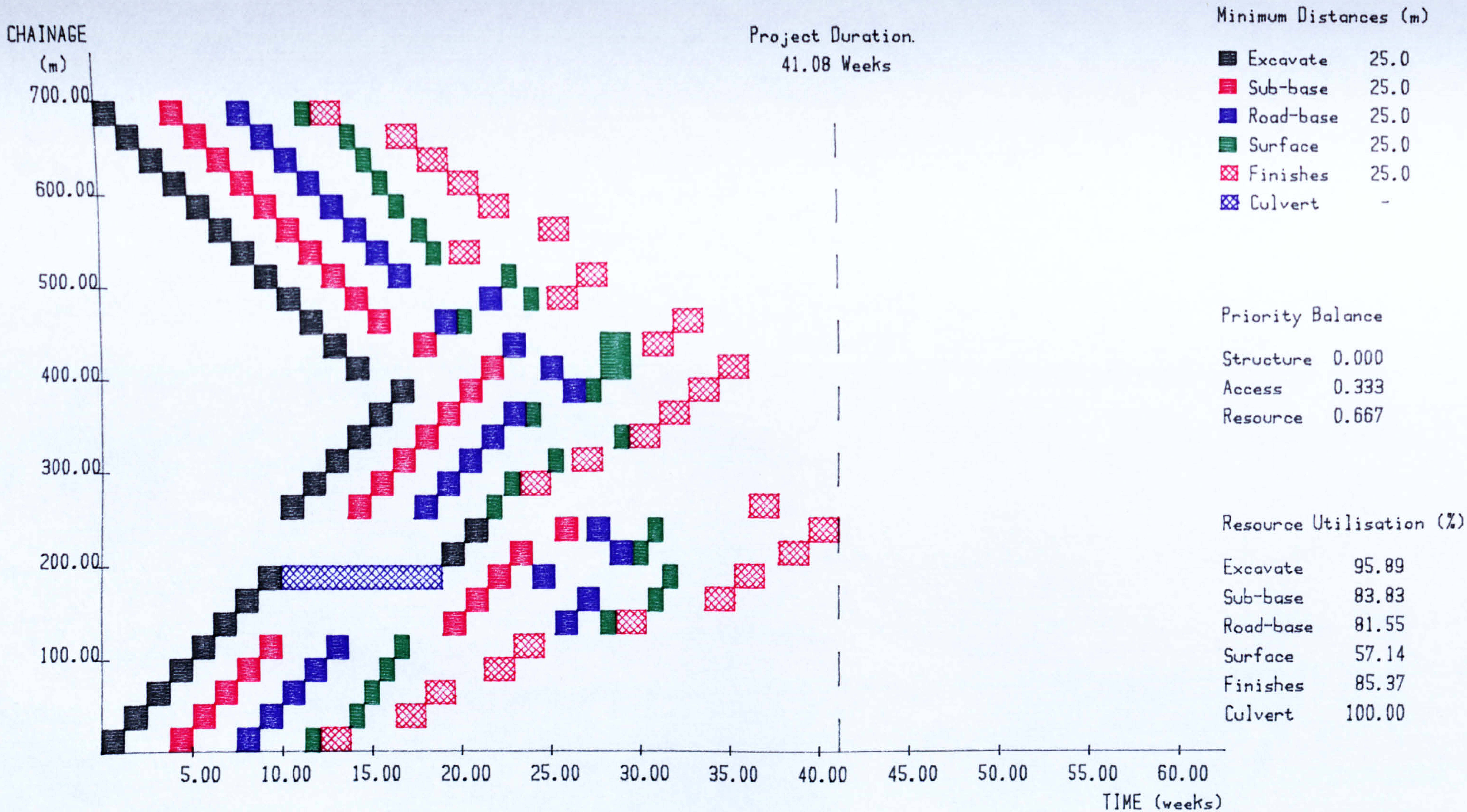


FIGURE NUMBER (B49) ROAD AND CULVERT TEST RUN NUMBER 49

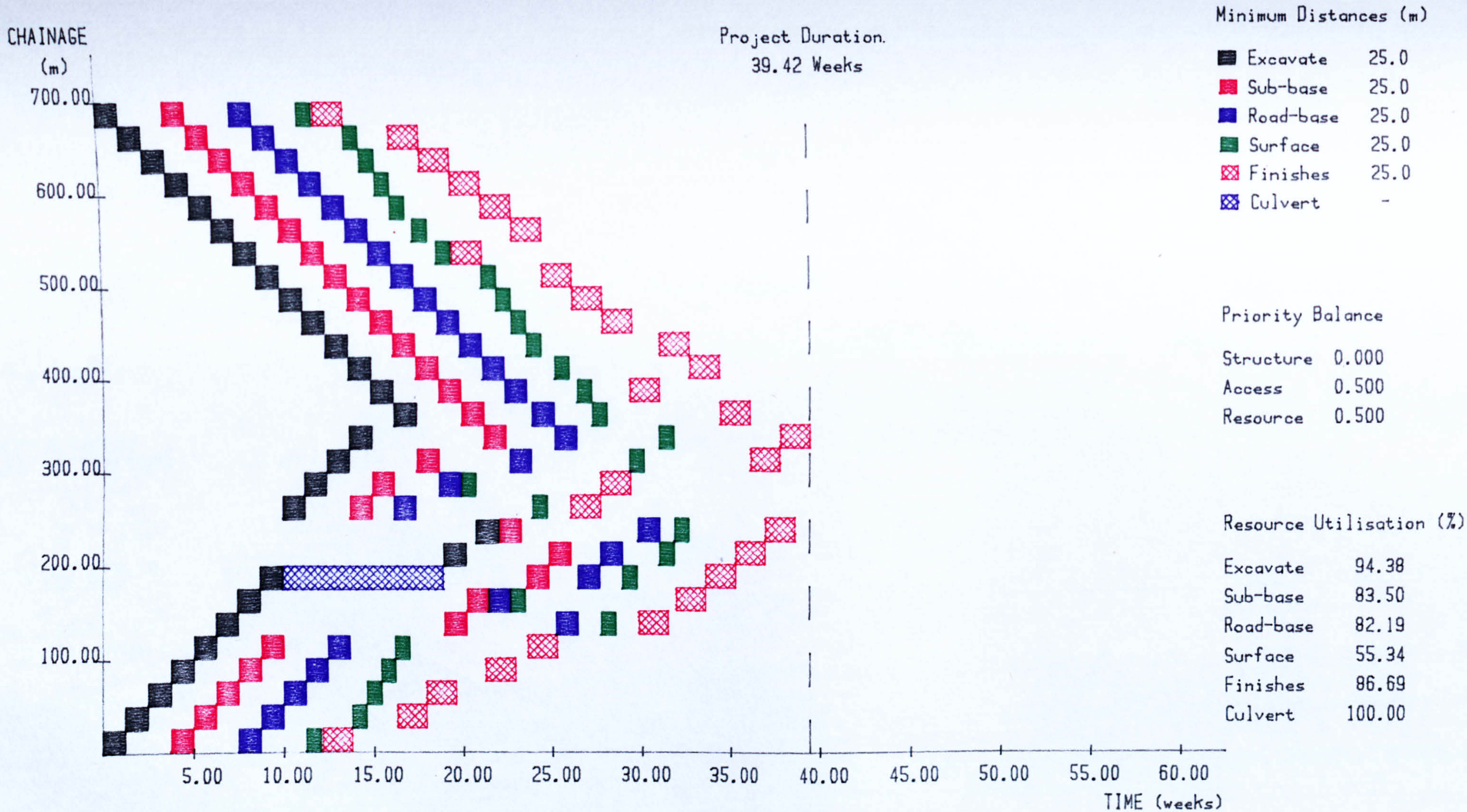
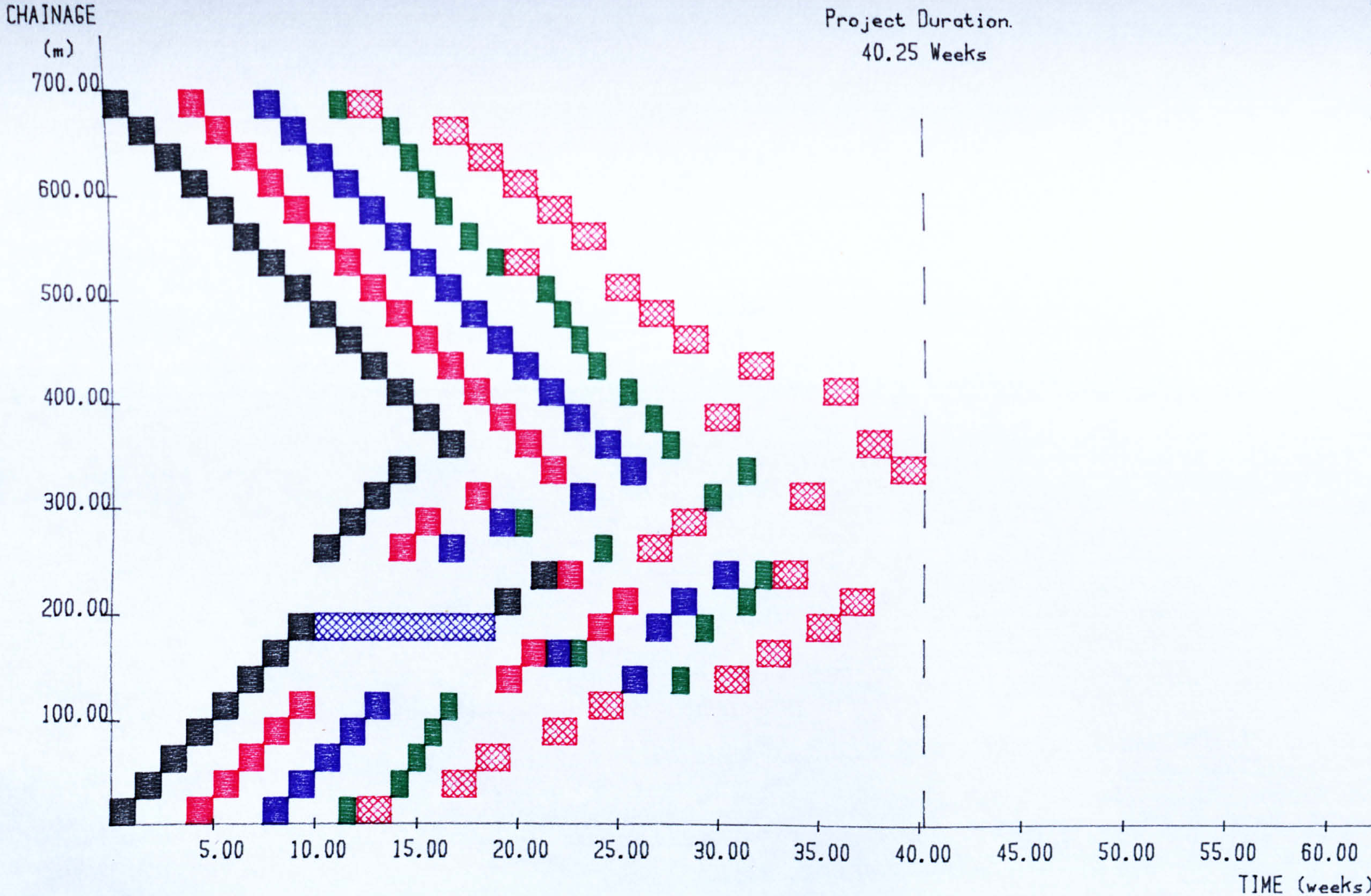


FIGURE NUMBER (B50) ROAD AND CULVERT TEST RUN NUMBER 50



Minimum Distances (m)

Excavate	25.0
Sub-base	25.0
Road-base	25.0
Surface	25.0
Finishes	25.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.667
Resource	0.333

Resource Utilisation (%)

Excavate	94.38
Sub-base	83.50
Road-base	82.19
Surface	55.34
Finishes	86.69
Culvert	100.00

FIGURE NUMBER (B51) ROAD AND CULVERT TEST RUN NUMBER 51

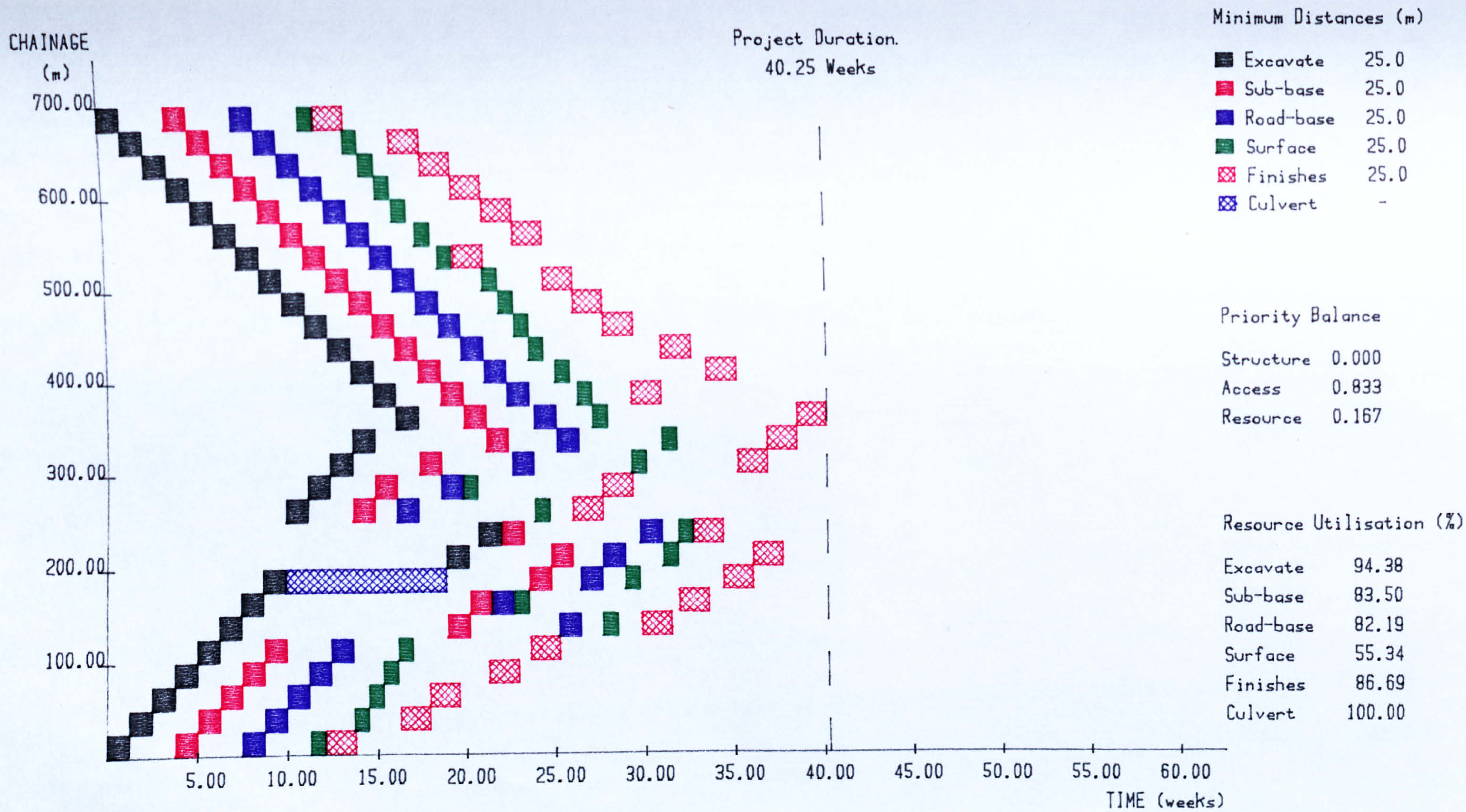


FIGURE NUMBER (B52) ROAD AND CULVERT TEST RUN NUMBER 52

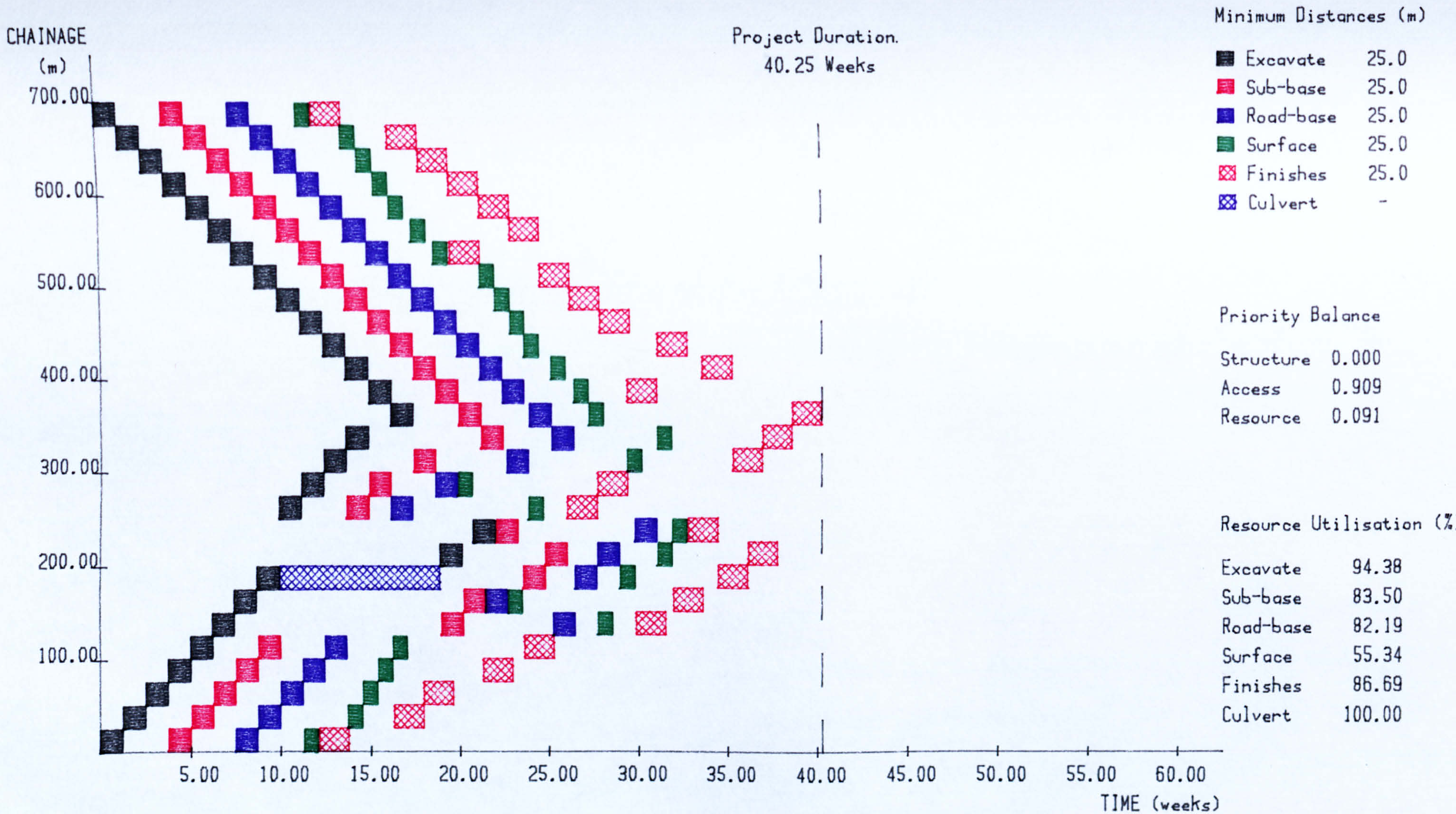


FIGURE NUMBER (B53)   ROAD AND CULVERT TEST RUN NUMBER 53

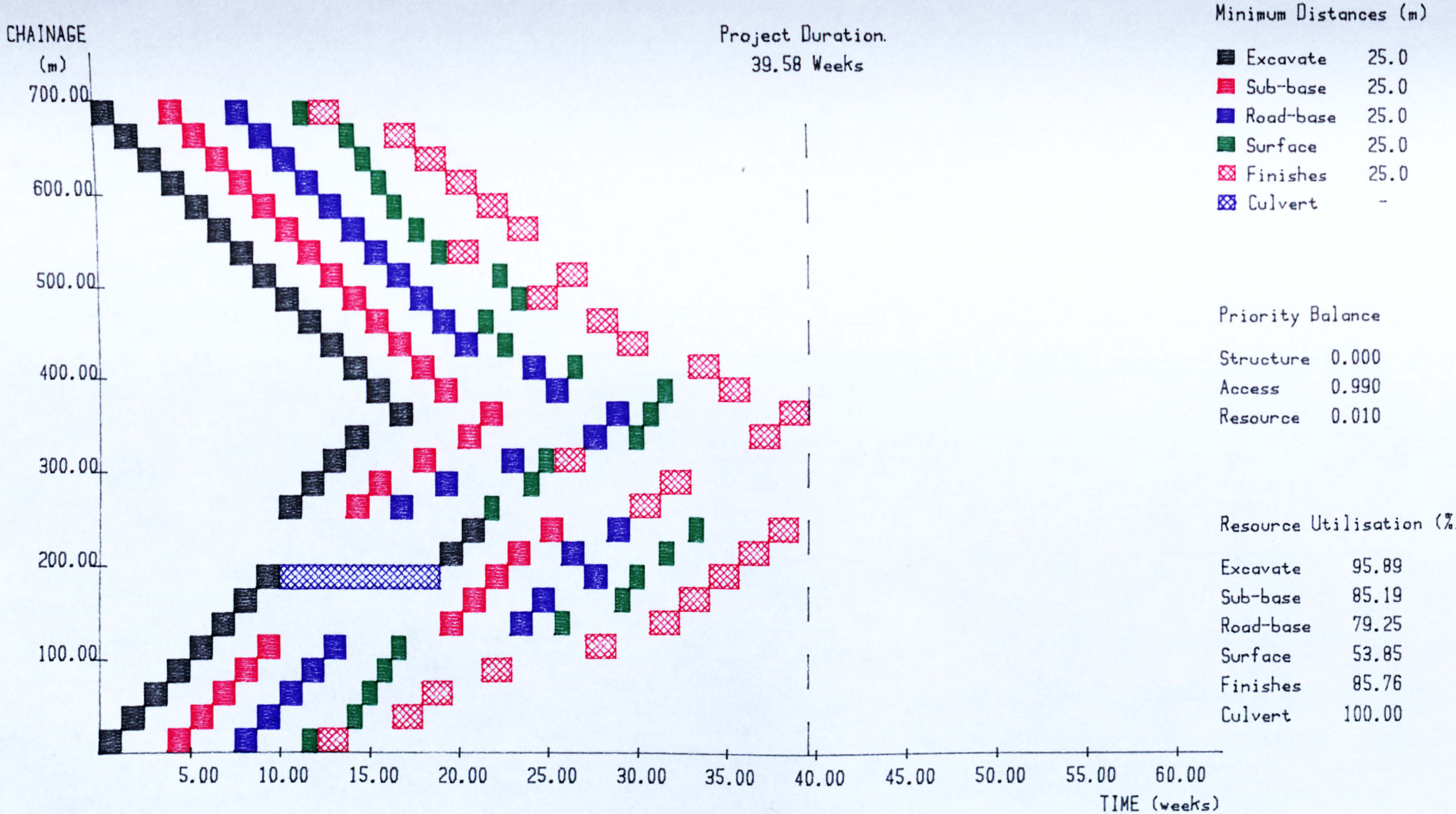


FIGURE NUMBER (B54) ROAD AND CULVERT TEST RUN NUMBER 54

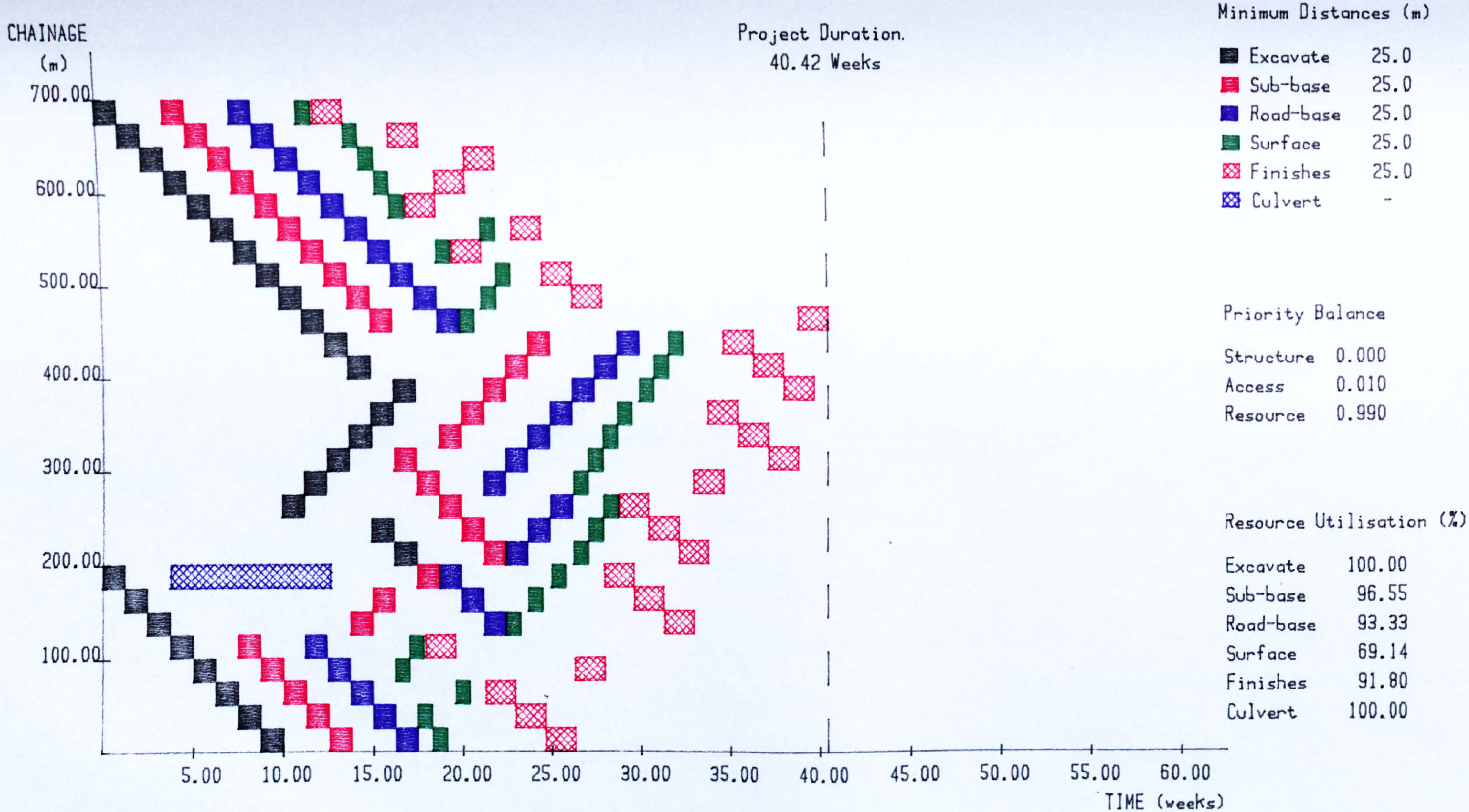


FIGURE NUMBER (B55) ROAD AND CULVERT TEST RUN NUMBER 55

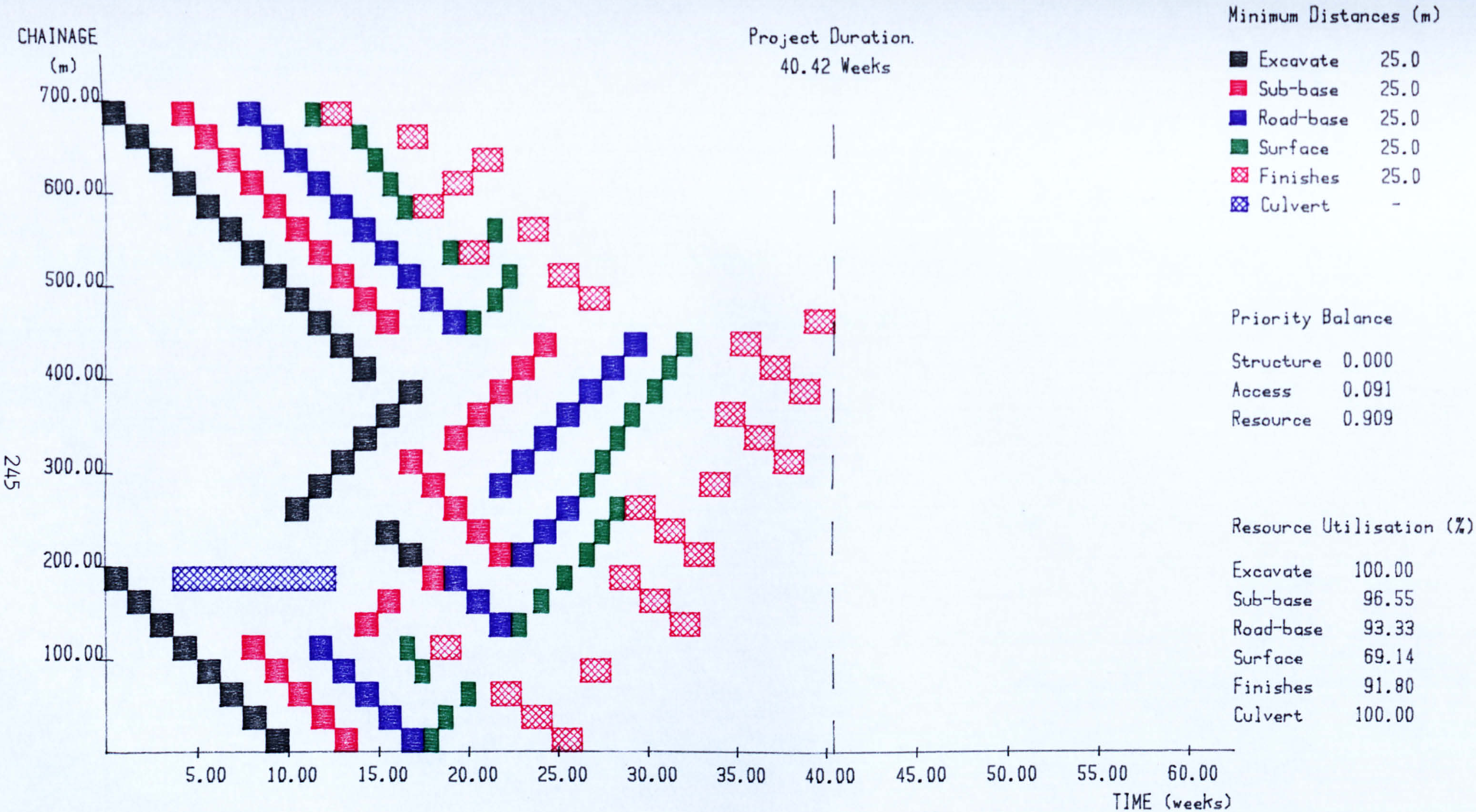


FIGURE NUMBER (B56) ROAD AND CULVERT TEST RUN NUMBER 56

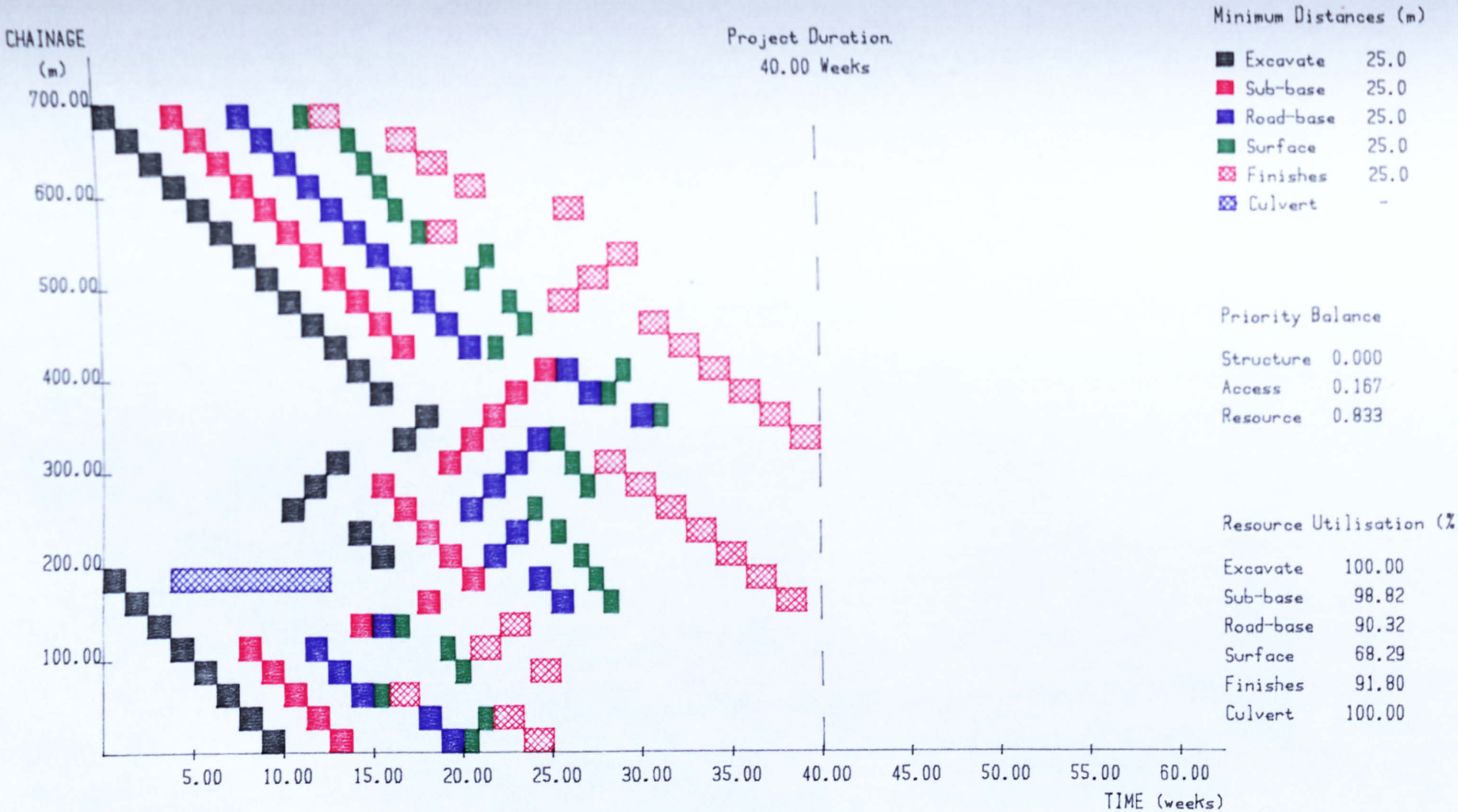


FIGURE NUMBER (B57) ROAD AND CULVERT TEST RUN NUMBER 57

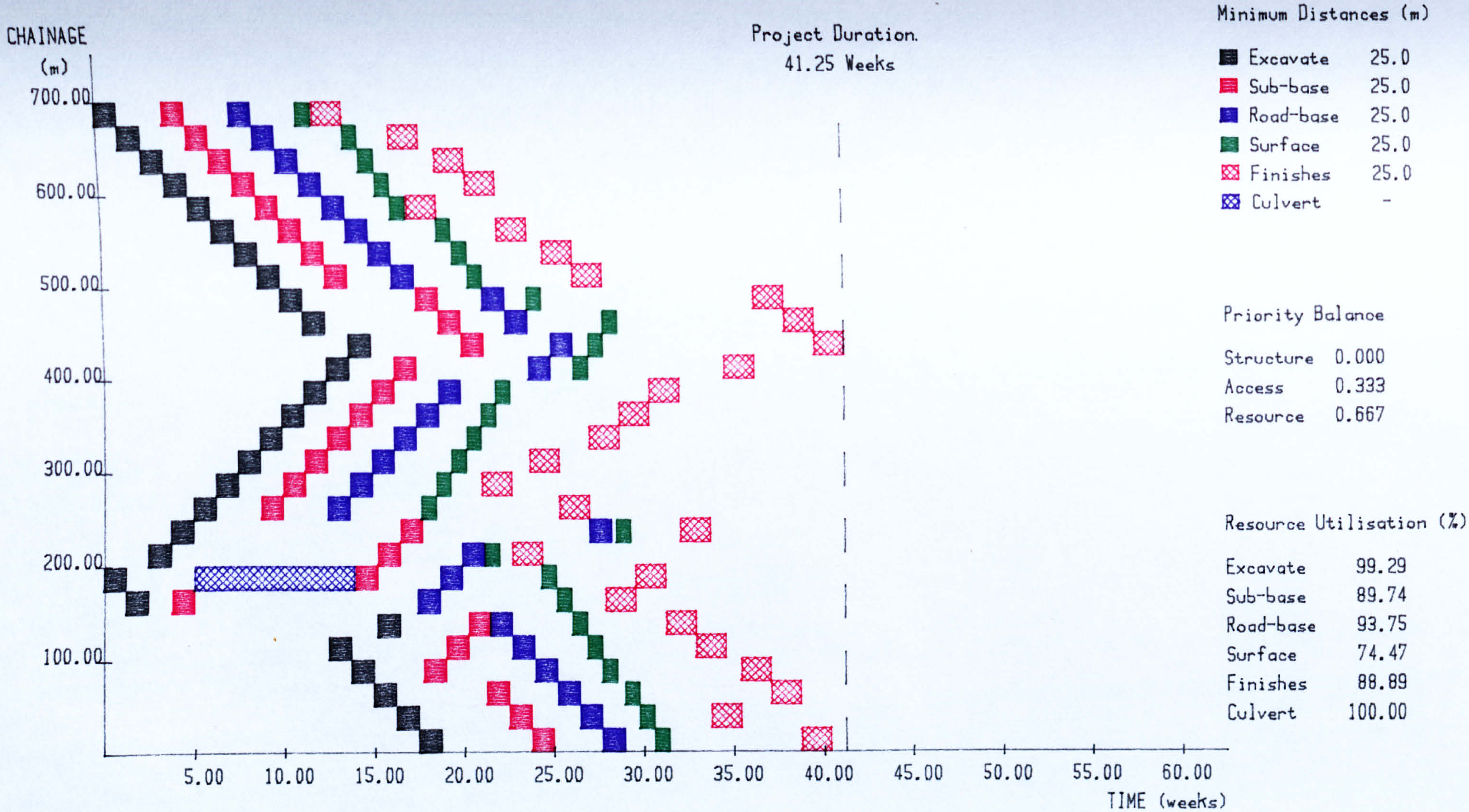


FIGURE NUMBER (B58) ROAD AND CULVERT TEST RUN NUMBER 58

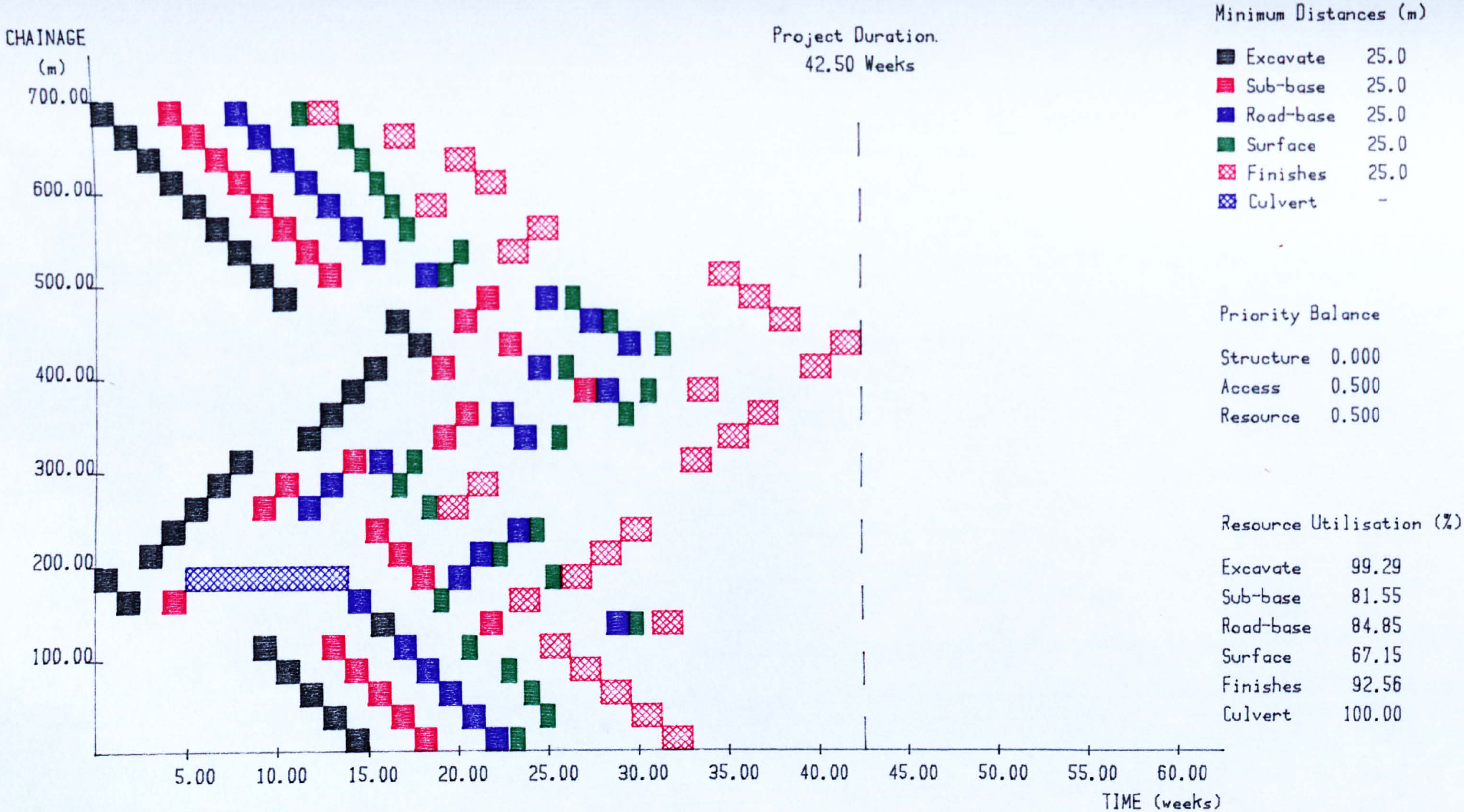


FIGURE NUMBER (B59)

ROAD AND CULVERT TEST RUN NUMBER 59

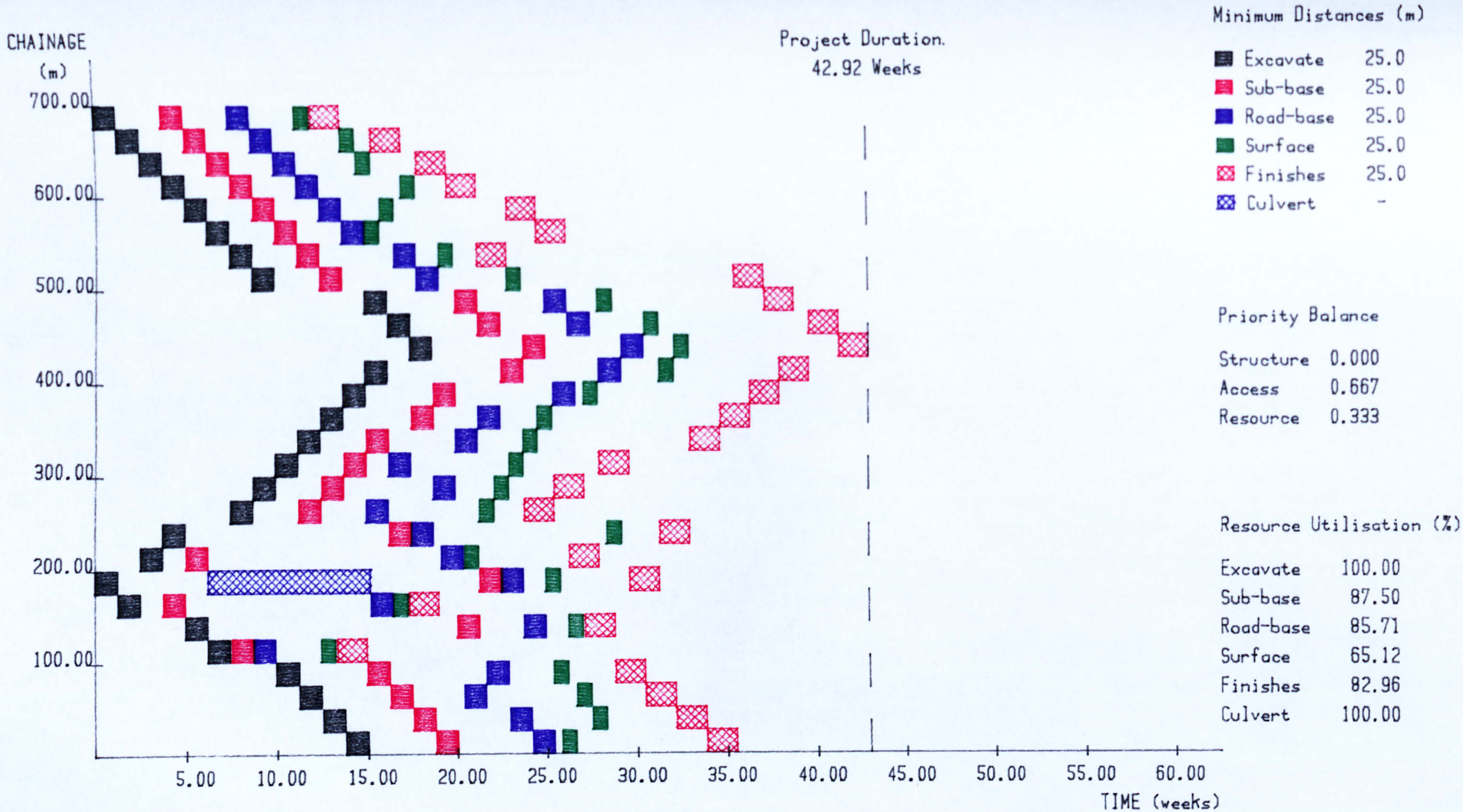


FIGURE NUMBER (B60) ROAD AND CULVERT TEST RUN NUMBER 60

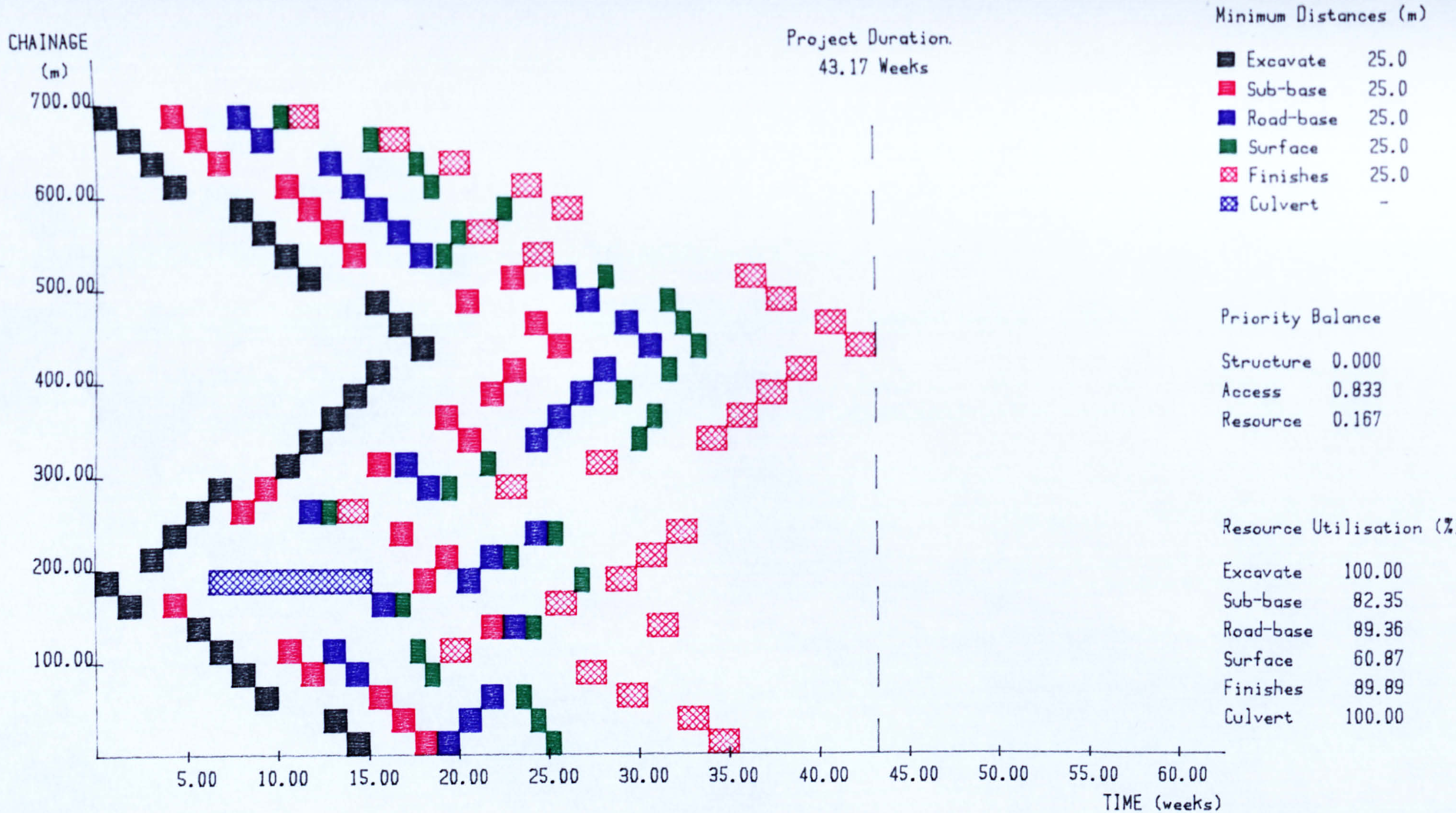


FIGURE NUMBER (B61) ROAD AND CULVERT TEST RUN NUMBER 61

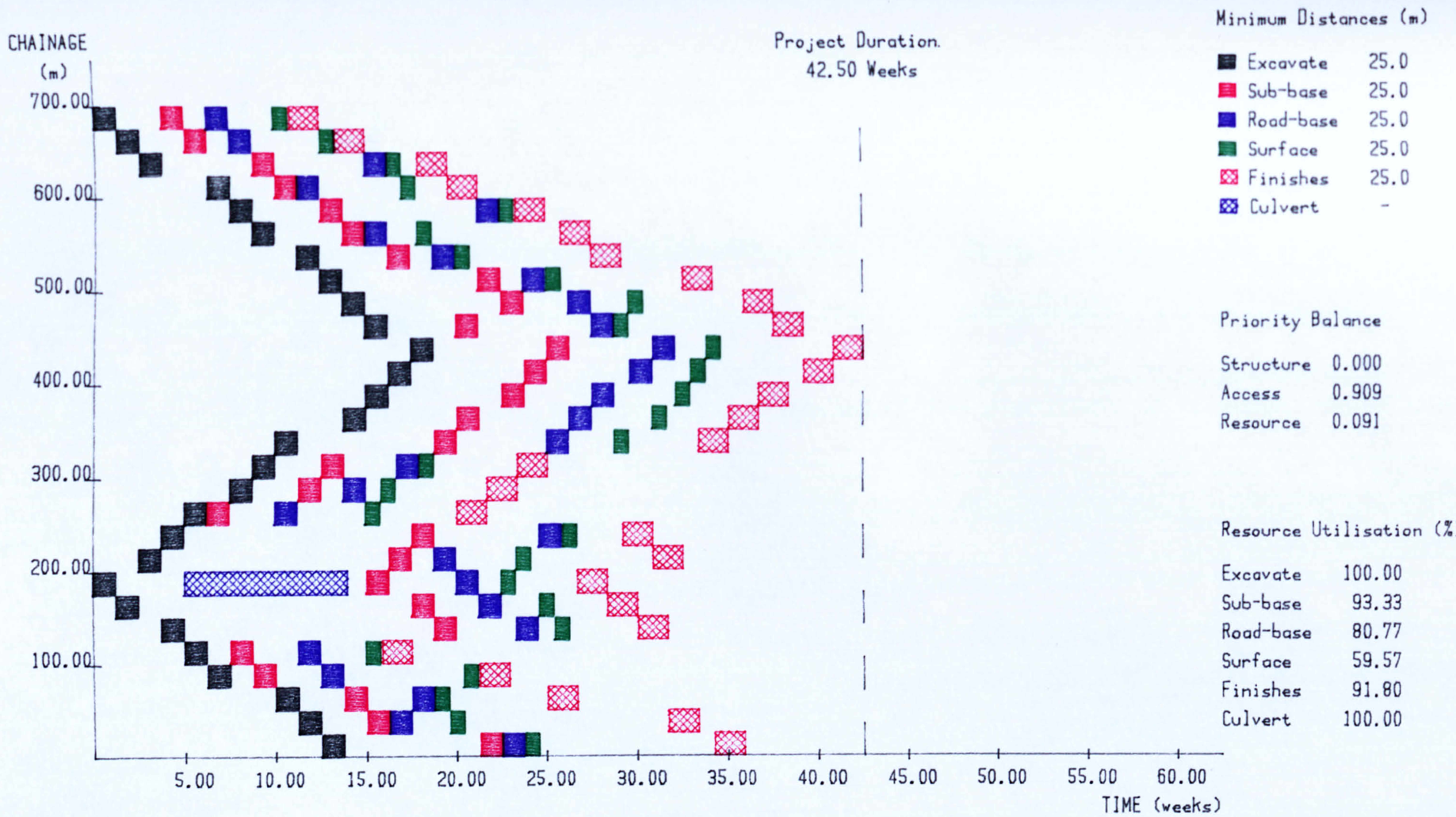


FIGURE NUMBER (B62) ROAD AND CULVERT TEST RUN NUMBER 62

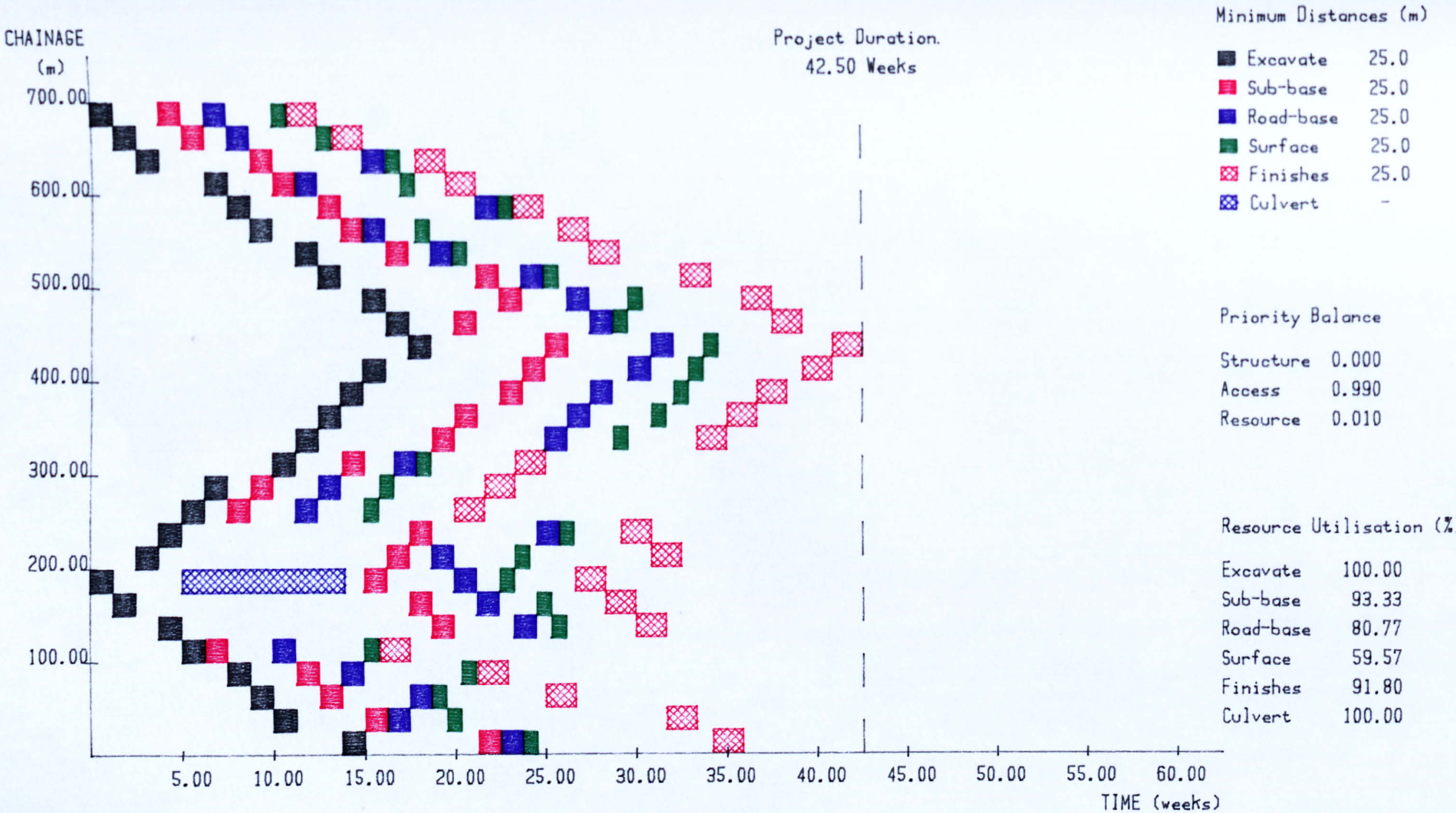


FIGURE NUMBER (B63) ROAD AND CULVERT TEST RUN NUMBER 63

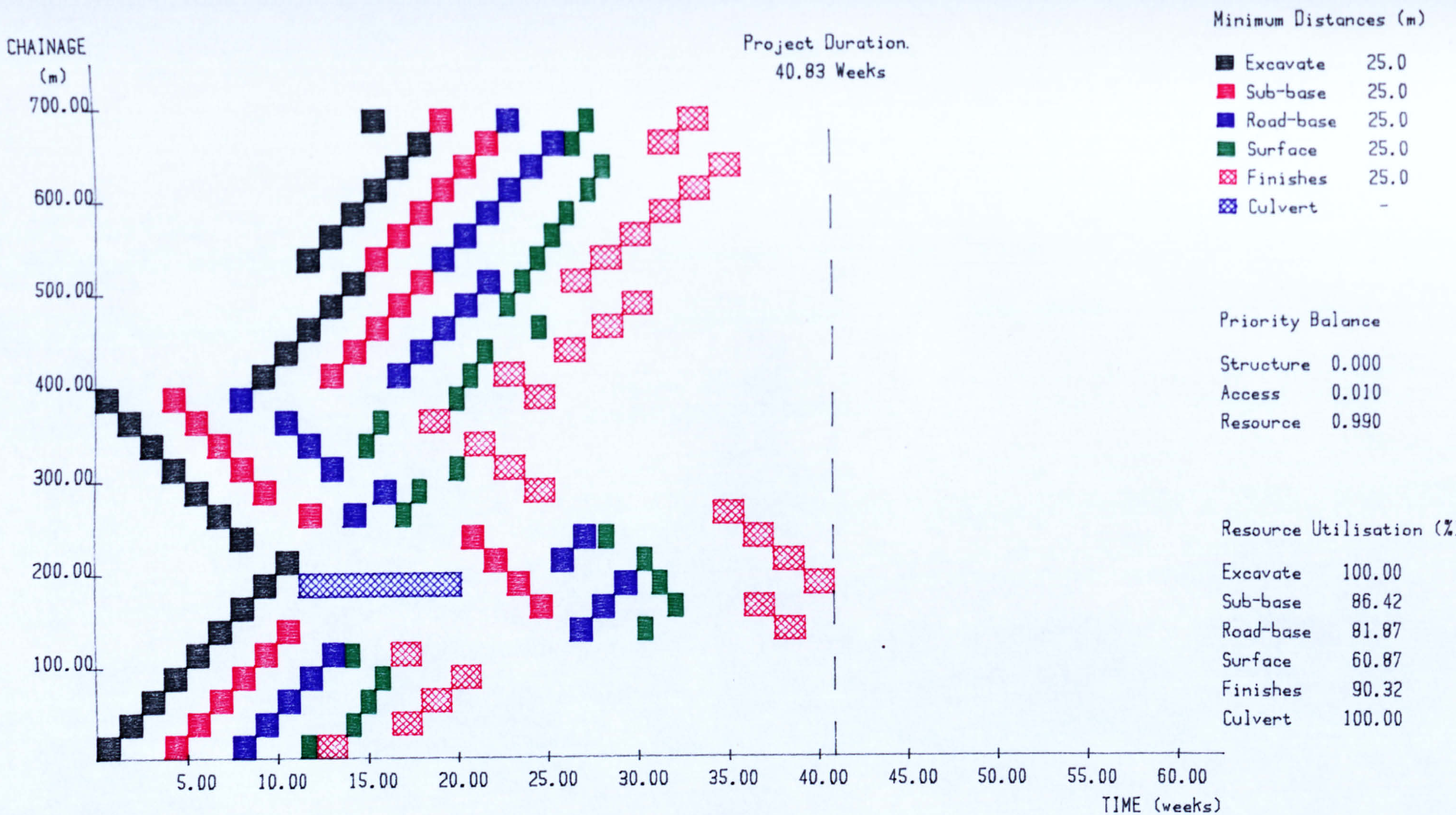


FIGURE NUMBER (B64) ROAD AND CULVERT TEST RUN NUMBER 64

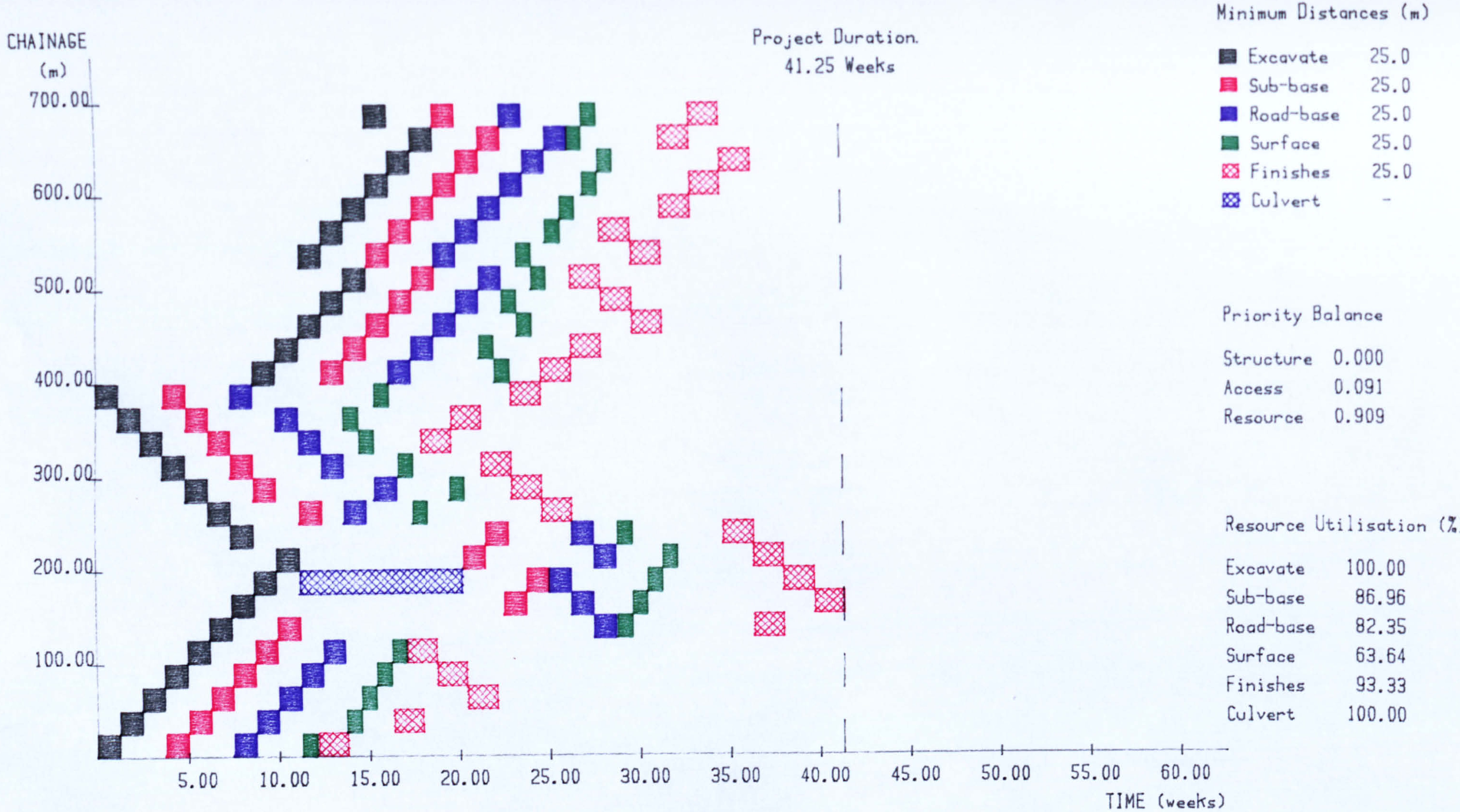


FIGURE NUMBER (B65) ROAD AND CULVERT TEST RUN NUMBER 65

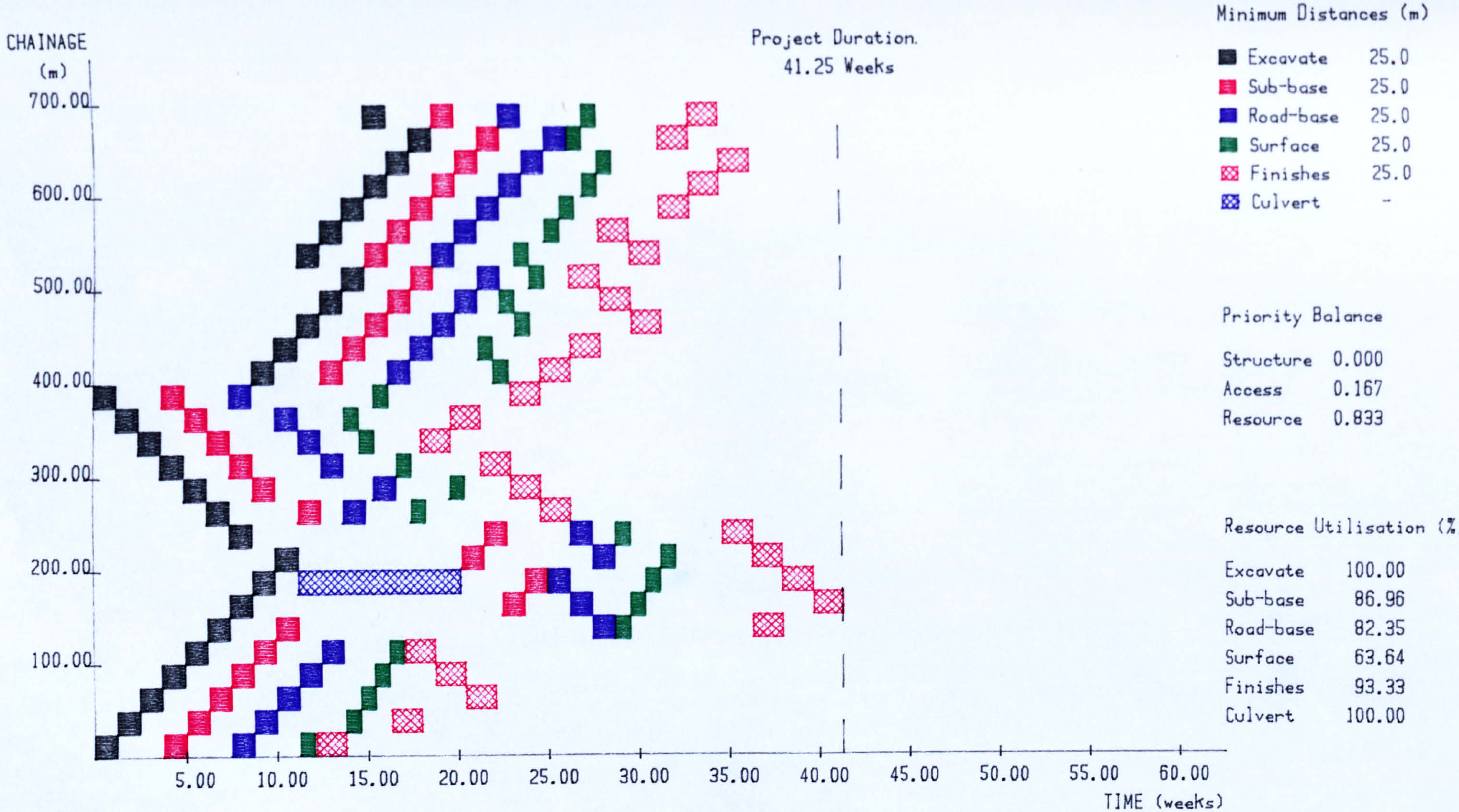


FIGURE NUMBER (B66) ROAD AND CULVERT TEST RUN NUMBER 66

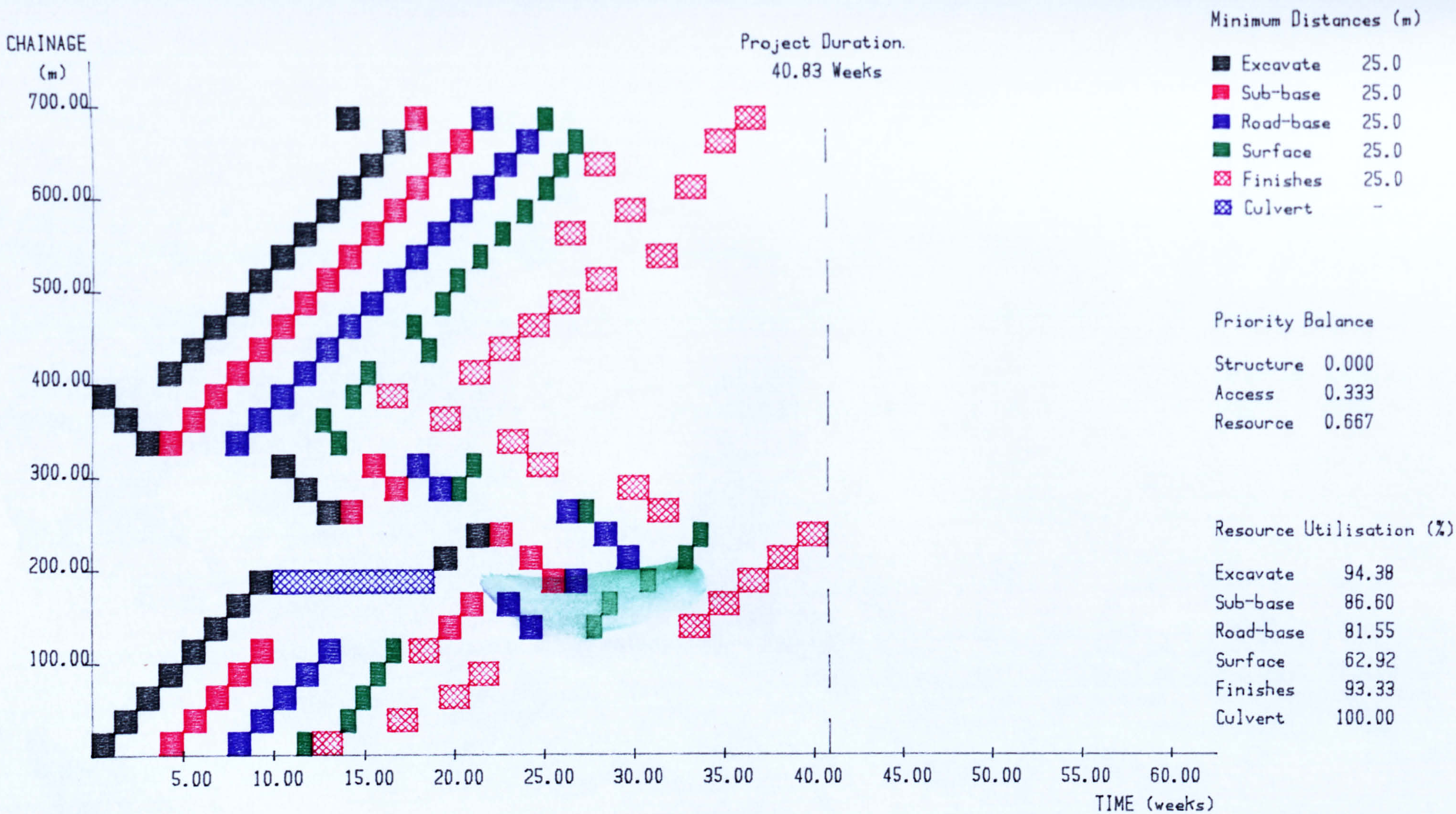


FIGURE NUMBER (B67) ROAD AND CULVERT TEST RUN NUMBER 67

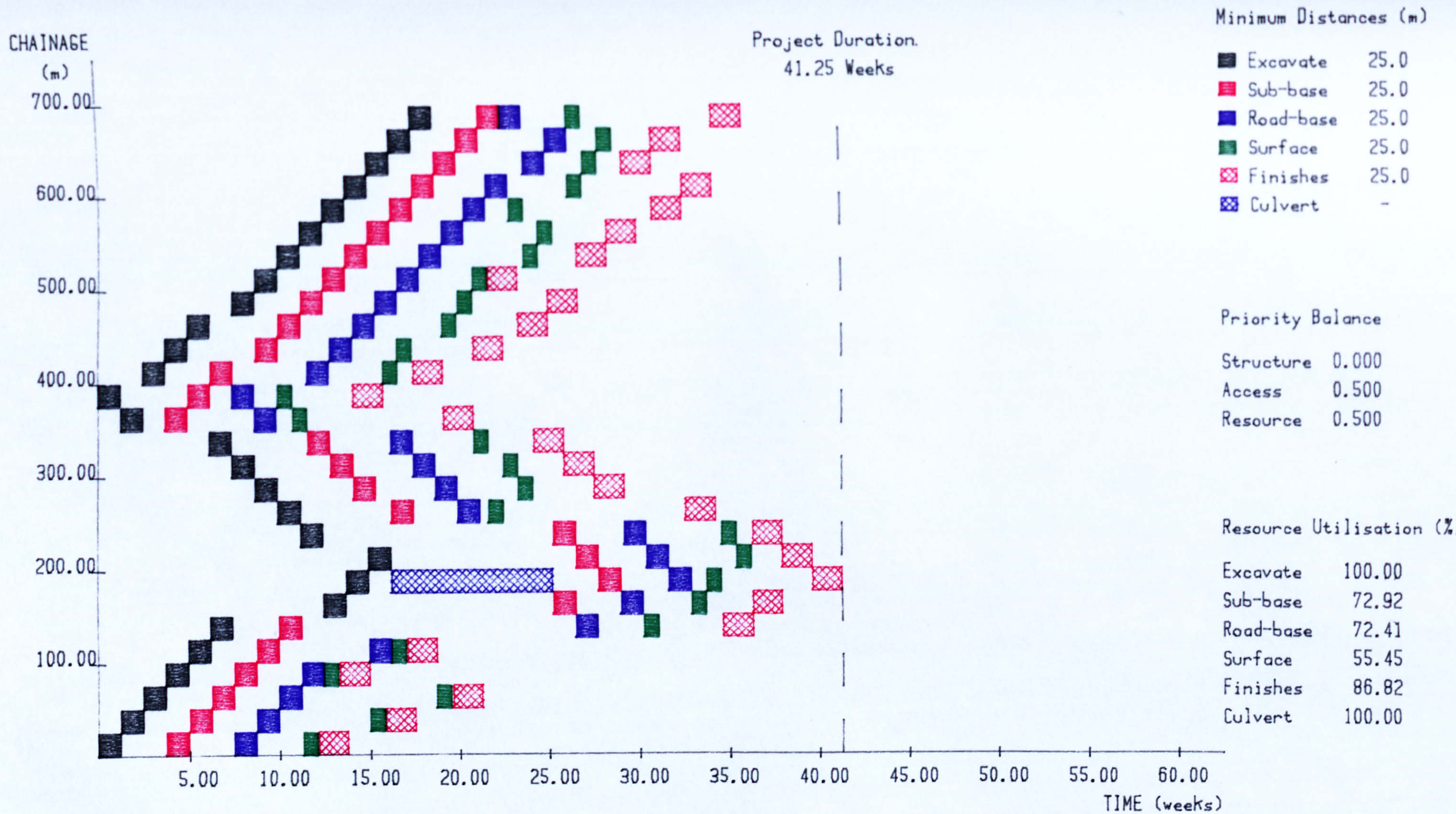


FIGURE NUMBER (B68) ROAD AND CULVERT TEST RUN NUMBER 68

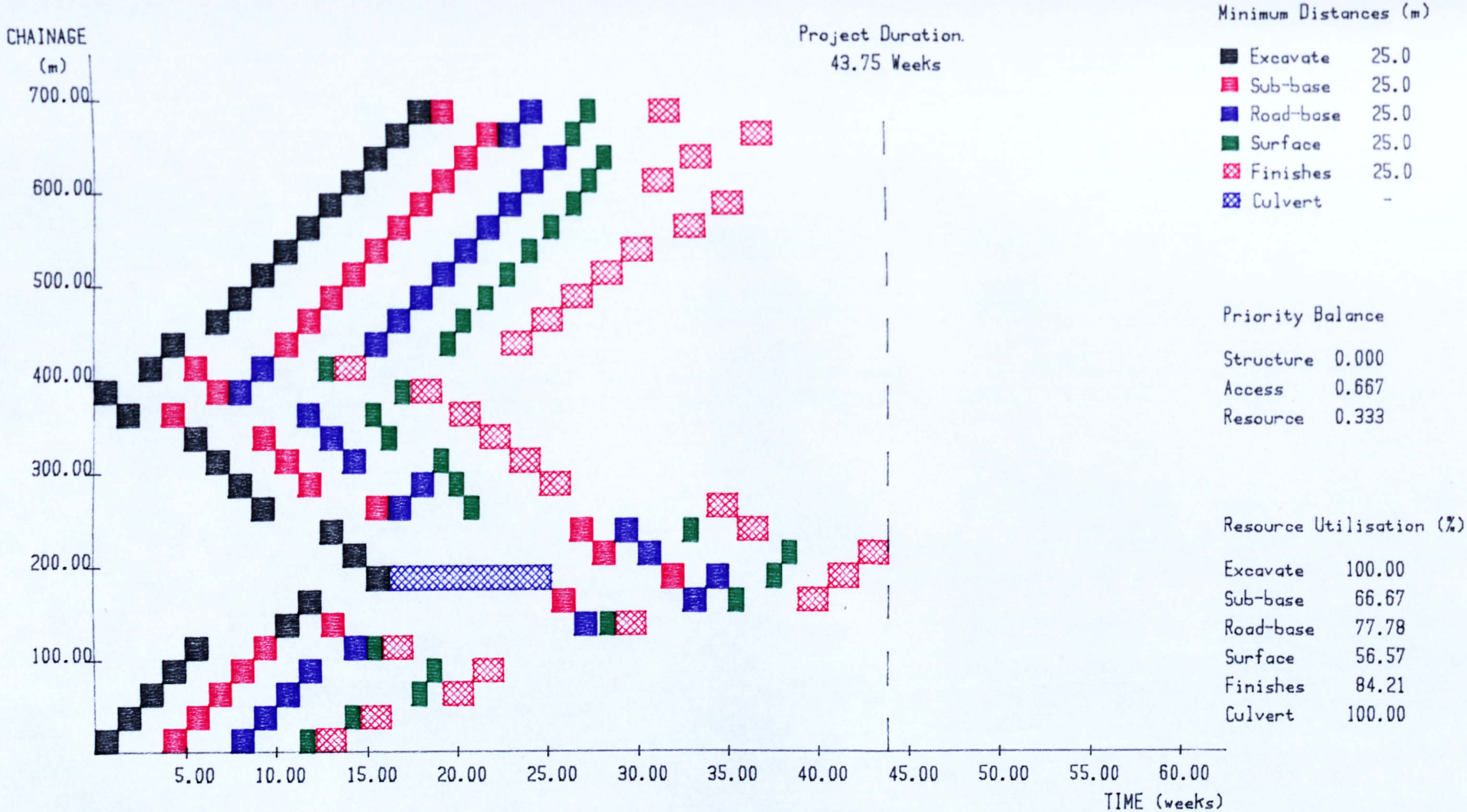


FIGURE NUMBER (B69) ROAD AND CULVERT TEST RUN NUMBER 69

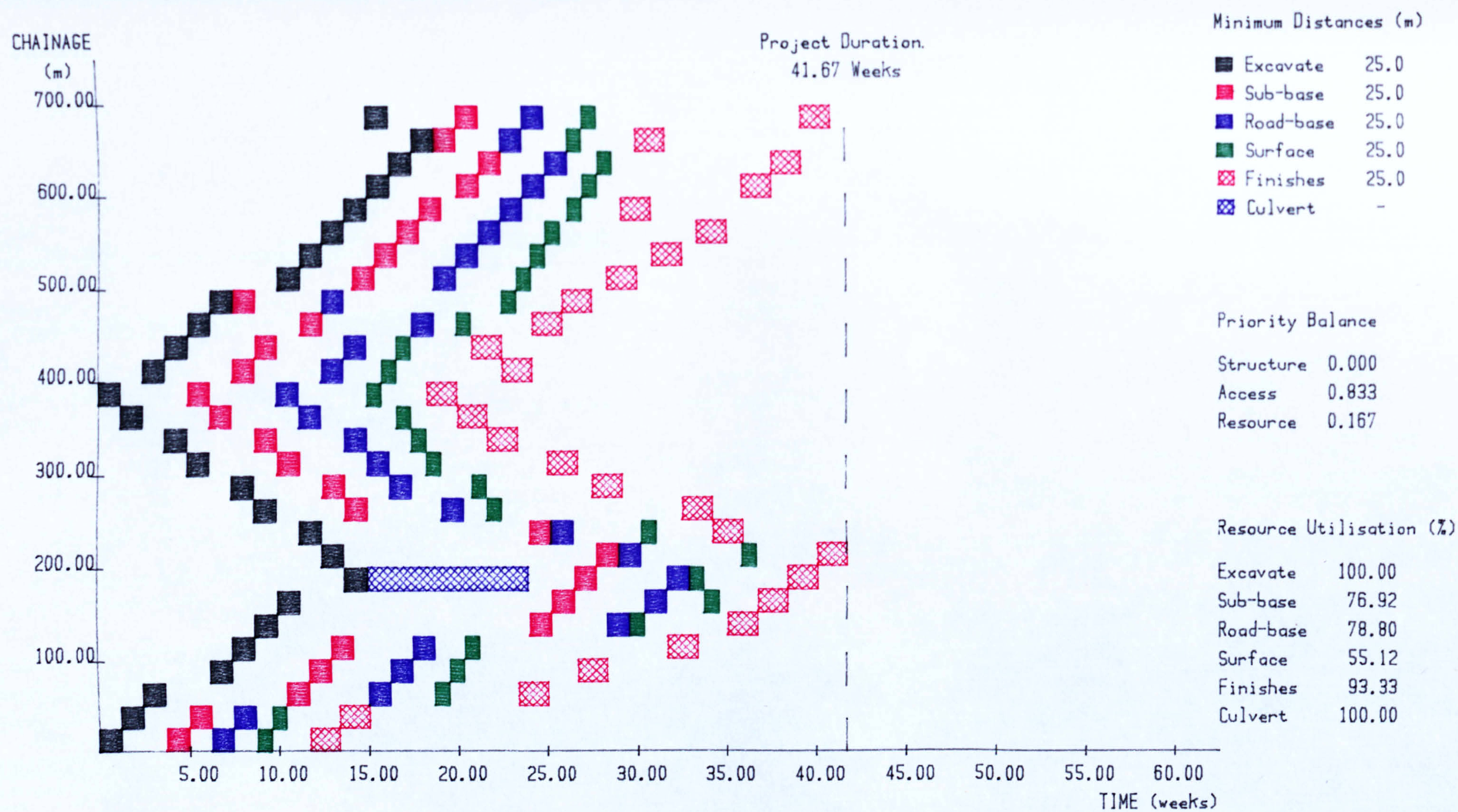


FIGURE NUMBER (B70) ROAD AND CULVERT TEST RUN NUMBER 70

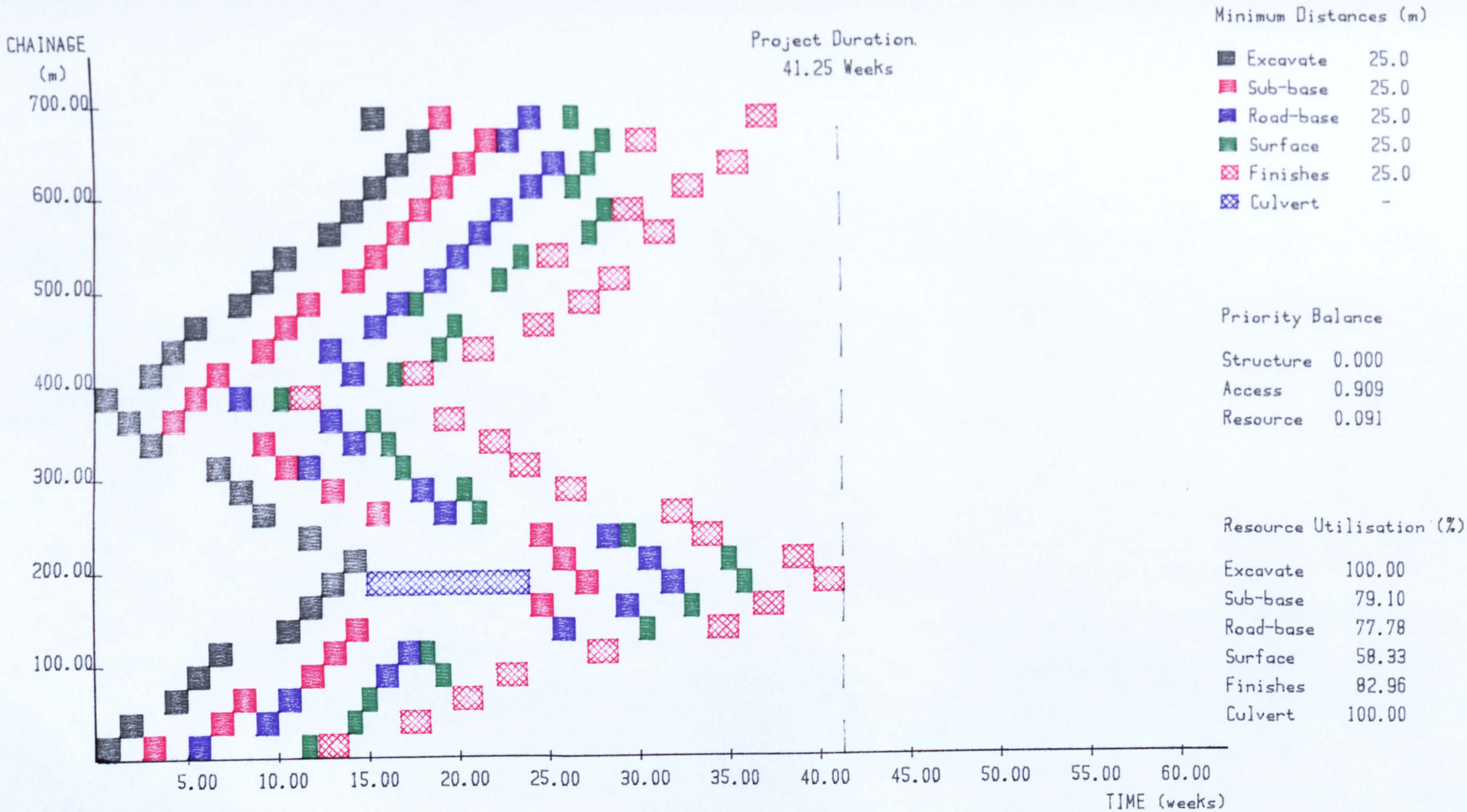
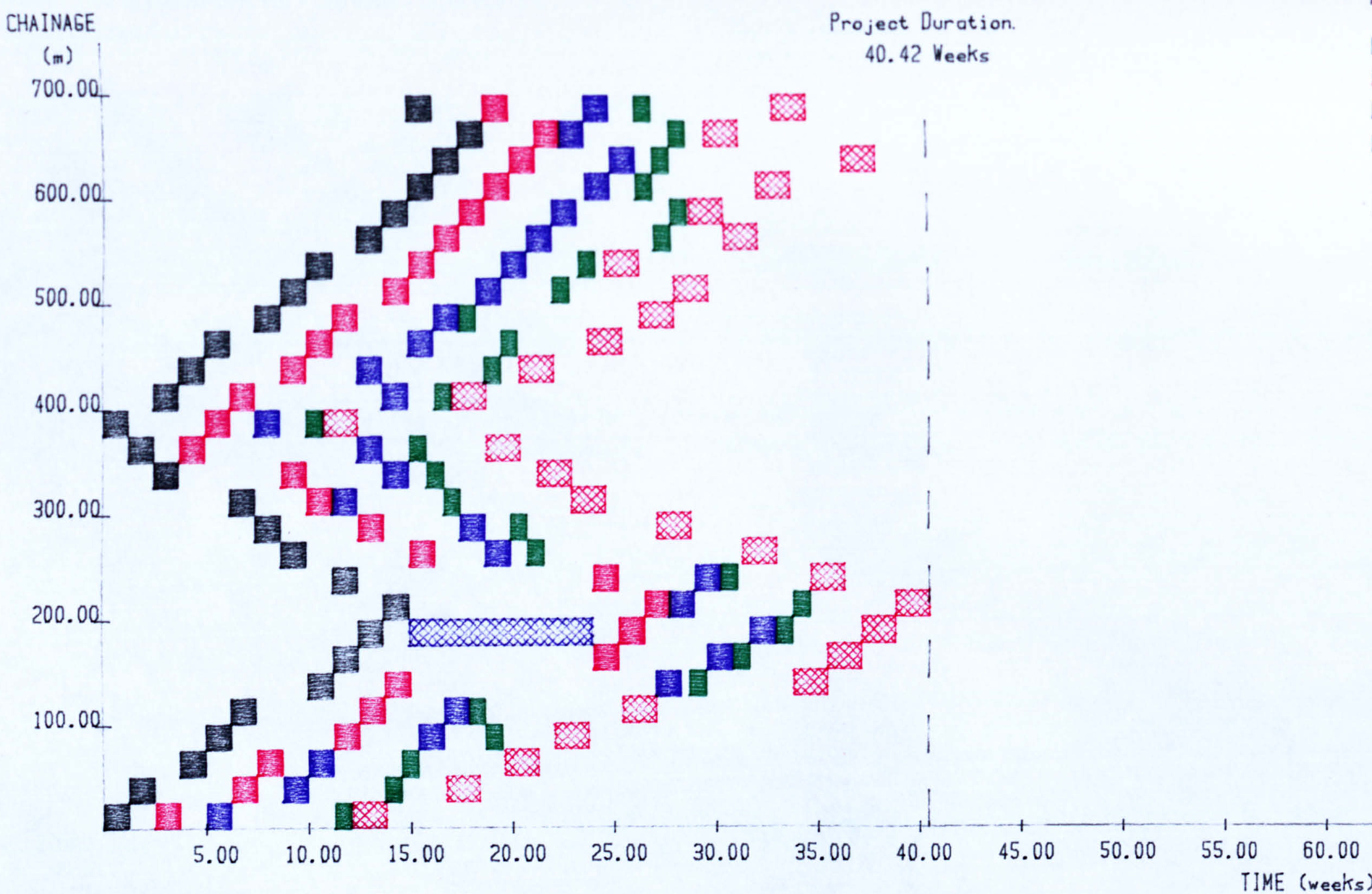


FIGURE NUMBER (B71) ROAD AND CULVERT TEST RUN NUMBER 71



Minimum Distances (m)

Excavate	25.0
Sub-base	25.0
Road-base	25.0
Surface	25.0
Finishes	25.0
Culvert	-

Priority Balance

Structure	0.000
Access	0.990
Resource	0.010

Resource Utilisation (%)

Excavate	100.00
Sub-base	79.10
Road-base	75.68
Surface	56.57
Finishes	84.21
Culvert	100.00

FIGURE NUMBER (B72) ROAD AND CULVERT TEST RUN NUMBER 72

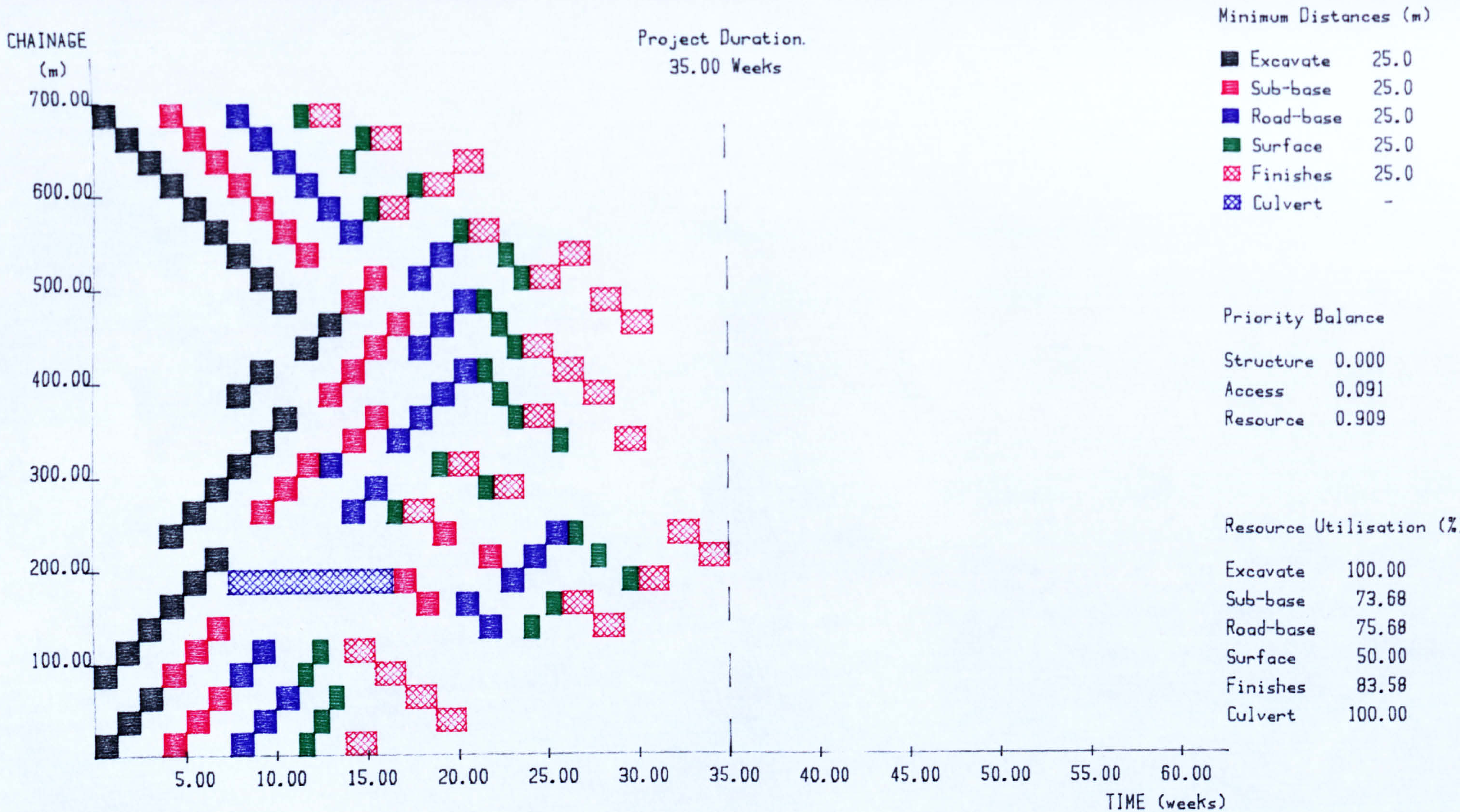


FIGURE NUMBER (B73) ROAD AND CULVERT TEST RUN NUMBER 73

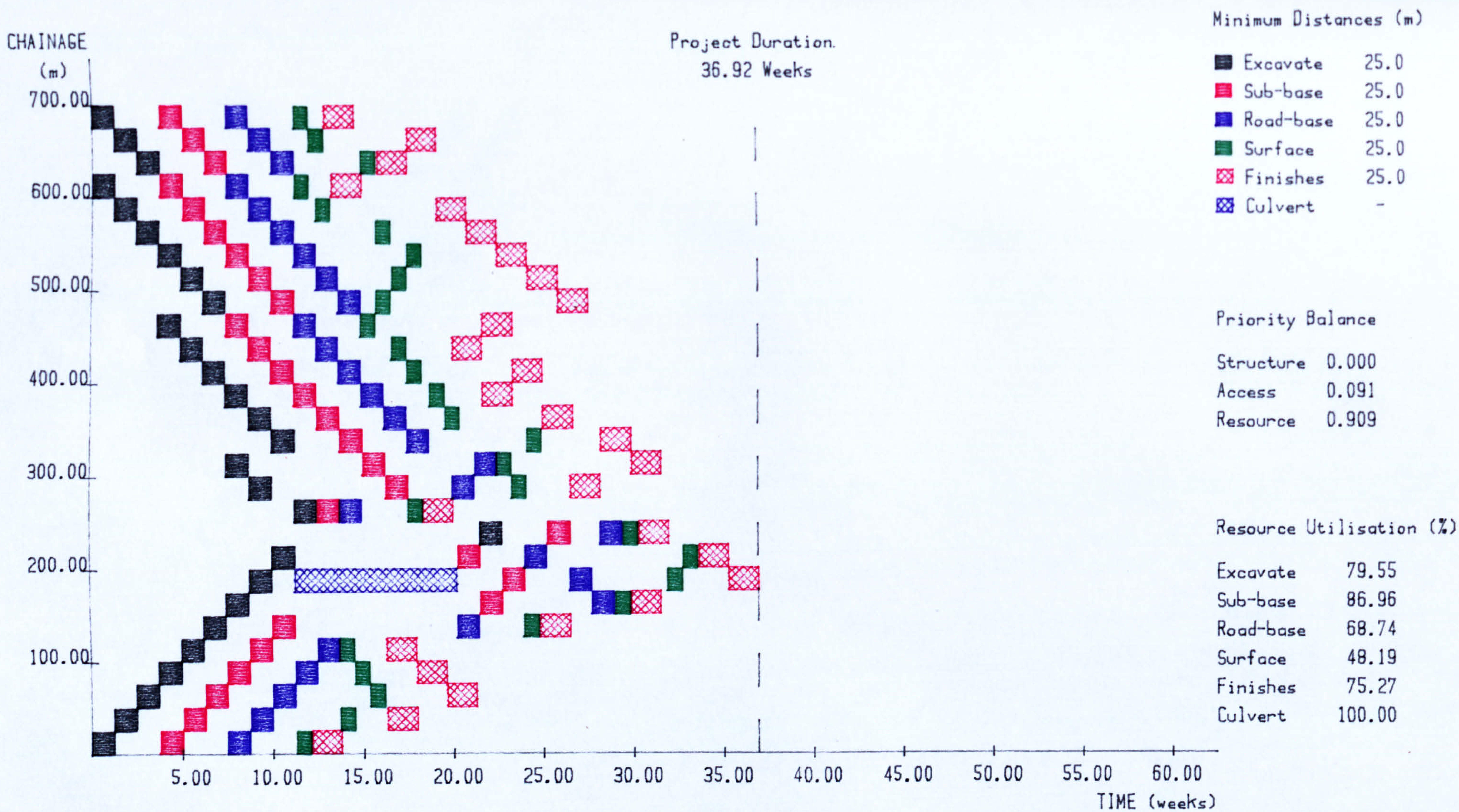


FIGURE NUMBER (B74) ROAD AND CULVERT TEST RUN NUMBER 74

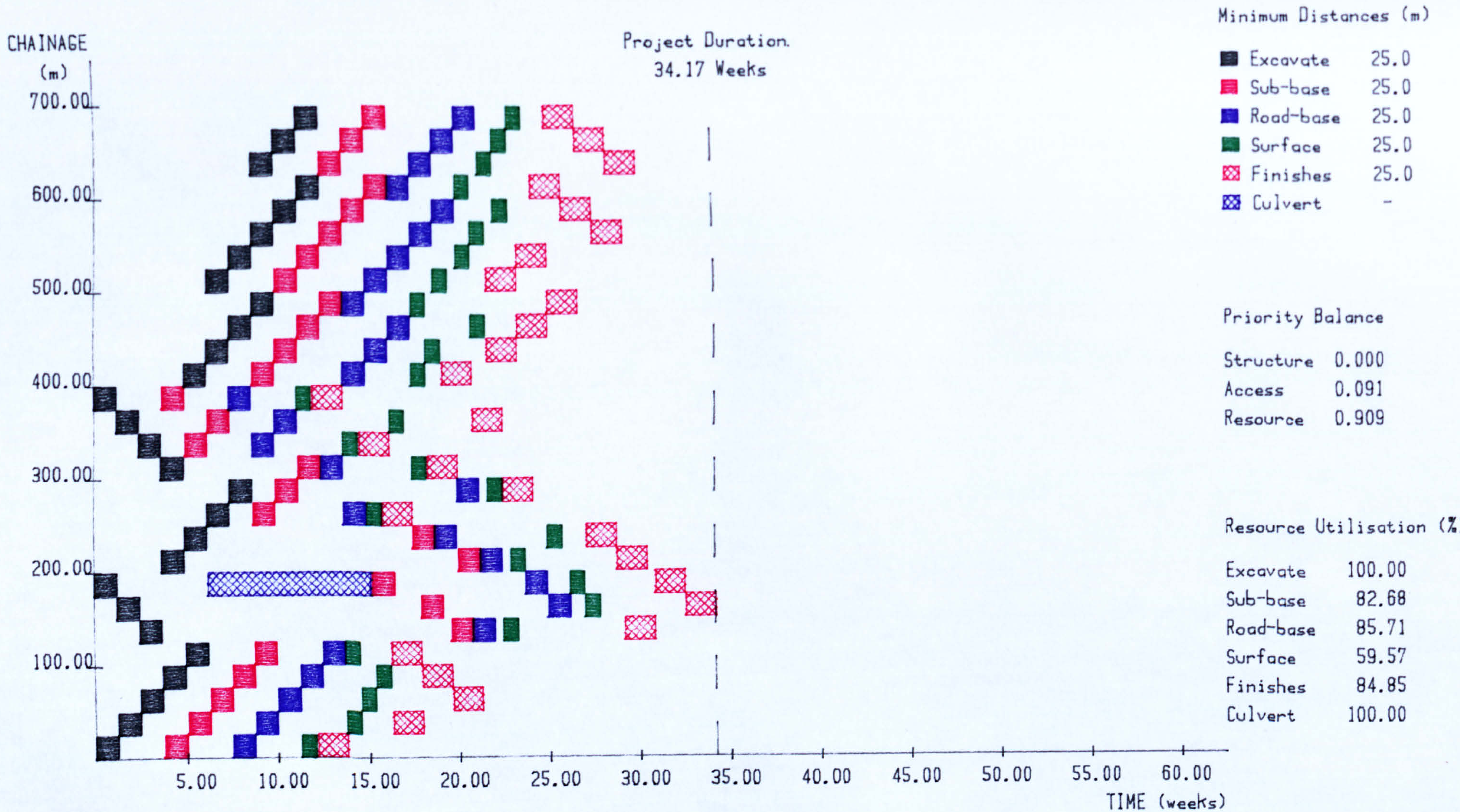


FIGURE NUMBER (B75) ROAD AND CULVERT TEST RUN NUMBER 75

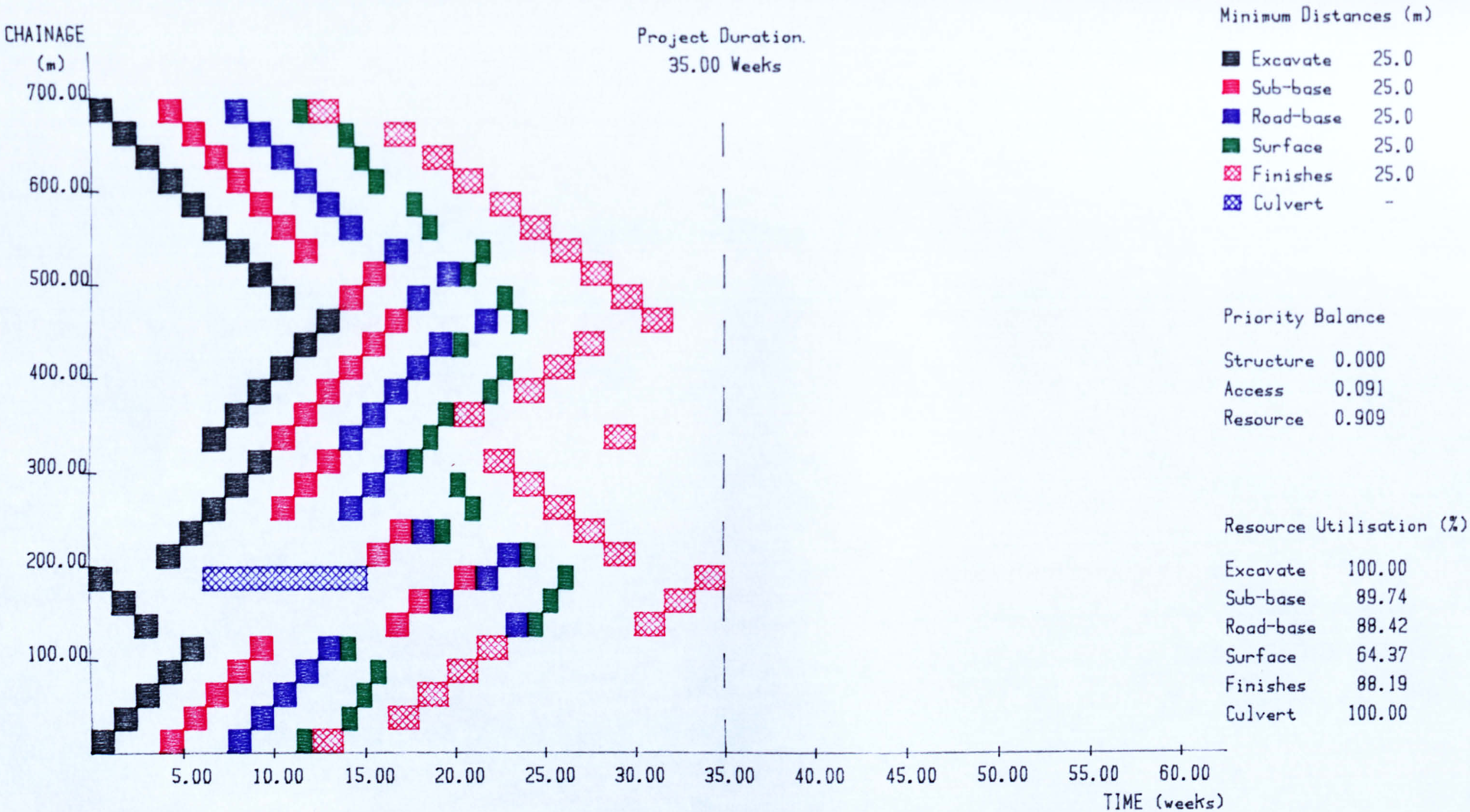


FIGURE NUMBER (B76) ROAD AND CULVERT TEST RUN NUMBER 76

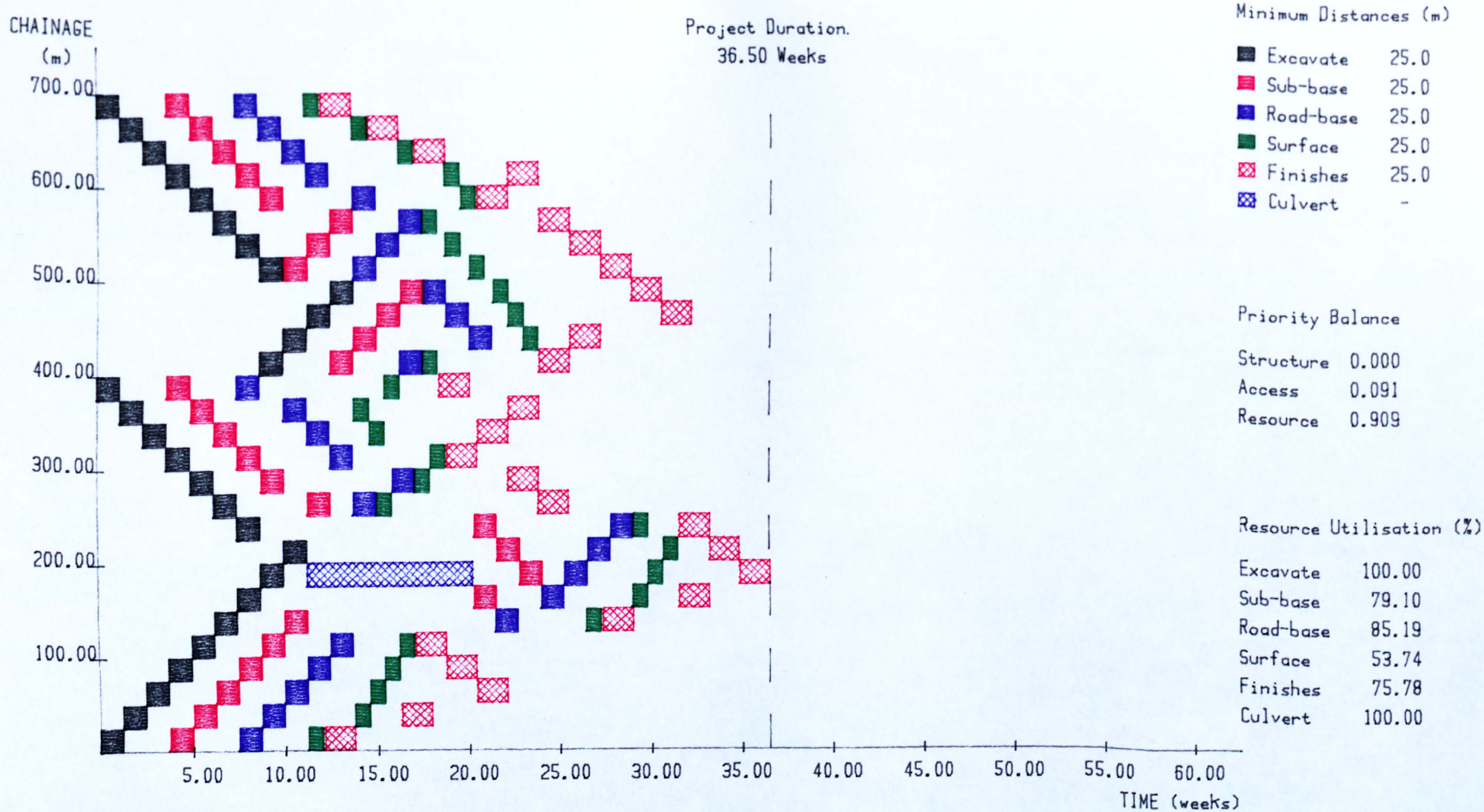


FIGURE NUMBER (B77) ROAD AND CULVERT TEST RUN NUMBER 77

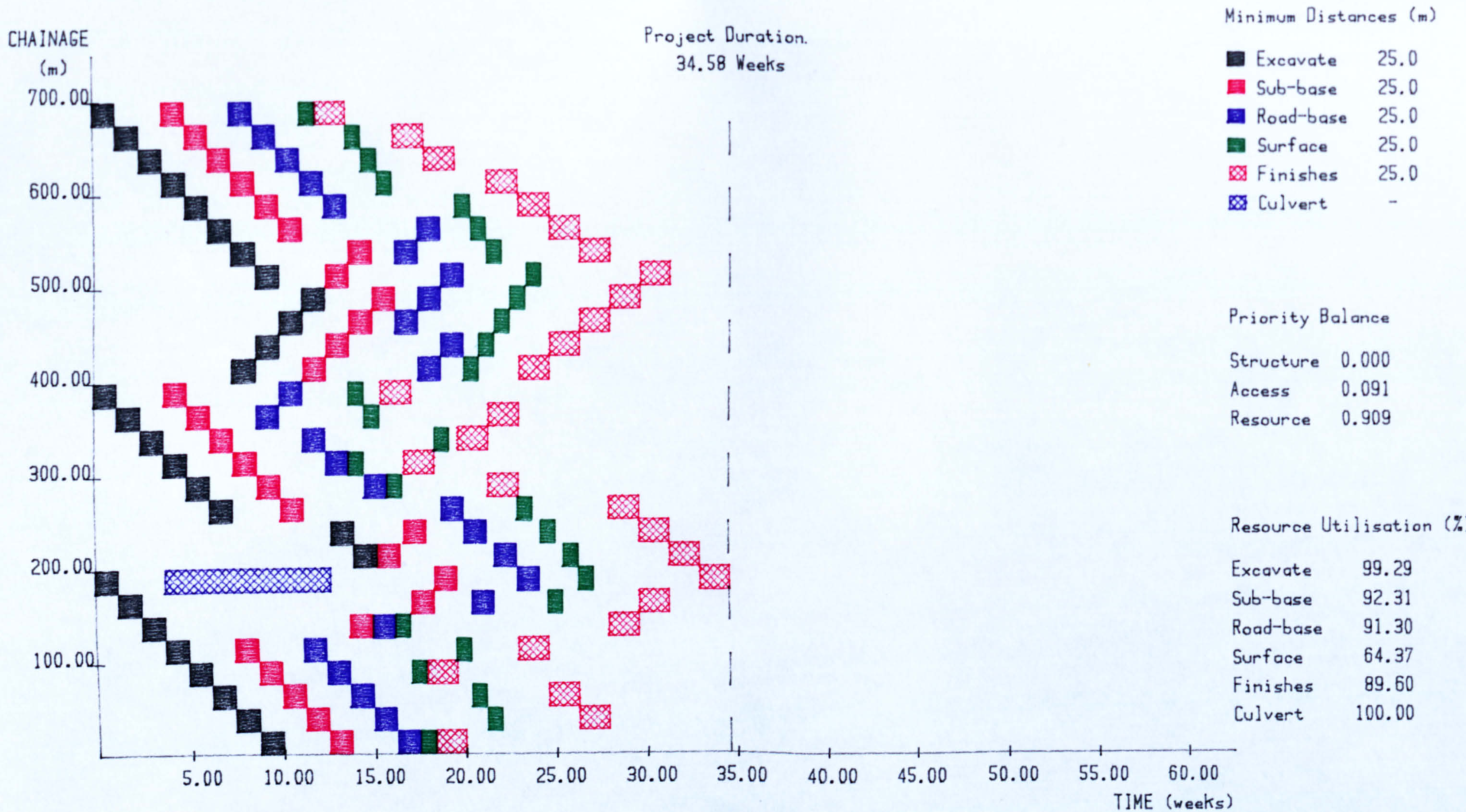


FIGURE NUMBER (B78)　　ROAD AND CULVERT TEST RUN NUMBER 78

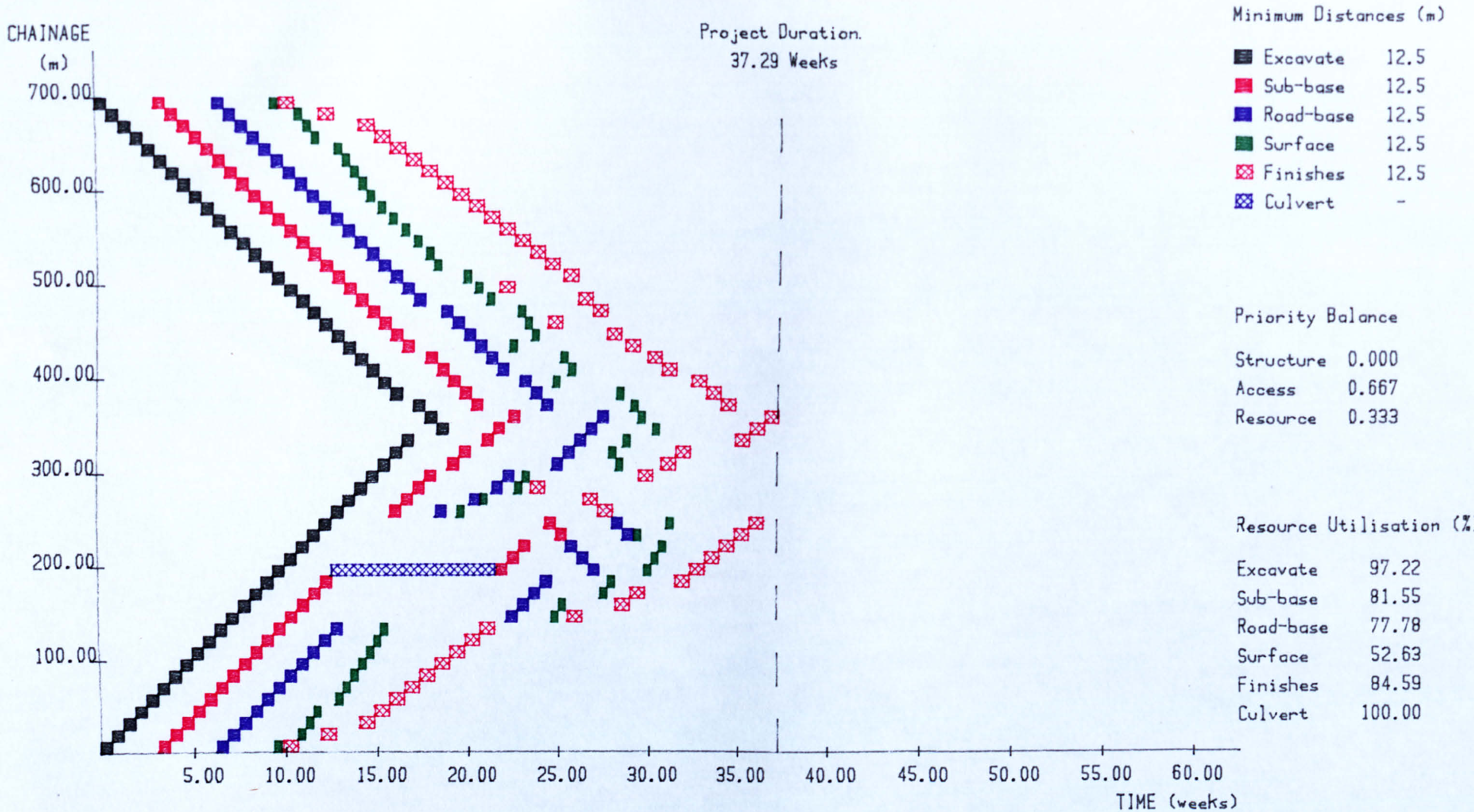


FIGURE NUMBER (B100) ROAD AND CULVERT TEST RUN NUMBER 100