ON THE ANALYSES OF ACTIVITY DURATIONS ON THREE HOUSE BUILDING SITES

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CHAPTER 1

INTRODUCTION

The simplest of the programming techniques, bar charts, was introduced by Gantt at the start of this century. During the late fifties and early sixties the programming issue was boosted by the advent of network techniques. A good review of the basic techniques, their development and the state of the art can be found in the papers by Davis (1966, 1973), the classical books on the subject like "Project Management with CPM and Pert" by Moder and Phillips, and "Critical Path Methods in Construction Practice" by Antill and Woodhead, and current issues of the American Society of Civil Engineers Journal of the Construction Division. Definitions of terms used in network programming can be found in the British Standard 4335-1972.

This research work makes no distinction between Critical Path Methods, Pert and Line of Balance programming techniques, because they draw on the same concepts. While reference is made primarily to network programming, other programming techniques like bar charts and "s" curves can benefit from the discussion in this work.

The seventies saw a decrease in the number of publications in the area and increased criticism of the real usefulness of network techniques. Despite the fact that potential benefits in terms of total time or costs saved were claimed to be in the range of 10 to 20% (Antill and Woodhead, Lumsden, Patterson, Rickard) against total extra project cost of 0.2 to 2%, the application of network techniques has not yet matched the expectations raised during the early years of their introduction (Davis-1974, Johnston, Ling, Mehra, Moder and Phillips, Nunally, Popescu and Borcherding, Vazsonyi). The Davis Report on the use of Critical Path Methods in the top 400 U.S. construction companies showed that only 7% of them have employed the technique in all their projects, while 80% have used them only occasionally.

It is agreed by several authors that the major benefits of the network programming techniques are concentrated in the initial phases of their use, when the logic of how the project should be undertaken is established. Indeed, Battersby stressed that the greatest advantage of networks over bar charts is the possibility of separating planning from scheduling; first the work is thought of (planning), then dates are given to the ' events (scheduling). These 2 activities should be performed simultaneously to produce bar charts. Other possible benefits of network techniques, such as its employment as a project control tool, are not being used by the contracting companies (King-1971, Moder and Phillips).

Possible causes of this lack of success in the application of network programming techniques can be found both at the conceptual and practical level. At the conceptual level, network schedules do not take into account the complexities of real life problems (F.L. Bennet-1973). Abernathy and Demski had proposed what is probably the nearest model to the real life programming and control of projects. The model involves an integration of the initial planning of activities and their subsequent control and updating: for every planned action it is necessary to take into account the possible outcomes, the measurement of such outcomes and the timing of management intervention to correct possible deviations from the planned action. In their own words this model represents a "colossal dynamic programming exercise".

The complexities of this integrated approach led the majority of research work in the area to simplify the programming problem, dividing it into two distinct phases, initial planning, and subsequent control. Authors like Thompson, and Fine and Whattingham emphasized the relationship between the framework established by the initial planning and the flexibility still remaining for the contractor, in terms of using his particular methods of work and management reactions to deviations from the schedule.

Implicit in the hypothesis that network programming should consider simultaneously the initial planning and control

is the assumption that deviations from the schedule could occur. It is an undisputed fact that variability is the norm and not the exception in the construction industry, despite the fact that some authors considered that deterministic models are more suitable than stochastic ones for the building environment (Antill and Woodhead, R. Harris, Moder and Phillips). Even if productivity and the duration of activities were to be considered deterministic, the effect of variation orders would be sufficient to justify the need for the joint consideration of initial planning and possible future deviations. N. Barnes and Thompson (1971) reported that in some civil engineering contracts only 27% of the items in the Bill of Quantities remained unchanged throughout the building process. Bromilow (1970) found that variations ranged from 6 to 20% of total project cost in 225 projects.

The conceptual shortcomings discussed in the preceding paragraphs can be thought of as the lack of simultaneous integration of the various phases of planning and construction, that is, an horizontal lack of integration. Other possible conceptual shortcomings can be grouped under the lack of vertical integration heading. The various tasks of the preparation of a program of work are better assigned to different managerial levels within a contractor's organization; decisions on project duration are likely to be taken at a strategic level, the choice of method of construction would be placed at a strategic/tactical level, while the duration of activities and the allocation of labour resources to the building tasks should be worked out at the operational level (Cowell, Dabbas and Halpin). J. Bennet, Birrel, and Harris and Evans provided other examples of strategic and tactical decisions affecting network programming.

Theoretically, all the various levels of decision can be integrated and evaluated simultaneously. The obvious example is total project duration, a strategic decision that can be obtained with a single pass network calculation, an operational exercise. However, Borcherding (1977) suggested that the separation of decisions at the policy, strategic, tactical and operational levels simplifies the otherwise tremendously complex

programming problem. R. Harris pointed out that while it is theoretically possible to establish the project duration through network calculations, final handover dates are generally set by different means, usually direct negotiation between the contractor and promoter.

Moreover, studies by the Environmental Research Unit, (1974) showed that project durations are a function of the demand for services in the construction industry. Bromilow (1969) suggested that project durations should be established according to standards of project cost vs. project duration relationship naturally found in the building industry: whatever the wishes of promoters and the optimistic promises of contractors, projects tend to take as much time as they normally take in a particular construction environment.

Pilcher (1977), and Dabbas and Halpin argued that the logical relationship between activities, a tactical decision, should be arranged through network techniques, while the study of the efficient use of resources on site should be made by cyclical simulation models (operational models). Barroso-Aguillar (1973) proposed to establish the general framework for project construction through network analysis, but to solve day to day allocation problems through the use of linear programming models. Barroso-Aguillar et al. (1972:1:2) tried to integrate network programming and the linear programming models with little success: the two problems were still tackled separately, with simulation bridging the gap between them.

The lack of vertical integration in the planning process goes back to the origins of network techniques. The original paper on Pert by Malcolm, Roseboom, Clark and Fazar proposed a technique to estimate the probability of overruns on intermediate project milestones previously set by different techniques. No attempt was made to derive the dates for the intermediate milestones using systematically the newly invented Pert method. More recent publications in the area of network programming are devoted to the integration of simultaneous scheduling of activities and intermediate milestones (D. Morris-1982, Crandall and Woollery).

The definition of intermediate milestones is of particular importance in the construction industry, because it relies on a great number of individual participants like subcontractors, component and material suppliers, public authorities, consultants, etc. (Cowell). The majority of research effort on programming techniques was devoted to the examination of project total duration. With total project, durations measured in years, the final completion dates are of little meaning as motivation factors. The intermediate milestones are more important than the final dates for a great number of participants in the project, that as a rule, become only temporarily involved in the process.

Halpin and Woodhead (1978) suggested that milestones set the framework within which the contractor has to formulate its construction plan. Peer and Selinger stated that clients and project managers are eager to set the milestone events as soon as possible, in order to start coordinating the independent organizations that will be involved. R. Harris argued that many owners agree that the establishment of optimal project duration and milestones dates is of little consequence, but once they are established, it is essential that the dates are met. Successful achievement of all milestones dates is the key to successful project management (D. Morris-1982).

Birrel put forward a different type of network programming conceptual shortcoming: the main contractor is usually interested in setting the program of works for just one project, while the subcontractors that will take part on it are preoccupied with the work on 6-12 simultaneous sites. In an industry more and more dominated by the presence of subcontractors, this should be a cause of enormous conflicts of interest.

On the practical side, several difficulties could have hindered the integral application of network techniques to construction sites. At a broader level, the following can be listed: difficulties with the implementation and acceptance of the technique at all echelons of the construction company; lack of communication of the schedules in a meaningful way to all participants in the construction process; incapacity to cope with the demanding requirements associated with updating

exercises. At a technical level, several theoretical concepts used by network techniques are yet to be compared with practical evidence stemming from construction sites. Examples of possible difficulties connected with technical concepts are:

- incapacity for properly defining the activities;
- subjective approach to the setting of duration of activities and the lack of supporting evidence for the objective approaches;
- overlapping precedence relationship between activities;
- variability in the amount of resources required by the activities;
- varying rate of deployment of resources to the individual activities;
- lack of adherence to a pre-determined sequence of work from construction unit to construction unit;
- lack of quantitative factors to allow the modelling of productivity;
- inaccuracy and bias in the estimation of resources required by the activities and their durations;
- feasibility of providing a multitude of cost vs. durations pairs of values in order to draw time/cost trade-off curves;
- daily variation on the level of total amount of resources available on site;
- subjectiveness in setting multiple objectives to be attained by the schedules of work;
- disparity between the theoretical capabilities of network techniques and the timely availability of feedback information from the sites.

Any of the conceptual or practical difficulties suggested above would warrant an investigation as one of the possible causes of the apparent failure of network techniques. The literature is not conclusive on the relative importance of different causes. Moder and Phillips expressed the view that if useful results were not obtained from network techniques it was due to inadequately prepared networks, mainly in terms of their logic. R. Harris maintained that more failures of network

programming owed their origin to the lack of realistic and valid feedback information than to any other cause. King (1971) stated that the single greatest behavioural obstacle to the effective use of network techniques is the use of arbitrary or subjective time estimates. Similarly, Nunally said that one of the major limitations for the use of Pert or network simulation techniques in the construction industry is the need to provide three or more time estimates for every activity. In his view, it is very difficult to provide one accurate time estimate, let alone three or more.

On the other hand, Bishop (1968) and Bromilow (1969) claimed that the simple existence of a schedule, independently of its characteristics, was sufficient to improve substantially the site organization and the attainment of the objective criteria previously set for some building projects. Bromilow showed that in Australia project durations were on average 49% greater than stated in the contractual documents: however, projects using programming techniques had durations only 1% greater than initially agreed. This view was contradicted by Stewart and Torrance and by the NEDO report on industrial plant construction (1976); they found no relationship between the existence of programs of work (or their sophistication) and the progress of work on site.

Lacking an indication of the most promising areas to investigate in terms of the adequacy of the modelling concepts used in network programming and their possible influence in the failure of networks, it was decided to concentrate on the time aspect of schedules and, more precisely, on the duration of activities.

The original Pert and critical path method techniques were essentially concerned with time. The authors of the first paper on Pert (Malcolm et al.) recognized the existence of three interrelated aspects in every project: time, cost and technical performance. As time was the essence of the Polaris Project (the project with which Malcolm et al. were concerned), the programming technique was devised to deal initially only with this aspect. The first paper on critical

path method (Kelley and Walker-1959) included the concept of cost as well, but cost was expressed as a function of time, through the use of time/cost trade-off curves.

Moder and Phillips said that up to the late sixties the majority of developments in the critical path area were geared to analyse the time parameter, with the examination of project costs playing a minor role. Antill and Woodhead considered that time was the primary concern of early researchers in network techniques: a natural extension was the inclusion of secondary network analyses, mainly in the financial area. R. Harris expanded the concept by saying that time, manpower, equipment, materials and money could be the object of separate schedules, but that the time schedule should be taken as the master one, to which the other four schedules should conform. King (1971) pointed out that time is the critical dimension of project planning and control. In addition, the duration of activities is the first information needed to examine other aspects of the production process, like overlapping precedence, the rate of allocation of resources, and the so called time/cost trade-off curves.

The above discussion has set the framework for this research work and has conduced to the establishment of its broad objectives. The author intends to review existing methods of providing estimates for the duration of activities, examine the actual duration of activities on some building sites, and propose a model for the prediction of durations based on feedback data.

It is implicit in these broad objectives that research work in this area can lead to improved applicability of network programming to construction sites. Either the reassurance that existing methods of providing durations are able to model within reasonable limits the actual progress of work on site, or the introduction of new more accurate methods, would increase confidence in the use of network techniques by practioners, thus making it possible to achieve the cost/benefit ratios mentioned earlier on. R. Harris stressed that a more realistic modelling of the project is important in order to prevent the

whole planning exercise from failing; if due dates are not correct, the schedule quickly becomes outdated and unmanageable. The better the input, the better will be the resulting schedule.

More accurate schedules would obviate the need for frequent updates and its associated problems. Kappaz showed that it is not easy to perceive the various small deviations from the schedule that are continually ocurring, but if left unattended amount to a critical situation after a period of time. Streeter mentioned that the cost of providing feedback data and stopping on-going activities, if decisions are taken to divert resources from them, prevent the use of frequent updates. Elvers examined the best timing policy of intervention in a project in order to update the schedule. He reached the conclusion that different projects have different optimal policies of intervention. Finally, Ferdows found that more frequent updates improved project performance in general, but resource idleness increased with more frequent interventions. Due to the beneficial effects of updating, he proposed the definition of less comprehensive initial schedules of work, with provisions for its updating at further points in time.

On the other hand, if it is concluded at the end of this work that variability in durations, inaccuracy in their estimation, and disruption of work are so significant in the building industry as to prevent the meaningful use of programming techniques, the contribution of this research work would be to highlight the importance of feedback from building sites, and the need for managerial and design action to minimize the influence of those aspects.

Pilcher (1977) questioned the need for planning in a very stochastic environment. He wondered if the variability in productivity in the construction industry is not excessively large to be taken into account by present forecasting methods. Nuttall (1965) investigated the construction of some repetitive units using a simulation approach. He arrived at the conclusion that, for the projects under investigation, progress obtained

without a previously established program but with systematic day to day decisions on how to allocate resources was better than the progress that could have been attained by following strictly an initial program of work. Moreover, he produced an interesting example of the horizontal integration of planning and the subsequent updating of projects: the systematic decision rules used on a day to day basis to allocate resources were also employed to produce an initial program. This program was virtually the same as the initial program obtained by conventional means. Thus the scheduling techniques used at the early programming stage could be theoretically used again during the construction stage, as part of a set of tools available to site management to put the project back on its course.

One of the reasons preventing the consideration of the early programming of work and daily site management as similar problems is the difference in the quality of information at the pre-construction and construction phases. It can be said that at the pre-construction stage the uncertainty about the building process is at its maximum, but the programmer has a great deal of flexibility in terms of scheduling options. During the construction phase the certainty about the building process could be expected to increase, but the scheduling flexibility decreases. The early program of work is done when the information is in its worst form: more often than not, design is not yet complete. Abernathy, after finding that the accuracy of time estimates can improve during the construction phase of a project, recommended an adaptive strategy to scheduling and updating:

> "Action taken on early information may degrade overall project performance rather than improve it. By adaptative strategy we mean the particular pattern of rescheduling action that is pursued over the life-cycle of a project. The objective of the adaptative strategy is to minimize the sum of (1) the cost of rescheduling, (2) the cost of inappropriate scheduling action resulting from the use of poor estimates, and (3) the costs of foregone opportunities to make inexpensive corrections at an early period. It is appropriate to think in terms of strategies rather than optimal scheduling, since the derivation of optimal schedules is frustrated by the presence of an unknown component of bias (optimistic bias in estimating durations)".

The discussion presented in the preceding paragraphs makes the investigation of models to predict duration and other building process characteristics more challenging: it is necessary not only to propose better models, but also that they should be much better in avoiding the use of poor quality information in establishing the framework for the project (definition of milestones and commitments for the various participants).

The requirement for constraining the building process through initial schedules based only on accurate and unbiased data could be made less stringent by different forms of program presentation, or by strategic decisions. Johnston maintained that one of the reasons why bar charts are more attractive than network techniques is the fact that they do not impose locational commitments to contractors: bar charts show the amount of progress that should be made, but do not specify where it should occur. Cooke had similar views, arguing that programming and control should be independent of progress on physical units of construction. On the strategic side, two decisions can increase the applicability of programming in the presence of uncertainty: time buffers can be allowed for between succeeding activities (Danoon, Pilcher and Oxley); and the high proportion of external works on building sites can be used to accommodate delays and variations in productivity in the construction of the main units (BRS digest 91, 1956).

The accuracy in predicting durations can improve not only as the project progresses but also through deliberate efforts by management to acquire information (Bjornsson). In either case it would be interesting to know the limits of accuracy that can be achieved.

The previous broad objectives and background discussion motivated the design of the investigation work described in the next chapters. The following limitations should be noted. This research work deals with house building sites of a repetitive nature. Some concepts, however, can be extended to building in general or even to civil engineering works.

The word resources always refers to labour resources, unless otherwise indicated: it is generally accepted that labour is the most important resource in building construction (Thompson). Duration refers to the duration of activities, operations, and stages of work. Activities, operations and stages are treated as synonymous. It is worth mentioning that activities were called operations for one of the sites investigated, while for the other 2 sites they were called stages of work.

The research work draws on activity sampling data obtained at the Building Research Establishment. Conclusions and remarks presented in this report express only the author's view. The negative aspects of the building process found on the sites should be taken as general comments on the construction industry and building process; they should not be viewed as sources of criticism of the particular designers, contractors, labour force or managers of the sites analysed.

The data bank comprises only three house building sites; generalization of results should be made with caution.

The major emphasis is on the analyses of the duration of activities, but, inevitably, other related topics like the rate of allocation of resources and the precedence between operations are brought into the discussion.

Conclusions regarding the duration of activities and the allocation of resources are derived from data obtained through activity sampling. Activity sampling is a statistical technique whose accuracy is only partially predetermined.

The working objectives of this research are to:

a) review the literature on the production characteristics of house building sites (duration of activities, resource consumption, precedence and overlapping of work, rate of progress, time taken to build a house, etc.);

b) review methods of predicting the duration of activities, in particular, methods based on labour resource vs. duration relationships;

c) review methods of obtaining feedback information from building sites with special emphasis on activity sampling methods;

d) produce a comprehensive report on the author's experience in using the Building Research Establishment Site Activity Analysis Package;

e) improve the computer output of the Site Activity Analysis Package;

f) analyse qualitatively the progress of work on three house building sites with 71, 108 and 278 dwellings respectively;

g) develop a methodology to measure durations on construction sites through the use of activity sampling;

h) examine the quantitative aspects of the duration of activities on the 3 sites, with special attention to their relationship to the consumption of labour resources;

i) produce a model for the estimation of durations of activities on house building sites of repetitive nature;

j) critically assess the implications of the accuracy of the activity sampling method of obtaining feedback information, and of the duration estimating models for the programming of house building work.

The following chapters deal with the research effort to satisfy the above objectives. Chapter Two contains the review of literature in connection with objectives "a" and "b" above. It begins by discussing the first major difficulty in the application of programming techniques and evaluation of durations, namely the definition of what should be considered an activity on construction sites. It then examines the concepts behind the respective arguments for a deterministic or stochastic approach to programming as the more suitable to the construction environment. Methods of predicting duration are reviewed, with special attention to the problems of estimating as a science and as an art. A unique section on the actual progress of work on building sites is presented, condensing the scattered results of research produced by several authors. This section covers the total duration of projects, total duration of activities, rate of allocation of resources, discontinuity of work, spreading of work to various parallel construction units, rate of progress, variability of labour output, fluctuation in the availability of labour resources on a day to day basis, and non-productive time.

Chapter Three deals with objectives "c" and "d". Methods of obtaining production information on building sites are briefly reviewed; activity sampling is treated in greater depth, especially the Building Research Establishment activity sampling method. The three sites that provided data for this research work are described, and drawings and lay-outs are produced. The author relates how the Building Research Establishment analyst planned the recording of observations for the three sites and how the data was retrieved for the study of durations and progress of work. Difficulties in using the computer printouts produced by the Building Research Establishment Site Activity Analysis Package are described. The suitability of the data with regard the broad objectives of the research work is discussed.

Chapter Four addresses itself to objectives "e" and "f". The set of computer programs developed to improve the output of the BRE Site Activity Analysis Package is described. Major qualitative evidence on the total time taken to build each unit, on the duration of activities and on the precedence of work are commented upon and illustrated.

Chapter Five reports the work done in connection with objectives "g", "h" and "i". It concentrates on the analyses of durations of activities. However, durations cannot be treated in isolation; it is shown that durations are highly related to the spreading of work to various construction units, to the overlapping of work between different and identical activities, to the rate of allocation of labour resources, and to their total consumption. This chapter explores in greater depth the relationship of durations to the rate of allocation of resources and to the total consumption of resources. These two aspects of the production process are used to develop a methodology to measure and estimate the duration of activities on house building sites.

Finally, Chapter Six produces a summary of findings, deals with objective "j", and puts forward suggestions for further work.

CHAPTER TWO

REVIEW OF LITERATURE

This chapter reviews the literature on a number of aspects involved in the observation, measurement and estimation of durations. The first step is to give an overview of how activities were defined by different authors.

2.1 The Definition of Activities

The British Standard BSI 4335:1972 defines activity as "an operation or process consuming time and possibly other resources". This very broad definition has as its main shortcoming the recurrent use of the synonym operation. Moder and Phillips in their classical work also gave a broad definition: "an activity is any portion of a project which consumes time and resources". Thompson, and Antill and Woodhead insisted on this concept but added that the type of work to be done, the type of resource to be employed (preferably only one leading resource per activity), the location of the work, the costing system being used, and the managerial level of the prospective users of the schedule information should be taken into account to define the activities of a project. Thompson remarked that within these boundaries each activity should be the biggest package of work that could be defined.

Forbes (1980:2), and Barrie and Paulson took a more pragmatic view, emphasizing that the definition of an activity should take into account the possibility of providing feedback information on its performance. Antill and Woodhead expressed the view that any level of breakdown of the total work of a project is feasible.

Eardley and Murphree did some research on how to provide different network schedules for the different managerial levels of an organization: at a higher level, several activities are

combined into single activities. They recognized the need for a systematic approach to the redefinition of activities in broader groups, that is, the possibility of going from one level of definition to the other through a scientific procedure, as opposed to the subjective regrouping that was being done by practitioners. Their procedure starts with the definition of activities and schedules at the lowest possible level of breakdown. An activity at this level is defined as part of the work described in such detail that no further breakdown is required, and such that, once started should be completed without interruptions. At this level Forbes (1980:2) stated that an activity is the smallest unit of construction in the sense of being measurable.

Battersby observed that one criteria for defining activities in a network schedule is the existence of previous feedback information. However, he warned about the unrealistic effects that overuse of this practice could have on the logic of the network. The existence of some sort of production information at the time of preparing traditional Bills of Quantities led to the practice of defining activities according to design elements or trade demarcations. Roderick maintained that successful use of network techniques is only possible if activities describe building processes rather than design elements, or if all connections between design-element defined activities are specified. He added that, not surprisingly, this latter type of activity will show a disrupted flow of work.

Design-element activities could also be defined at various levels of aggregation. N. Barnes and Thompson (1971) suggested that Bills of Quantities measured in accordance with the new 5th Civil Engineering Standard Method of Measurement should keep the number of items to a minimum. Items of low value or plant/labour dominated, with rate differentials of up to 40% should be grouped under the same heading: for high value or materials dominated items, a minimum rate differential of 10% would be acceptable in order to create a new item in the bill.

Thus the grouping of basic activities into larger ones is motivated by two main types of reasons: first practical reasons, like the desirability of controlling the building process through the outcome of significant elements (Beaumont), or the impossibility of obtaining feedback information at lower levels of detail (Forbes-1981:2); second, the need to provide higher levels of management with concise information.

Unfortunately this grouping of activities has some theoretical associated problems that stem directly from the network precedence relationship (network connectedness). MacCrimmon and Ryavec, and Battersby said that the combination of serial and parallel activities in a network, in an attempt to reduce its size, is not very effective due to the numerous cross connections that exist. R. Harris stated that higher level networks should still be able to reflect the multiple interrelationships that exist between groups of activities.

Parikh and Jewell proposed a technique to combine activities into chains of strong precedence relationship, and then consider the weaker relationships between groups of activities. The technique is subjective as far as identifying strong and weak precedence relationship is concerned, and is not suitable to very interconnected networks.

Healy showed that the Pert statistics are dependent on how stages of work are further subdivided into smaller operations, if simplified linear transformations are applied to the pessimistic, modal and optimistic durations of the sub-operations. His procedure is not entirely sound because it assumes that the sub-operations are statistically independent: this is not the case, because if activities are able to be grouped into stages they have some characteristics in common, and thus cannot be truly independent.

It is concluded from the preceding sections that the definition of activities is a subjective matter. Objective procedures to define higher levels of aggregation are sensitive to the presence of varying degrees of interconnection in the construction industry schedules. However, it is still necessary

to provide some form of relationship between activities defined at different levels: for example, it would be interesting to be able to relate the durations of individual decoration operations to the duration of a stage of work comprising the whole work of decoration in a construction unit.

Fine (1974) wrote in a paper dealing with tendering and estimating:

> "Some part of almost every job lies outside the experience of the estimator or other people whom he may consult. In these circumstances a guess must be made and the major guess is nearly always the one which purports to define the sub-tasks out of which the project is to be built".

2.2 Nature of the Duration of Activities and the Programming Approaches

The duration of activities on construction projects were taken as deterministic or stochastic variables by different authors. The stochastic approach subdivides in two groups: in the first, activities were supposed to follow certain statistical distributions; in the second, the duration of activities was expressed by frequency distributions with no need for underlying assumptions on their characteristics. Three different formulations of the programming problem originated from these different concepts regarding the nature of durations: the deterministic view led to critical path method techniques; the stochastic assumption led to Pert and to simulation models.

The initial application of the deterministic approach in the construction industry is linked to the origins of the Critical Path Method, as opposed to the origins of Pert. The Critical Path Method was developed to program maintenance and construction work at Du Pont, while Pert was created for research and development projects (Moder and Phillips). Clearly there is a difference in the amount of uncertainty in the duration of activities in these two environments. What is

lacking is quantification of the differential of uncertainty between these two environments to justify the application of different approaches.

Antill and Woodhead, Moder and Phillips, Pilcher (1976), and R. Harris stated that it is possible to predict adequately time and cost for construction activities and that their expected variances are small. They recognized that durations could be subject to some variability, but suggested reasons why this would not make it necessary to use stochastic models. Moder and Phillips argued that for every variation in productivity, management could counteract with more or less resources, thus bringing the duration of the activity back to the scheduled value. Antill and Woodhead added that activities should be considered stochastic only if management is not able to react, stabilizing their durations. R. Harris maintained that updating is an integral part of the critical path methods: deviations from planned durations can theoretically be overcome by updating exercises. Moreover, he considered that only genuine oscillations associated with a fixed method of operation and a fixed deployment of resources should be included in the variability of the duration of activities, if any. On those lines, the variability associated with the productivity of gangs would be considered, but hazardous events like bad weather would not be taken into account.

Fine (1977:2) proposed that one of the major functions of site management is to reduce the variability in the production process. Simulation of the building process allowed him to conclude that reduction in variability of durations is more important than reduction in the cost of operations, as far as minimization of total project cost is concerned. Bishop (1968), Talbot, and Walker (1972) expressed the view that incentive schemes are especially suited to reduce variability in durations and resource consumption on site.

The literature review found Nuttall (1965) the first to consider the duration of activities in the building industry as stochastic variables, six years after the publication of the first paper on critical path methods (Kelley and Walker-1959).

Nunally observed that contractors quickly recognized that the durations of building activities are far from deterministic. While there is a reasonable amount of research work on the variability of resources consumed in similar activities, very little has been published on the variability of durations. R. Harris pointed out that as late as 1978 no study had been made to definitely establish time distributions for any activity, thus extending MacCrimmon and Ryavec's similar conclusions for the period up to 1964.

On these grounds, apart from common sense, it is difficult to show that the deterministic approach is not appropriate. Nevertheless, Jewell, and Britney conducted two separate studies on the application of an "extra effort" in order to bring the durations of activities back to the schedule values. They found that the conceptual formulation of the critical path methods does not apply for this case. In particular, Britney showed that in order to minimize the expected total cost of a project, the scheduled duration of activities should be greater than the average one, if the extra cost of speeding up an activity is greater than the savings associated with its slowing down (a reasonable assumption).

The Pert approach provides a simple and elegant solution to the evaluation of schedules under stochastic conditions. The same calculations employed with the critical path methods in order to find project duration, scheduled dates and the slack of activities are used, with the advantage of providing probability statements on any of these time-related variables. The lack of justification for the use of a beta distribution (Clark, Grubbs, Van Slyke) is an important shortcoming. Nonetheless, it is possible to calculate upper and lower bounds for the errors introduced in using the beta instead of the true unknown distribution (MacCrimmon and Ryavec). Some authors doubted whether it would ever be possible to obtain historical data in sufficient quantity to check the beta distribution and its parameters, or to formulate any other actual activity time distribution, due to the non-repetitive character of activities on construction sites (R. Harris, MacCrimmon and Ryavec, Nunally).

It appears that the more important shortcomings of the Pert approach are the identification of just one of the possible critical paths, the assumption of statistical independence between the various activities, and the non-resolution of the "milestone effect" integration problem; if milestones are always to be achieved, the Pert calculations are valid only in-between milestones; if the milestones are just allowed to happen, with no extra effort to guarantee their achievement, the Pert calculations are valid for the whole project; there is no simple method of evaluating intermediate situations, where some extra effort is applied to increase the chances of achieving the milestone dates, but the outcomes of these actions are also stochastic in nature (Moder and Phillips). It should be added that the inclusion of secondary project characteristics in programs of work (financial control, materials delivery, etc.) is made more difficult under the stochastic approach. Battersby reported that by 1970 no serious use was being made of Pert; the author did not find evidence to show that this situation has changed during the last decade.

The simulation approach is a hard way of evaluating scheduling information based on a large number of repetitions of the construction process. Van Slyke in his classical study used 10,000 repetitions, while Moder and Phillips suggested that 1,000 repetitions could have been used instead, relaxing the accuracy of the final results. Anything can be studied under schedule simulation, given sufficient computer programming effort and computer processing time; for example, D. Morris (1982) described a simulation solution to the "milestone effect" integration problem mentioned earlier on.

Simulation exercises can be performed with the duration of activities as random samples draw from theoretical distributions or from historical data. Apart from the advantage of obtaining almost any time-related information in exchange for computing effort, simulation avoids the biases (optimistic expected project duration and pessimistic expected project duration variance) present in Pert, and allows the calculation of a criticality index for each activity. The criticality

index is a measure of the probability that an activity will lie on a critical path. It is a good indication of the attention which should be devoted to the progress of the activity, if the project is to be completed on time.

The major problems of the simulation approach are the costs involved in getting the actual time distributions for the activities and the computing cost itself. The assumption of theoretical time distributions does not preclude the need to check their suitability through the observation of actual performance on building sites. Ever increasing computer availability dictates that computing costs should not prove to be a deterrent to the use of simulation. The costs of getting actual time distributions are yet to be investigated by research workers.

2.3 The Estimation of the Duration of Activities

2.3.1 Subjective Methods

R. Harris, Dabbas and Halpin, and Moder and Phillips affirmed that the estimates of duration for CPM and Pert are based upon judgement rather than upon any scientific procedure. Moder and Phillips added that the lack of a scientific procedure to arrive at estimates of the duration of activities is a reflection of the comparatively low importance given to the time factor as opposed to the cost factor in normal practice; recognition of the importance of the time aspect would result in techniques for working out durations as accurate as the existing techniques for estimating costs. In their introductory paper, Kelley and Walker (1959) proposed the setting of durations by "fiat"; the duration of activities would represent "reasonable" performance under "normal" circumstances.

In particular, the Pert approach is based on subjective time estimates of the optimistic, modal and pessimistic durations. This information is obtained from interviews with engineers, foremen or persons directly involved with the actual

execution of work on site (Doyle, Malcolm et al., Van Slyke). Given subjective estimates for the optimistic, modal and pessimistic times, the expected average duration and its variance can be calculated as follows:

$$te = \frac{a + 4 \times m + b}{6} \qquad (1)$$

$$Var(te) = \frac{(b - a)^2}{36} \qquad (2)$$

where

a = optimistic duration;
m = modal duration;
b = pessimistic duration;
te = expected duration;
Var(te) = variance of duration.

The choice of a beta distribution and of the respective parameters to arrive at equations 1 and 2 is rather arbitrary (Grubbs), but Clark defended their use on practical grounds; no information is available beforehand on appropriate time distributions, but the scheduler is faced with the problem of providing estimates periodically, formally, and at a low cost for thousands of activities probably never done before. Van Slyke added that in these circumstances the use of arbitrary values is unavoidable. The author was not able to find in the literature any philosophical discussion of the benefits of a technique heavily based on arbitrary assumptions. Van Slyke concluded that the Pert estimates should not be taken seriously.

There is an argument on the meaning of "a" and "b" in the above equations. Originally "a" and "b" were proposed as the limits of the beta distribution, that is, the probability of occurrence of a duration smaller than "a" or greater than "b" would be null. Conceptually this is a weak point of the Pert approach, because technical personnel are asked to provide estimates of parameters for which they could have no possible practical experience. Pilcher (1976), and Antill and Woodhead suggested associating "a" and "b" with the 1 and 99 percentiles,

that is, "a" and "b" would have a probability of occurring of one in one hundred. There is no mathematical basis for this proposal. Moder and Phillips investigated a great number of theoretical time distributions and concluded that if "a" and "b" were set at the 5 and 95 percentiles (a chance of occurrence of one in 20) the variances of different distributions would be very similar. This procedure not only sets more reasonable limits to the pessimistic and optimistic values but also makes the calculation of variance almost distribution-free. The variance would be calculated by the following equation:

$$\text{Var}(te) = \frac{(b - a)^2}{3.2^2} \qquad (3)$$

where:

a = optimistic duration, observed once every 20 repetitions of the activity;

b = pessimistic duration, observed once every 20 repetitions of the activity;

3.2: for various common distributions the difference (b - a) varies from 3.1 to 3.3, with an average of 3.2 standard deviations.

2.3.2 Objective Methods

Procedures that involve the recording of data from previous experience and its subsequent use to estimate durations are examined under this heading. The techniques here described should not be taken as necessarily more accurate than subjective ones, nor are they entirely independent of human judgement.

2.3.2.1 Resource-related Methods

These methods are generally applied to the deterministic approach to programming; they can be easily extended to the stochastic case by allowing variance to affect the parameters

involved in the calculation of durations. The differences between the methods reviewed in the next paragraphs are subtle: all of them assume the existence of a relationship between duration and the consumption of resources. As Battersby noted, time and resource consumption are theoretically recorded together by work study techniques; there is no need to formulate a relationship between the 2 variables but only to consult the existing integrated work study historical data. Nevertheless, there are situations where only the expected resource consumption is available, for example when cost estimates are based on labour rates provided by estimating books (see Geddes, and Geoffrey, Smith and Partners). On the other hand, theoretical developments in the area of operational estimating (Skoyles-1964, 1967, 1968) indicated that time is the commanding factor in terms of costs: the consumption of labour would be just a formal calculation, involving the multiplication of number of men assigned to the job by the number of days the activity took to be completed.

2.3.2.1.1 The Labour Content Method

Battersby, Antill and Woodhead, Fine and Whattingham, Harris and McCaffer, and Pilcher and Oxley obtained the expected duration of an activity by dividing its expected labour content by the number of men assigned to the job multiplied by the normal number of working hours in a week (or in a day). Fine and Whattingham warned that durations thus obtained should be rounded down to the nearest number of days, otherwise the activity would extend to the whole of the next period (there is a tendency for the job to "fill" the day).

The uncertainty regarding the production characteristics of the activity will be entirely concentrated in the estimation of its labour requirements. Nunally proposed that the standard deviation of the duration of an activity could be directly related to the standard deviation of its labour requirement. According to the review of literature undertaken by the author, there is no published report dealing with the

actual relationship between labour consumption and the duration of activities. The direct linear relationship between these 2 variables is thus not supported. Fine and Whattingham stated that the direct linear relationship they have used is just an approximation of the true non-linear relationship yet to be derived from practical experience.

The labour content method assumes that the gangs will work efficiently throughout the working period in which they are engaged in the activity. Any non-productive time is included in the labour content of activities.

2.3.2.1.2 The Output of Resources Method

Johnston, Thompson, N. Barnes and Gillespie, and Halpin and Woodhead (1972) proposed the calculation of the duration of activities by dividing the physical quantities of work to be done by the output of resources allocated to them. The output of resources can also be taken as the rate of progress for the activity. The output of resources can be varied by increasing the number of men allocated to the job. The output of resources is also subject to the variable efficiency of operatives over time. Halpin and Woodhead (1972) said that the rate of allocation of resources is usually variable on building sites: it varies, for example, with the amount of remaining work in both on-going and succeeding activities. Johnston stated that the initially scheduled output of resources should be the one associated with minimum direct costs; this rate can be varied, though, to suit optimization procedures in repetitive construction.

Nunally separated the concepts of output of resources for the whole activity and output of resources for the sub-tasks that constitute the activity. Sub-tasks are generally repeated on different sites, while the activity is often of a one-off type: for example, the building of a particular wall is probably unique to a given site, while the sub-tasks of laying bricks, spreading mortar, etc. are happening all the time on any construction site. Therefore, the output rates for sub-tasks are more easily obtained than for activities, and hence more reliable.

The output of resources approach has the advantage of incorporating non-productive time in a more direct way, that is, labour resources are not thought to be working efficiently throughout the day or week. The main disadvantage is the need to observe and record the productivity of individual gangs, which is more difficult than just to record the total amount of hours spent per activity.

2.3.2.1.3 The Number of Operatives Method

R. Harris, Gates and Scarpa (1978), Kavanagh et al. and Peer and Selinger produced examples of less restrictive procedures for arriving at the duration of activities. Labour content is expressed in terms of man-days or crew-days; duration is then obtained by dividing the labour content by the number of operatives assigned to the job. This method makes no implicit assumptions of the number of hours worked per week nor of productivity constancy in the labour force throughout the duration of the activity. Records should be kept in an "operational" format, that is, the number of days the activity took and the number of men assigned to the job. The failure to implement operational estimating in this country (J. Bennet) shows that this approach is less practical than it seems.

Gates and Scarpa (1977, 1978) provided techniques for optimizing the number of operatives allocated to a job. Basically they did an exercise in trading-off the following factors: gains in operative performance and mobilization costs if a smaller number of crews is assigned to a job for a long period of time; larger overhead costs associated with extended durations. The techniques rely on a number of assumptions including the constancy of productivity for multiple gangs working simultaneously in the same activity. R. Harris argued that in normal circumstances the most efficient crew will be assigned first; the following crews are less and less efficient, making the overall productivity of multiple crews smaller. On the other hand, Selinger maintained that, within boundaries,

the amount of resources consumed does not vary with the number of men assigned to the task. If this is so, the direct cost of performing a task would be constant, thus not showing the classical concave time/cost trade-off relationship.

The 3 methods assume that resources would be deployed on a constant basis throughout the duration of the activity. However, no difficulty arises under the assumption of varying patterns of allocation. Examples of "s" patterns of resource allocation are given in the section dealing with total duration of activities and intensity of work. Battersby put forward a mathematical relationship, derived from practical experience in the manufacturing industry, to calculate the number of men to allocate, depending on the urgency of the job.

The author argues that the above 3 methods, the labour content, the output of resources and the number of operatives methods are in essence the same thing. Construction firms will not have separate systems of estimating durations for each of these methods of obtaining and recording feedback information: the 3 methods would be convertible one into the other by the use of the number of hours effectively worked per operative per time period. The definition of this parameter is critical.

The author stated previously that he has not been able to find research reports on the relationship between the consumption of labour resources and the duration of activities to warrant the use of the above methods. Indeed, durations have not been measured systematically by construction feedback systems; they have generally been derived from resource-like information. Attempts to measure directly the duration of activities in construction projects are dealt with in the next section.

2.3.2.2 Measured Duration Methods

The methods described in the previous section imply a cause/effect relationship between durations and resources. A totally different concept was introduced by Lumsden with what

he called the "natural rhythm" of performing activities on construction sites. The "natural rhythm" is a vague concept but can be interpreted as the time taken to complete an activity if it is performed by a single, "natural" crew and just allowed to happen under the normal conditions prevailing in the construction industry. The reasoning behind this concept is that durations tend to converge to specific values, given present technology, methods of construction, standards of progress normally accepted, and the expectations of those involved. Increases in the speed of construction would determine a multitude of new requirements different from the ones the participants in the building process are acquainted with. Decreases in the speed of construction would affect wage standards and company turnover.

The "natural rhythm" approach is similar to the number of operatives approach. The difference is that the former considers the crew as the smallest unit of resource that can be applied to an activity. Moreover, activities of different magnitude are not directly comparable: each particular magnitude of activity has its own "natural rhythm". A similar activity twice as large neither takes necessarily twice as much time nor employs a gang twice as large, as would be the case with the number of operatives method. The rate of progress on a repetitive site can be varied only by employing multiples of "natural crews", with each crew working in a separate construction unit. Thus, the rate of progress can only be varied in steps: it is a discrete variable, not a continuous one.

Duff (1980) created the first practical technique to measure natural durations on building sites of a repetitive nature. He assumed that each construction unit is tackled in sequence, with no overlapping. The total time the trade stayed on site, less delayed, suspended and non-productive time, divided by the number of houses and the number of crews gives the natural duration for the activity.

The fact that repetitive construction usually comprises slightly different units is not a deterrent to the

use of his technique. Some form of weighting can be used to derive the duration for individual units. It is worthy of mention that Lumsden proposed this weighting in connection with his Line of Balance programming technique in order to accommodate the durations of work in units of different size.

Measuring natural durations is difficult because it would be necessary to separately record and estimate different magnitudes of similar activities. Duff (1980) introduced the concepts of standard size of activity and standard size of gang in order to overcome this problem. For example, ground-floor concreting operations performed on different numbers of construction units, with different average areas, by different sizes of gangs would be used to obtain the duration of the standard operation, through the use of a regression model. This step brought his technique nearer still to the number of operatives method.

The major shortcomings of his technique are the assumption of independence and no overlapping for the work performed in succeeding blocks, the inability of taking into account the learning phenomenon, and the use of physical measures of work to predict possible durations of activities on new sites. Physical measures like the area of ground-floor slab, or lineage of concrete strip foundations could correlate well with the durations of the respective activities; however, 2 or more physical measures are necessary for the finishing stages, thus requiring multi-collinear regression analyses.

Despite its shortcomings, Duff's technique is most welcome as a first step towards systematically recording the duration of activities independently of labour resource usage.

Duff's method assumes that the individual durations per unit of construction follow a normal distribution. Under this assumption, Moder and Phillips gave a practical formula for transforming the range of observed durations into Pert-like "a" and "b" parameters. At least 4 values should be available in the range of observed durations. Given "a" and "b", the expected duration of the activity and its variance can then be

calculated. The convenient assumption of a normal distribution is unfounded, but, as with Pert, at least it is possible to keep within boundaries errors caused by taking the normal instead of the true unknown distribution.

Duff (1980) argued that if a sufficiently large number of sub-operations are defined within an activity, the time distribution for this activity will be approximately normal, due to the Central Limit Theorem. However, Alder and Roessler, in their statistics text, recommend that at least 30 variates (sub-operations) should be defined within the activity in order to guarantee the accuracy of this approximation.

King (1971) proposed a model for combining the stochastic nature of durations and the inaccuracy in their estimation. It is necessary to build a joint distribution of time estimates vs. actual durations, that is, the probable actual durations associated with each given estimate. He found that a lognormal distribution was sufficiently accurate to represent the joint distribution. He warned that to obtain practical data to check the validity of this joint distribution was still more costly than simply to provide data for activity time distributions. The technique should only be applied to a class of project that could afford this level of refinement.

The simplest form of collecting durations of activities is to build-up frequency distributions. Pilcher and Oxley showed a simulation exercise where the duration of activities obtained from actual construction sites did not follow any stochastic distribution. A discrete frequency distribution was successfully used.

The fitting of a particular stochastic distribution to discrete data organized in frequency distributions is only of academic interest, as far as providing data for simulation exercises is concerned. The computer effort to draw random durations from both types of distributions is not markedly different.

2.3.3 Discussion

The review of methods to estimate durations failed to disclose an entirely satisfactory technique. The subjective approach relies on the vagaries of human nature (King-1971). The objective approaches rely on assumptions about the relationship between resources and durations, or on observation of durations on actual building sites. Very little has been gathered in terms of factual experience in these areas. Several authors expressed pessimistic views on the possibility and economical viability of collecting statistically significant information about durations for the huge number of activities contained in each type of project.

Peer and Selinger argued that the estimation of durations cannot be done in isolation; activities on a site form an integrated production system. This integrated approach is reflected in the idea of balancing the duration of activities on a repetitive site (Building Research Station Digest No. 91-1956). However, Eden maintained that this is seldom possible due to the significant differences in duration of building activities. Lumsden showed that sites with large rates of progress (say 10 units/week) pose increased difficulties for the balancing of crews, thus making small rates of progress preferable.

Due to differences in size and type of units normally found within house building sites, the collection of data and the estimation of durations will be more meaningful in terms of average values.

Regression models have not yet been sufficiently explored to provide the duration of activities.

Finally, the concept of a natural duration is an important contribution. It shows that durations of activities are not necessarily a function of labour content, number of resources allocated, output of these resources, estimates, or management wishes. Other factors could be more influential in determining why activities take the time that they do take on construction sites.

It is appropriate to review in the next section other problems that can be found in the art/science of estimating.

2.4 Difficulties in Estimating Durations

This section covers possible difficulties associated with the estimation of durations of activities. It takes illustrative examples from the estimation of prices and costs. It examines in greater depth the prediction of labour resources; the estimation of labour resources is an integral part of the calculation of durations for the labour-related methods seen in the last section.

Estimating difficulties can arise from three different sources:

- subjective influence of human nature;
- methods of collecting, recording and using production-related information;
- variability of output in the building process.

2.4.1 Subjective Influence of Human Nature

Estimates will depend on the basic optimistic or pessimistic nature of the estimators and their present state of mind (King-1971, Malcolm et al). N. Barnes (1978) stated that:

> "Its part of the human nature to expect a task to be more simple than it actually is. Our vision of a job leaves out the ration of unexpected and unpredictable interruptions. Our mental images are only sketches of the main shapes which omit the effort-consuming detail".

Fine (1974), R. Harris, King (1971), and Moder and Phillips recognized the psychological and sociological nature of estimating: estimating takes into consideration what is socially acceptable, or generates values which do not cause

embarrassment for estimators during the project construction phase. This is particularly true for Pert estimates; as there is a likelihood that actual durations will be concentrated around the mean value, optimistic and pessimistic values are biased towards the centre (R. Harris). Malcolm et al. suggested that estimators could be tempted to reproduce the schedule, that is, given a milestone plan of events, they will produce estimates for the duration of intermediate activities that would make it theoretically feasible to arrive at the scheduled due dates.

N. Barnes (1978) pointed out that estimates are based on biased assumptions of the 3 major components of any project, time, cost, and technical performance; time and cost are underestimated, while the potential technical performance of the project is overestimated. Targets for any of these factors could be achieved only at the expense of the others. Bromilov (1970) reported Australian experience where final costs were remarkably kept within initial budget at the expense of a great number of variation orders that disrupted the building process and produced large time overruns.

Comparisons of estimates of durations and costs (resources) with actual values are seldom published. Roderick reported that estimates of durations were on average only 30% of the actual durations observed on one building site. Abernathy, Kidd and Morgan, and King and Wilson found that on average estimated durations were 70-75% of the actual ones. Cooke maintained that estimates of durations are always optimistic, even if made after project construction had begun. Ashworth et al. arrived at an average 27% overestimation of labour resources consumed by the bricklayers trade on 9 different projects. Panerai and Roderick produced even higher figures (50 and 66% respectively) for the average overestimation of labour resources for different stages of work in 2 projects. The underestimation of durations and overestimation of resources were subject to high variability from estimator to estimator, from stage of work to stage of work within a given project, and from project to project.

The influence of human nature and its bias on the estimating process would be expected to be at its greatest in the absence of feedback information. Nevertheless, King and Wilson, King et al., and Kidd and Morgan found that the bias in estimating durations was maintained as the projects under investigation went into construction and new estimates for the duration of remaining activities were required. Abernathy, and Munoz negated this assertion, stating that the bias decreased as more feedback information became available for the projects they examined. King and Lukas reported an interesting academic experiment, where the bias in estimating oscillated according to the previous estimated/actual duration ratio: an overestimate for the previous activities determined an underestimate for the foregoing ones and vice-versa.

The fact that some estimators were found to predict the total project cost with an accuracy expressed by a coefficient of variation of 6% (N. Barnes-1972:2, Beeston-1975, Fine and Hackemer) illustrates that somehow the influence of human nature can be greatly removed from the estimating process. The role of feedback information, both as a potential method of increasing the accuracy of predictions, and as a source of unreliability in estimates is discussed next.

2.4.2 Methods of Collecting, Recording and Using Production Information

The feedback of information and its relation to the estimating process can be looked at from 3 different angles: the nature of the information available in construction; methods of obtaining the information; and uses of the information for managerial purposes.

2.4.2.1 Nature of the Information Available in Construction

Beeston (1975) stated that ideally at least 10 repetitions of identical projects would be needed to provide feedback data suitable for estimating. In practical terms this

number of repetitions is never available: projects are more often than not unique (Pilcher-1977). Even if design is similar, the conditions prevailing at the time of construction are likely to be different (Duff-1976).

Duff maintained that factors determining variance are often complex and that their individual effect on progress of work are rarely quantified. Furthermore, it is usual to find a conflict of interests between those capable of providing feedback data (operatives, foremen, clerks of works, and site agents) and those needing to use the information for further planning and estimating.

Fondahl (1962) claimed that costs and durations experienced on site are not the most economical ones: due to the constant pressures on site, contractors tend to crash their activities, without much regard to optimization techniques like time/cost trade-off curves.

Fleming came to the conclusion that labour constants published in estimating books have not been systematically updated during the last century. He questioned their reliability in providing indications of the labour requirements of activities, but argued that this lack of updating may not have altered their usefulness in terms of estimating prices for Bill of Quantities items.

2.4.2.2 Methods of Obtaining Production Information

It was found appropriate to review methods available to obtain feedback data in the next chapter dealing with data acquisition for this research work. For the moment, suffice it to say that the available methods are not able to record information at a very fine level of detail. Some form of data aggregation is needed to improve accuracy, coverage, or even workability of feedback methods (Duff-1979, Fine and Hackemer, Forbes-1980:2, F. Harris-1976:2). Duff suggested recording information at the level of trades. Forbes maintained that statistical accuracy sets a limit to the level of detail

that it is possible to measure on site using activity sampling. He said that due to sampling error, even while expending the considerable effort required by the Building Research Establishment experimental work, many small items were not measurable on site.

2.4.2.3 Uses of the Production Information

The first obvious use of feedback information would be its incorporation in presently used Bills of Quantities. This approach stems from the need to avoid duplication of managerial information systems. Notwithstanding this, the present Bill of Quantities has three major drawbacks as a framework to the incorporation of production-related information. The first drawback is the breakdown of work into an enormous amount of items; information cannot be gathered at this level of detail; moreover, the accuracy in estimating in some research experiments did not increase with greater breakdown of work (N. Barnes-1971, Bennet and Barnes). The second shortcoming is the use of finished work or design elements as the unit of measurement, with no consideration for the process of building. Finally, the Bill of Quantities records information obtained from actual sites (price, cost, and resource usage) as a function of physical quantities of work. Forbes demonstrated in several of his papers that the expenditure of resources on site is not only related to physical quantities of work, but also to the organization of the site and the building company. N. Barnes and Thompson introduced the concept of time-related charges, recognizing that some resources are not consumed in relation to the quantity of work done, but to the period of time they are made available on site.

These three shortcomings make it extremely difficult to derive from Bills of Quantities the durations and costs of activities for network programming purposes. Popescu (1977) said that the production of network-related information from conventional bills is a formidable task, usually never accomplished by building contractors. Alternatives to the Bills of

Quantities as a framework for the incorporation of feedback information are not without problems. Laing proposed an "one use one document" approach, that is, feedback information for scheduling purposes would be obtained and processed separately from price-related information used for Bill of Quantities. From time to time both systems of information would be reconciled. The method seems reasonable, but Laing advocated a too detailed level of work breakdown.

The operational approach to Bills of Quantities (Skoyles-1964, 1967, 1969) had two major areas of criticism. First, it is necessary for the estimator to group tasks into activities that the contractor is likely to use on site. N. Barnes and Thompson reported cases where the contractor had to rearrange this activity-bill once more, because the actual operations to be performed on site were different from the operations assumed by the quantity surveyor. J. Bennet pointed out a misconception in operational bills in terms of the responsibilities within the construction industry: the contractor is responsible for dividing the work into activities, not the quantity surveyor. Secondly, Fletcher, at a seminar in Dublin (see Shanley), argued that activity-related information is only one of the types of data needed for a complete analysis of the project: while the contractor is interested in site management, the designer could be interested in performance cost-related information. Neither the conventional Bill of Quantities nor the operational approach would provide this latter information.

2.4.3 Variability of Output in the Construction Process

The estimation of prices, costs, consumptions of resources, and durations is complicated by the variability of output in construction processes. Fine (1975) concluded that even with the best of feedback information, the managers are not able to predict the next month's production with an accuracy better than ± 20%, purely due to the variability of output.

The variability of labour resource consumption and duration of activities should be studied at a number of different levels: variability within the construction industry as a whole, within a building firm, and within a site. Furthermore, variability of activities, stages of work, and trades should be separated from variability at higher levels of aggregation (houses, blocks, or projects).

Bishop (1965), Clapp (1965), Forbes (1969), Fraser and Evans, Howenstine, Shippam, Wahab, and Lemessany and Clapp (1978) reported coefficients of variation of between 20 and 30% for the total labour consumption of individual houses built by different contractors. The same authors gave coefficients of variation of between 30 and 40% for the labour consumption of activities, groups of activities, or trades for different contractors. Hall and Ball produced coefficients of variation of between 40 and 68% for the formwork activity on a series of bridge projects. The increased variability associated with activities, groups of activities, or trades could have been expected from the smaller level of aggregation they imply. However, Bishop (1972) made the point that in some cases there was no difference for the coefficients of variation associated with different levels of work breakdown.

This information is of little use for the individual contractor or estimator. More pertinent information is given by Bishop (1965), Pigott (1974:2), Shanley (1970:2), and Walker (1971). They found coefficients of variation of between 6 and 10% for the total labour consumption on houses built by the same contractor on different sites. No information is available on the coefficients of variation that can be expected for individual activities or groups of activities built by the same contractor on different sites.

Finally the same authors measured coefficients of variation of between 4 and 7% for the total labour consumption of houses built by a contractor on the same site. The variability in the consumption of labour by individual activities can be expressed by a coefficient of variation of between 10 and

20%, caused mainly by the differences in the productivity of crews. Reiners and Broughton maintained that the productivity of individual gangs was fairly constant while working on the same site, irrespective of the operations they were engaged on. However, the productivity of different gangs was markedly different. It is interesting to note that the British Standard Scale of Ratings for Work Study (BSI 3138:1969) covers a range of operative's performance from 0.5 to 1.5, roughly equivalent to a coefficient of variation of 30%. Currie asserted that the great majority of ratings of operative's performance will in fact be in the range 0.75 - 1.10, roughly a coefficient of variation of 12%; similar ranges of variability were found by Forbes (1965,1966) and Nuttall (1968). Langier gave a range of 1:2 for the performance of operatives in the manufacturing industry; he added that this performance follows a normal distribution.

Coefficients of variation for durations are rarely found in the literature. The author did some calculations based on the regression model of total project duration vs. total project cost for 225 sites in Australia (Bromilow-1979) and found an approximate coefficient of variation of 40%. A similar value was obtained for the Soeterik and Foster regression model.

Klingel arrived at a coefficient of variation of between 33 and 50% for the durations of activities on individual sites. Nuttall (1965) used a coefficient of variation of 23% in a progress simulation exercise, claiming that this value was obtained from actual building sites.

The coefficient of variability for resource consumption within a site should be used with caution. While different authors arrived at similar values, none of them stated clearly if the learning phenomenon was taken into account. The learning phenomenon is a well documented factor affecting productivity (see the reports by the Committee on Housing, Building and Planning, UN); given certain conditions, its effect on the variability of the use of resources can be predicted with reasonable accuracy. For a usual 90% improvement curve, the

range of man-hours expended between the first house on site and the last would be 1.00:1.60, 1.00:2.13 and 1.00:2.37 for sites with 10, 50 and 100 houses, yielding apparent coefficient of variations of 15%, 22% and 25% respectively.

Coefficients of variation mentioned so far were given in the literature or calculated by the author. The coefficient of variation is obtained by dividing the standard deviation by the average value. The standard deviation was calculated according to the Moder and Phillips formula (see equation 3). The average value was considered as the middle point between the extremes of the ranges of output reported in the literature. This approximate calculation of the coefficient of variation is valid for a number of symmetric distributions, like uniform, normal, and triangular.

2.4.4 Accuracy in Estimating

Given the nature of the information available on site, the difficulties associated with collecting, recording, and incorporating feedback information into a proper managerial document, and the variability of output on building sites, it is not surprising that the coefficient of variation for the estimation of resources consumed by activities, group of activities or trades was found to be 68% by Panerai, 52% by Roderick, and between 25 and 60% by N. Barnes and Thompson (1971). In a more rigorous study, Ashworth et al. reported that 9 different estimators had coefficients of variation of between 14 and 21% while estimating the labour content for the brickwork trade in 9 projects.

The use of historical data combined with regression analyses did not provide better results; Ashworth et al. arrived at a 30% coefficient of variation for his experiment relating resource usage to physical parameters, while McCaffer reported coefficients of variation between 15 to 30% for the estimation of costs, in a similar experiment. Beeston (1978) argued that regression models applied to information outside the data bank

from which they are derived produce coefficients of variation up to 50% higher. McCaffer maintained that this increase is between 25 to 50%.

The Lemessany and Clapp (1978) model for estimating the total duration of local authority traditional and non-traditional housing projects used the number of houses to be built as the independent variable; it was able to explain some 60% of the variability found in total project completion times. Dallas produced regression models to estimate the duration of the pre-construction planning stages in hospital building using total project cost as the independent variable; more than 95% of the variability found in the duration of planning activities was explained by the models.

Roderick reported a 53% coefficient of variation for the estimation of durations in a single project. Abernathy, Kidd and Morgan, King and Wilson, and King et al. agreed on figures between 40 to 50%. Abernathy examined one case where the coefficient of variation for the estimation of durations was halved from the start of the project to its completion, while the former group of authors concluded that the variability in estimating durations did not improve as the project was carried out.

J. Bennet maintained that there is no point in including in the estimates items whose influence on total resource usage is less than the accuracy in their prediction. Stacey (1980) recommended that only the more important sources of uncertainty in estimating should be considered: any factor causing uncertainty with an absolute error smaller than a quarter of the absolute error caused by the largest source of uncertainty could well be ignored. Beeston (1975) demonstrated how the knowledge gained through the study of small sources of uncertainty adds very little to the increase in overall accuracy in estimating.

The next section reviews the observations of different authors on the actual progress of work on building sites; this section is intended to illustrate the difficulties in applying network programming concepts and in obtaining information for the estimation of durations.

2.5 The Observation of the Actual Time-related Performance of Some Building Sites

The complexity in estimating durations can be related to a series of characteristics of the building process. The previous section reviewed one of these characteristics, that is, the variability of durations and labour requirements. This section is mainly devoted to the observation of the durations of work for entire projects, construction units, stages, or activities. It also deals with some time-related aspects, like the spreading of work to various units, the shapes of the resource allocation curves, the variability in the level of labour resources available on site, etc. These aspects could be important to explain the observed magnitude of durations.

2.5.1 The Duration of Building Jobs

2.5.1.1 The Total Duration and the Intensity of Work

Bromilow (1969), the Environmental Research Group (1972), Lemessany and Clapp (1978), Price and Horn, and Soeterik and Foster found that total project duration was not a linear function of the quantity of work to be done (expressed by total contract sum or the number of units on site), but a power function where the exponent was less than one: this indicates that large projects were completed in comparatively less time than small ones.

The average time taken to build individual houses on sites of a repetitive nature varied from 59 weeks in England (Forbes-1969), 58 weeks in the USA (Shippam), and 51 weeks in Scotland (Fraser and Evans), to 23 weeks in Australia (Thorpe and Woodhead), for traditional public house construction. Lower figures, in the range of 30 to 40 weeks, were given by the same authors for system building or private construction. Typically the average labour content for the above cases was in the range of 1200 to 1700 man-hours. Thus, the average weekly

allocation of resources could be taken roughly as something between 20 and 50 man-hours/week, that is, approximately half to one man-week throughout the housing construction period. Forbes (1977-2) reported cases in which the average intensity of work was around 20 man-hours/week even for houses with a comparatively small labour content. These are very low figures if it is considered that the usual minimum crew is made up of 2 operatives; thus, at least 80 man-hours per week would be expected to be allocated to the activities. Bishop (1972) concluded that typically design and construction proceed at a slower pace than justified by the amount of work to be completed.

Approximately the same figures for intensity of work were obtained from the observation of individual activities. Forbes (1975) pointed out that a 8 men crew devoted only 80 man-hours/week to a suspended ceiling operation, that is, only 25% of what would have been theoretically possible. M.J. Bentley observed an average intensity of 30 man-hours/week for the electrical work in a school project. Roderick arrived at an average of 29 man-hours per week (range of 9 to 51) for the 21 stages of work needed to build an office block and central store warehouse for a public utility; if the weeks in which no work was observed are disregarded, the average intensity of work for this project increases to 56 man-hours/week (range of 15 to 112).

The small observed intensities of work could have been caused by 2 factors: low number of operatives engaged in the activities or discontinuity of work. Very little is available in terms of quantitative information to substantiate the hypothesis that the low intensity was caused by the allocation of a minimum number of operatives to the task. Schlick studied the urgent refurbishment of staff facilities (toilets, cafeteria, kitchen, etc.) in a large industrial building: the number of men allocated to the highly critical activities was very variable, but on average it was at a minimum (one or two men). This made some critical activities take twice as long as scheduled, but without disturbing the general progress of work

due to overlapping with preceding and succeeding activities.

R. Harris argued that the allocation of resources is not constant throughout the duration of an activity, but that in practical terms it is almost impossible to predict a rate of allocation other than a constant rate. Roderick, and Carr and Brightmann concluded that the allocation of resources to stages of work followed an "s" curve. High intensity of work occurred only during part of the duration of activities: their starting and finishing were undertaken with small allocations of resources. It is worth pointing out that "s" shaped curves were also found to be representative of the allocation of resources (labour or capital) to the whole project (Battersby, Bromilow and Henderson, Cooke, Gates and Scarpa-1976, Handa et al., R. Harris, Kleinfeld, Lemessany and Clapp-1978, W. Perry).

Possible advantages of working continuously with the minimum number of operatives are:

- increase in productivity due to the learning effect: this effect is proportional to the number of repetitions faced by individual crews (Gates and Scarpa-1978, Pigott-1974:1);
- simplification of problems related to supervision and provision of basic site amenities (McNally and Havers, NEDO-1971); Kappaz reported that productivity decreases on sites with an average labour force greater than 300 men; these coordinating problems will seldom affect building sites, where the average labour force is in general smaller than this threshold figure;
- prevention of work place overcrowding; Kappaz stated that more than 10 workers per sq. m. of construction area will cause a decrease in productivity, while McNally and Havers found a threshold of more than one worker per 20 sq. m.;
- larger utilization of resources; it is easier to maintain small crews fully occupied; losses in man-hours due to delays (weather, shortage of material, lack of instructions) are also minimized (Forbes-1965, McNally

and Havers, NEDO-1971); however, the major advantage of working with a low resource profile in order to minimize resource idleness will be in connection with the discontinuity of work on building sites.

2.5.1.2 The Discontinuity of Work

A number of authors (Bishop-1968, the Committee on Housing, Building and Planning-UN, Duff-1976, Eden, Forbes-1977:2, Hall and Ball, Lumsden, Madden, Piggott-1974:1:2, Roderick, Shanley and Keaney, Woodhead-1976) found that work was done discontinuously on site. The report by the Committee on Housing, Building and Planning-UN discussed a comprehensive survey of the process of building in a number of european countries: they came to the conclusion that very rarely was an operation performed without interruptions. Pigott (1974:2) was the first to quantify the number on interruptions for a set of stages of work on a building site. He found that the average number of interruptions was twice the minimum number; the maximum number was four times the minimum number. The importance of considering the minimum number as the parameter for comparisons is explained by the fact that stages of work were defined as finished components (design elements) rather than as true operations (for example, internal painting rather than painting first coat, second coat, etc.). It should be borne in mind that Roderick concluded that discontinuity of work is observed because activities are defined according to the finished component approach used in the Bill of Quantities. However, Forbes (1977:2) stated that BRE studies found as many as 300 operations on a typical site where theoretically only 100 true operations were needed and expected to occur.

Without further discussion of the appropriateness of the definition of activities and its relationship with the apparent discontinuity of work, it is worth pointing out that the trades concerned will perceive the process as discontinuous. In traditional construction (and even more so in some cases of non-traditional systems) the trades are usually required to

perform a great number of separate tasks (Bishop 1966-2, Madden). For example, Woodhead (1977) reported that, according to Australian practice, plumbers may have to visit each construction unit 10 times before finishing their job; Pigott (1977:2) found a minimum of 6 visits by the plumber trade (and, incidentally, an average of 14 and a maximum of 22 visits) on a site in Ireland.

The causes of this discontinuity of work and the great number of interruptions are concentrated in 2 main areas, according to the opinions of different authors. Eden, Forbes (1977:2), and Madden maintained that design not taking into account the construction process was the main cause of discontinuity. Madden summarised the Building Research Establishment experience of the observation of the building process by saying:

> "Activity sampling studies by the BRE have in many instances been able to demonstrate that construction is not a flow process of creation at all, but rather a discontinuous progression, which relies for its completion on the fact that supervisors and men do not allow the regular interruptions to their work to frustrate the advance. Indeed, construction is quite often seen to be not a planned production or assembly sequence, but a series of improvised solutions to temporary production impediments; the latter are intrinsic to the process because they are associated with design".

One obvious way of reducing the number of visits, and hence discontinuity, would be to eliminate some building operations (Bromilow-1977, Eden, Woodhead-1977). A more refined proposition is to design out the interrelationships between operations, like the complete separation of first-floor joisting from ground-floor and first-floor brickwork, as devised by Forbes (1977:2). Finally, Kellog and P. Morris proposed the integration of design and construction in an hierarchical strategic/tactical/operational framework; design would take into account production aspects, but being at a higher hierarchical level, would not be dominated by construction requirements.

The second possible cause for discontinuity of work was identified by Pigott (1974:2). He detected a much greater number of visits to each block than required by design consider-

ations on three house building sites. He related the large number of work interruptions to the way subcontractors undertook their tasks on a number of different sites simultaneously: whenever there was a potential disruption to their smooth flow of work they tended to leave the site. Shortage of materials and design-related problem caused less than 10% of the total number of interruptions. Repair work and organisational problems were responsible for more than 88% of the total number of interruptions. The majority of the work on these sites was subcontracted, even for the initial stages like ground-floor slab and brickwork. He recognised that subcontractors tended to work faster, but the disruptions in the flow of work overshadowed any gains in productivity or reductions in the duration of activities. Pigott, and Logcher and Collins were able to correlate negatively the number of work interruptions and total production. Birrel, Bromilow (1977), Wallin, and Peer and Selinger reported on the difficulties in coordinating the work of subcontractors, and the possible losses in productivity that this could determine.

Bromilow's conclusion that poor time performance of contracts was positively related to the number of variation orders issued by architects in an attempt to keep the contract price within the initial budget, could be added to these two main groups of possible explanations for the discontinuity of work.

Whatever the causes, or the combination of causes, discontinuity of work and a great number of visits are detrimental to the progress of work on site. Bromilow (1977) claimed that a new approach to design, capable of reducing the number of visits, would save up to 10% on labour costs; Pigott (1974:2) went further, claiming potential savings of up to 20%. Moreover, Duff (1979) and Walker (1971, 1972) reckoned that lack of continuity and a great number of visits were associated not only with reduction in productivity but also with increased production variability.

Clapp (1980) introduced a new and powerful concept capable of explaining the influence of several factors affecting productivity, like the learning phenomenon, rationalisation of design, weather, and state of the construction activity in a geographical region. The "concentration effect" relates to the amount of work available for operatives, not only in terms of physical quantities per area of construction, but also in terms of quantities over time in each construction unit, in the whole site, or in a geographical region. Continuity of work, that is, the availability of free runs of work, is just one of the facets of the positive influence of the concentration effect on productivity. Similarly, Bishop (1972) inferred that discontinuity on building sites is just a corollary to the discontinuity, fragmentation, and lack of committment observed in the construction industry at a macro-economic level, caused by uncertain and fluctuating demand.

2.5.1.3 The Spreading of Work to Several Construction Units

Eden agreed with the already mentioned UN report, stating that, given the great number of visits and the complex sequence of work in each construction unit, the contractor has no alternative other than to follow one of two courses of action: either to allow work to spread to several blocks or to create a backlog of units waiting to be tackled. Both strategies will make it possible to achieve reasonable levels of efficiency, at the expense of extended durations. Lumsden entirely disagreed with the practice of allowing work to spread, attributing to it long durations, fluctuations in weekly pay of operatives, and high labour turnover. The essence of his Line of Balance Method is that each crew will be responsible for just one true operation, concentrating its effort in just one construction unit at a time, from start to completion of the task, and then moving in an orderly sequence to the next unit.

Bishop (1968) took a more pragmatic view: given the existing conditions in the building industry, the immediate

solution to the programming problem would be a compromise between a rigid sequence and the spreading of work to a restricted number of units. Eden added that the flow of work should not be optimised by looking at the best sequence of work from unit to unit, as proposed by Hareli, but by considering the group of units that will be better dealt with simultaneously at every point in time. This approach to the solution of the house building programming problem relies on the trade-off between 2 sets of factors:

- the negative effect of interruptions: increased ancillary time involved in prepatory work and cleaning up every time a new work place is visited; losses incurred in reallocating labour to activities already manned (Clapp-1965, Shanley and Keaney, Smith and Rawlings); increased non-productive time in "fill-in" jobs (Stewart and Torrance);
- the positive effects of decreased waiting time (Clapp-1965, Forbes 1980-1). Forbes reported that the Ladygate Lane Site, one of the projects examined by the author in the course of this research work, had a very low non-productive time ratio (9%), probably because the contractor allowed work to spread to the whole site.

Nuttall (1964) hypothesized that small sites have lower productivity than larger ones, because on the former the starting and finishing phases of the work of individual trades take a larger proportion of the time they stay on site: during these two phases a smaller number of working places is available, making it difficult to balance the number of crews and to divert operatives to alternative tasks.

The discussion in this section touches on the possible lack of sequence of work from construction unit to construction unit. The next section deals with this aspect in greater depth.

2.5.1.4 The Sequence of Work from Unit to Unit

Carr and Meyer said that in multi-storey construction, or in house building construction of a repetitive nature, there is no rigid sequence of work from storey to storey or from

house to house. Birrel mentioned that construction activities within a unique unit or a group of units have an absolute logic and a preferred logic (precedence). The flexibility given by the preferred precedence should be advantageously used by site programmers and managers. P. Morris showed that one way of constraining the construction process through bad design is to impose an inflexible sequence of work. Obviously, the lack of a rigid sequence of work should be systematically exploited: Pigott (1974:2) reported that on the 3 sites he observed, operatives moved from block to block apparently without reason.

It seems that the sequence of work should not be seen as the orderly arrangement of consecutive activities and units, but as the creation of "pools" of work by the preceding trades, waiting to be tackled by the succeeding ones (Halpin and Woodhead-1972). This concept applies either to the sequence of work for identical activities in different units or to the sequence of work between theoretical preceding-succeeding activities within the same unit.

The difficulty in defining a unique sequence from block to block and in guaranteeing no spreading of work to neighbour units makes the use of Line of Balance programming techniques an unrealistic exercise.

2.5.1.5 The Relative Magnitude of the Duration of Activities

Low intensity of work and discontinuity contribute to longer durations for the activities. However, there is little published material on the relative magnitude of these long durations. Nuttall (1961), and Price and Horn divided the construction process for each house into a number of sequential preceding-succeeding milestones events and then calculated the time-lags between them. For example, Nuttall found that from "housing start" to "complete to D.P.C." took 4.7 weeks, "complete to D.P.C." to "eaves" 12 weeks, "eaves" to "roofed-in" 3.5 weeks, "roofed-in" to "plastered" 9.5 weeks, and "plastered" to "handed-over" 11.5 weeks (a total of 41.6 weeks).

He pointed out that the time-lags did not vary with the size of contract, and were very slightly correlated to the rate of progress and productivity of the trades concerned. This is probably a good example of the "natural rhythm" approach to the duration of activities introduced by Lumsden: the average time-lags between milestones were virtually the same for all sites analysed; the inter-milestone activities absorbed the usual period of time found in this type of construction, with little regard to sizes of sites, rates of progress, or other influences. Similarly, Price and Horn showed that the time taken to complete the first house on different sites was not correlated to the size of the project (number of houses).

The division of the work on site into milestone events and the calculation of time-lags between them did not produce an indication on the relative magnitude of the duration of individual activities. This could only be found in the work of Roderick, and Shanley and Keaney. The 21 activities contained on the site analysed by Roderick took on average 1/3 or 1/6 of the total time needed to complete the site, including or excluding the weeks in which work had not occurred, respectively. The 6 major stages into which work was subdivided on the site analysed by Shanley and Keaney took on average 3/10 or 1/5 of the total time needed to complete each house, with internal finishings and services taking 1/2 or 1/3, again including or excluding weeks without work, respectively.

2.5.1.6 The Precedence Between Activities

Activities ought to be done in parallel in order to accommodate the relatively long durations previously mentioned. F. Bennet (1973) and Faherty maintained that rigid precedence of a head and tail type is the exception rather than the rule for the actual progress of work on site. Roderick, Schlick, and Hall and Ball reported that activities were done in parallel rather than in sequence on the sites they observed. Kelley and Walker, the originators of critical path methods, stated that the rigid precedence relationship is just a simplification

of how things really happen on site; they maintained that activities can be started as soon as their preceding ones are "almost" finished. Despite the existence of a number of approaches for dealing with overlapping precedence (see the works by Carr-1971, Faherty, and Halpin and Woodhead-1972) the cornerstone of the problem is the availability of information on how much overlapping can be allowed for at the programming stage.

Thus the review of literature showed that not only is there overlapping in the work of similar activities in different construction units, but also overlapping of different activities within the same construction unit.

2.5.1.7 The Rate of Progress

The programming of work on house building sites of a repetitive nature requires a third parameter in addition to the two parameters (duration of activities and their precedence) usually needed for critical path methods applied to non-repetitive buildings. The rate of progress is defined as the number of identical units completed per time period. Given no overlapping between identical activities in different construction units, the rate of progress is solely a function of the duration of activities: the time taken to complete "n" activities is the direct sum of the time taken to complete each individual activity. Sites with twice as many units would take roughly twice the total duration (in fact a little less, because the time taken for preparatory site work and the building of the first house would be similar for both projects - see the breakdown of project times given by Price and Horn). If the same total duration is required for both projects, the larger one will require twice as many crews, allocated to alternate construction units throughout the sequence of work.

However, the previous discussion of the duration of projects showed that its relationship to contract size (value or number of units) was not linear. This could be due to two factors:

- large projects would have been completed in relatively less time, even at the same rate of progress as those of smaller size, if the time taken by preparatory site work and the building of the first house was significant and invariant with project size. No published evidence is available to confirm this hypothesis, apart from the work of Price and Horn;
- larger projects were performed under an increased rate of progress. Nuttall (1961), and Price and Horn obtained rates of progress that increased linearly with the square root of the number of units in the project. Furthermore, Nuttall detected a small correlation between time-lags (inter-milestone times) and rate of progress: a quicker rate of progress was associated with smaller time-lags.

Nuttall found that the rates of progress for the various stages of superstructure were substantially the same; foundations, though, were built at a much faster rate. Queueing theory for a stochastic construction environment would determine that each succeeding activity should be built at a slightly slower rate than the preceding one, in order to minimize idle time (at the expense of greater total project completion time). Reflecting the greater importance of controlling costs over controlling time in the construction industry (Bromilow-1971, S.R. Harris), Price and Horn found that on a sample of 28 industrialized building sites the rate of handover was between 70 and 90% of the rate of shell erection. In large sites (more than 200 houses) this fall off in the rates of progress was observed only up to the 120th house; after that the rates of progress for the various carcassing and finishing activities were similar. Substructure (including ground-floor slab) proceeded at a much faster rate than the rest of the work, leading to some unnecessary capital lock-up.

The identification of the rate of progress of stages of work was practically impossible on the Finchampstead site analysed by Forbes and Stjernstedt. The first 3 stages of work, substructure beams, floor slab, and housing shell erection were done continuously, with few working places being tackled each week, producing clear and independent rate of progress lines.

Substructure and ground-floor slab also proceeded at a faster rate than the housing shell erection. However, the remaining 7 finishing stages of work (dry-linings, floor joisting, joinery, plumbing, electrical fittings, and decoration) were performed under a discontinuous and confused pattern of work: a progress control chart depicting these 10 stages of work was not able to clearly indicate the rate of progress for the finishing stages.

The required rate of progress is typically a high level strategic decision that will dictate the low level operational aspects of site programming (Birrel). The rate of progress relates directly to the project duration, as given by the contractual arrangements. It bears an important relationship to the organizational capabilities of each construction company: while any firm can built at a lower rate of progress, say 1 house/week, only specialized and experienced firms can undertake projects with higher rates, say 10 houses/week (Lumsden). A vigorous rate of progress will call for increased supervision, and, perhaps, the inclusion of extra staff in the building managerial team: Lumsden advocated the inclusion of a materials coordinator, while the Building Research Station Digest No. 91, 1956, proposed the presence of a process engineer on site, taking care of delivery of materials, scaffolding, equipment, and adjustments in the size of gangs.

2.5.2 The Availability of Labour Resources on Construction Sites

Activities can be delayed or interrupted due to the unavailability of labour resources on site, or because the resources deployed are not as productive as initially estimated. Both factors will lead to increased durations. The actual level of resources available on site can be obtained through the proper consideration of factors like labour absenteism, turnover, strikes, weekly hours of work (including overtime), scheduled holidays, and non-productive time. Non-productive

time affects the effectiveness of labour resources while they are present on site. The other factors affect the physical presence/absence of labour resources.

2.5.2.1 The Uncertain Presence of Labour Resources

Some of the factors discussed above are so deterministic, like holidays or weekends, that their inclusion does not present problems in the scheduling of work and in the calculation of durations. Others, like strikes, are better left out of the programming exercise: not only are the average direct losses for the construction industry small, but it is also very difficult to predict when industrial action will take place. Average direct losses ranged from 0.025 to 0.125% of the total number of man-days available to the construction sector, reaching 1 to 6% for the worst industrial plant construction sites (NEDO-1970).

Labour absenteism and turnover can be expected to occur regularly throughout the construction period. Average losses due to absenteism are small, ranging from 1 to 10%, with the most common figures being around 3% (Clapp-1965, Evenwell, NEDO-1976, Plant). The influence of labour turnover on productivity or on the reduction of labour resources available on site is yet to be quantified. The literature produced only turnover ratios. Common published ratios are around 50% per year (Evenwell, Miller-1975, NEDO-1976), but no information is available on the proportion of true turnover, that is, the voluntary or management decided laying-off/employment of operatives still needed to complete on-going operations. Information provided by the NEDO report on large industrial sites (1970) inferred that the turnover of operatives still needed was around 40 to 60%, contrasting with a total turnover of 120% for this type of project. A rough estimate by the author indicated that, even under this extreme conditions of true labour turnover, direct losses in labour availability are less than 5%, if it is assumed that operatives are replaced

within a week. The impact of turnover on productivity for the economy as a whole is significant: Swan showed that labour turnover and seasonal unemployment were responsible for construction operatives working only between 1/3 and 1/2 of the total number of hours they are able to work in a year (data valid for the U.S.A., covering the period June 1966 - July 1967).

The number of hours worked per day and the number of days worked per week is a function of management decisions and labour agreements. However, Blough, and McGlaum strongly opposed the use of overtime, claiming that scheduled or prolonged overtime (more than 7 days) leads to a reduction in total production per day.

Clapp (1966) demonstrated that harsh weather conditions in winter not only caused an increase in absenteism, but also reduced the normal working week by some 5-6%.

2.5.2.2 Non-productive Time in Building Operations

The major losses and uncertainties in the availability of labour resources are caused by non-productive time. A number of authors agreed on an average figure of 30% for non-productive time on building sites (M.J. Bentley, Borcherding-1976, Forbes-1977:2, Logcher and Collins, Peer and North, Sharma et al., Stewart and Torrance, Winstaley, Verschuren). Thomas proposed a 53% figure for nuclear plant construction. Forbes (1977:2) maintained that, as a general rule of thumb, 1/3 of the time on site would be allocated to truly productive work ("making the building grow"), 1/3 to ancillary tasks (handling, unloading, cleaning tools and the work place, supervision, setting out, and testing), and 1/3 to non-productive work (idle at the work place, idle around the site, unofficial meal breaks, unable to work due to weather, etc.). Sharma et al. found that skilled workers had an average of 30% non-productive time, but that an extra 8% was devoted to tasks normally associated with unskilled workers. This fact, plus the high proportion of ancillary work detected by Forbes, calls for the careful balancing of crews in terms of skilled and unskilled operatives.

The majority of observations on non-productive time was obtained through the use of activity sampling. Other methods like work study, production cards, etc. will not produce reliable results; operatives will not be seen continuously idle, it being part of human nature to find something to do while under close scrutiny. On the other hand, management will not tolerate continuous idleness, once aware of its presence. This is the reason why idleness due to bad programming of works will not be seen on site, apart from the obvious cases. Nuttall (1965) stated that the effects of bad programming would still exist and will be represented by a slow down in the pace of work.

Activity sampling has been used to measure non-productive time only while some form of work was going on. The NEDO report on industrial plant construction (1976), and Stewart and Torrance found that the active period on site was only between 84% and 94% of the paid period. The active period was defined as the daily period of work during which construction activity should be observable. Therefore it excluded all official breaks, official washing periods, and allowed travelling time. Similarly, M.J. Bentley arrived at a figure of 28% for the non-productive time in the construction of a school using the CLASP system, but if all subcontractors travelling time and absences were taken into account, the figure would rise to 50%. Work on site started at between 8:45 and 9:15 with the paid period beginning at 8:00. Thomas measured 6% as non-productive time due to late arrivals and early departures in nuclear plant construction in the U.S.A. One of the sites studied by the NEDO report on industrial plant construction produced a figure of only 14% for the time effectively applied to the growth of the building, once all possible sources of non-productive time (activity sampling measurable and not measurable) were taken into account.

Panerai, and Sharma et al. showed that non-productive time was not constant throughout the day on the sites they investigated. Sharma et al. arrived at a figure of 28 and 22%, respectively, for non-productive time in the morning and in the afternoon period, for a selected number of trades in India.

Panerai claimed that non-productive time varied from 70 to 85% throughout the day. The smaller proportion of non-productive time was detected at the start of each working section in the morning and afternoon, increasing steadily towards the lunch break and towards the end of the day. This did not compare well with the classical theoretical curve for non-productive time throughout the day. The classical curve has the shape of a bimodal distribution: non-productive time is at its highest at the start of the day, declines to 15% in mid-morning and rises again towards the lunch period; the pattern is repeated in the afternoon. Bishop (1966:2) argued that the distribution of productive and ancillary time can be expected to vary during the day: early morning is characterized by preparatory work, while late afternoon usually sees an increase in the proportion of cleaning up.

Panerai discussed the variability of non-productive time throughout the duration of an activity. Non-productive time ranged from 9 to 29% according to the elapsed number of days since the activity was started and the particular type of work carried out during the day. No mention was made in the literature of the quantitative influence of different days of the week on productivity, but Krick said that it is a well known fact that non-productive time follows a cycle throughout the week, being at a maximum on Mondays and Fridays.

Forbes (1980:1) concluded that non-productive time spent in building operations is more related to organizational aspects than to the physical quantities of work. Peer and North used time-lapse photography to study work on site: of the 33% non-productive time, 93% was caused by management. The management influence on non-productive time could be used to justify findings by Reiners and Broughton that the various trades tended to have similar non-productive time within a site, despite the differences in their jobs, and in their efficiency while at work.

The measurement and incorporation of non-productive time into the duration of the activities requires attention

to all forms of ineffective time that can occur. Winstaley classified the sources of inefficiency into non-productive time connected with working (waiting, receiving supervision, weather stoppages, minor mechanical breakdowns), and non-productive time connected with the operatives (unofficial meal breaks, relaxation, walking, late arrivals and early departures). Each category accounted for 50% of an average 32% non-productive time for Swedish building sites.

Peer and North produced more evidence on non-productive time while an activity is being performed. They found that relaxation time was only 2.5%, a very low value, probably caused by the fact that operatives had plenty of time to relax within the total 33% non-productive time observed on some Australian building sites. Another form of non-productive time intrinsically connected with working is process waiting time. The same authors found 10% for non-productive time in this category: Dabbas and Halpin maintained that process waiting time is inherent in some construction operations, like concreting and excavating, and can be estimated through progress simulation models.

Non-productive time can be observed outside the working place or could occur while the recording mechanism is not in operation. For example, the withdrawal of subcontractors from the site as soon as delays are imminent (Pigott-1974:2, Reiners and Broughton) determines that less non-productive time outside the work place is recorded for them than for the main contractor operatives. Subcontractors do not necessarily follow the official working hours imposed by the main contractor (Forbes-1966:1): recording of information only during these hours can leave some of the effective work done by subcontractors unaccounted for.

Thus, the inclusion of non-productive time into the estimation of durations should be made only after it is known what categories of ineffective time were recorded, and when and how they were observed.

2.6 An Overview

The first major difficulty in the study and estimation of durations is the definition of activities. Both the use of design-element activities and the aggregation of process-oriented operations are liable to misrepresent the interconnections of work on site and the duration of activities. Recorded production information based on both these types of activities will be similarly inaccurate as far as representing the true process of building. Nevertheless, it is still necessary to provide some indication on the expected duration of activities, whatever the level of interconnection and aggregation they imply.

The choice between a deterministic and a stochastic approach to network planning depends on two factors still not sufficiently investigated by research workers: the variability of durations, and the cost implications of positive management reactions to deviations from scheduled durations. There should be a limit to the variability of durations beyond which stochastic concepts would be preferred to deterministic ones. It can be hypothesized that at still higher levels of variability no benefit can be gained from the programming of building works.

Methods of estimating durations can be subdivided into three categories. Subjective methods would be used when no information is available to calculate durations. Durations thus obtained could be unreliable, but at least it is possible to establish a schedule of events in order to commit and coordinate the various participants of the building process. Resource-related methods are based on the assumption that durations are directly related to resource usage. The fact that the existence of this relationship appeals to common sense does not preclude the need to prove it by practical observations, which, to the best of the author's knowledge, has not been done yet.

The subtle differences between the three resource-related methods require precise definitions of how labour content, resource, outputs, and number of operatives assigned to the job were obtained from previous experience. Moreover, the combined use of the three methods by programming departments requires the definition of the number of hours effectively worked per time period. The definition of this number is critical.

The measured-duration methods are still waiting the development of techniques for recording and gauging the lapses of time in building operations. The major contribution made so far by these methods is the recognition that durations can be taken on their own, and not as a function of the labour content or the number of men allocated to the job. There could be a correlation between duration and resource usage, but not necessarily a cause-effect relationship. A useful outcome of a good correlation between duration and resource usage would be the possibility of using the coefficients of variation for labour consumption, already exhaustively investigated in the literature, as first approximations for the coefficients of variation of durations.

Estimates of resource consumptions and durations were found to be biased and inaccurate, even in the presence of feedback. The estimation of average durations rather than individual ones will be preferable, due to the differences in the physical type of units on house building sites. Moreover, average values imply data aggregation, and hence greater accuracy.

Regression models for estimating the duration of construction activities have not yet been tried. The accuracy of regression models was comparable to other estimating methods for the prediction of labour usage and cost.

Present programming techniques, like the Critical Path Method and Line of Balance, face serious difficulties in accommodating activities having large durations, the discontinuity of work, the overlapping of theoretically sequential activities, the spreading of work to various construction units,

and the lack of a compulsory sequence of work, reported in the literature as characteristics of some building sites. New programming techniques should be developed avoiding the need to specifically identify units of construction and operations within a stage of work.

Durations, precedence, overlapping, the spreading of work, rates of progress, varying rates of allocation of resources, availability of resources, and non-productive time are all integral and interdependent measures of the building process. They should be collected, recorded, and used in conjunction.

The development of rough techniques for estimating the duration of activities at any level of work breakdown, the calibration of resource-related methods of calculating durations, the creation of techniques for measuring the duration of construction activities, the investigation of the viability of providing cost-effective feedback information systems, the analyses of the influence of feedback on more accurate and less biased estimates, and, finally, the development of new programming techniques could only be accomplished if more attention is devoted to the observation of sites.

Madden concluded that very little is known about why production and assembly on site proceeds as it does. The review of literature showed that, apart from labour resource consumption, only qualitative evidence has been gathered so far on the characteristics of the building process. This report attempts to provide systematic quantitative information on one of its aspects, the duration of activities.

The first step in pursuing this objective is to collect production information from three house building sites. Methods of collecting information and a report on the use of an improved method of activity sampling are presented in the next chapter

CHAPTER 3

DATA ACQUISITION

One of the aspects that should be considered when estimating durations is the method of obtaining production information. This research work used activity sampling to build its data bank. Other methods of obtaining production information and the particular activity sampling package utilized are investigated in the following sections.

3.1 Methods of Obtaining Production-related Information

3.1.1 Generalities

If some of the views on discontinuity of work expressed in the previous chapter are accepted, it will be possible to agree with Forbes (1981):

> "The task of learning how operatives spend their time on site is much more difficult than it sounds, for the building process consists of large numbers of small units of work and operatives are dispersed over a wide area, frequently working on many parts of the site during the day".

The measurement of production-related information can be done at various levels. Kellog proposed a hierarchical model, where the macro-measurement of productivity at the level of society as a whole, or at the level of the construction sector of the economy, takes precedence over the micro-measurement of productivity at the level of building sites and individual operations. He was of the opinion that only very small gains in productivity can be obtained at the micro-level and perhaps these gains were already achieved by the majority of contractors. Along the same lines, Forbes (1975) suggested an overall view of site productivity, trying to identify the

influence of organizational factors rather than attempting to establish standards for the many thousands of activities that could take place.

The benefits of measuring production should be viewed not in terms of the quantitative information made available but in terms of the number of problems that are isolated and corrected (R. Barnes, Thomas). Blain argued that the weakness of the use of historical records in estimating is the perpetuation of standards of time of previous activities, instead of the analyses of the actual time they should have taken. Historical estimating could only prevent future losses, but does little to enhance productivity. While the measurement of productivity can be a difficult exercise, the implementation of better working procedures is the real stumbling block in the cycle measurement-identification-analyses-correction.

These preliminary considerations set the guidelines for what should be measured on site and for the amount of effort to be devoted to this management activity. Pilcher (1977) recommended that work measurement officers should be preoccupied with ranges of variability for duration and resource consumption, saying that average values are of little use for progress simulation and control. Duff (1980) took the opposite view by saying that treating duration and resource consumption as stochastic variables does very little to help understand how things happen on site. In his opinion, a thorough study of building sites and factors affecting productivity is necessary, with the objective of reducing the unexplained variability to a minimum. Nothing short of complete work study would be useful in achieving this objective.

A good example of the difficulties in defining what and how to measure production is the incorporation of non-productive time in cost estimates. Acceptance of the view that non-productive time can be more easily related to site organizational aspects than to physical measures of work (Duff-1979, Forbes-1977:2, Peer and North) recommends that the cost consequences of non-productive time should be added as a lump sum at the end of the estimating process. While this approach could be

correct in terms of prices and costs, no information is made available on the likely influence of non-productive time in the performance of individual activities, as it would be needed for day to day site management.

Thomas suggested the simultaneous use of various methods to record and present production data; each method views the production process from a different angle. Whatever quantitative aspects are measured by the different methods, they reflect only the consequences of production problems, not their causes.

McNally and Havers found that time-studies cost some 5% of their potential benefits. The NEDO report on Large Construction Sites (1971) estimated that work study would cost some 2% of the total labour expenditure on these sites. It seems that provided the potential benefits can be implemented, the economics favour the use of measurement techniques.

Woodhead (1976) found that measuring chaos was expensive and unrewarding. He sought the cooperation of the most organized firms in order to conduct his video-recording experiments. Clapp (1965), and Howenstine also reported this potential bias in time-studies.

The different methods of production measurement will produce different figures for durations, labour consumptions and non-productive times. Madden compared the average 1100 man-hours required to build a house according to a detailed survey made by the Building Research Establishment with the 2000 man-hours figure obtained at the macro-economic level by just dividing the total number of man-hours worked in the house building sector of the construction industry by the total number of houses completed within a year. Macro-studies are likely to yield the highest figures for labour consumption, because they theoretically include the totality of man-hours used by a construction sector or a group of projects under examination. Work study, by definition, will take into account time used by the operatives only while the operation is being performed: no consideration is given to time spent in-between operations. Even the same techniques could produce different

results: Thomas et al. reported that activity sampling studies of ironworkers in a nuclear plant construction yielded productive time of around 17%; however, if the sampling periods had excluded lunch breaks, late starts, and early departures, productive work would have risen to 40%.

Theoretically the information provided by different methods can be reconciled using proper allowances. In practice the lack of quantitative information on these allowances and proper definition of what had been measured by each technique make such reconciliation impossible.

3.1.2 Macro-Studies

Methods grouped under this heading deal with the totality of man-hours spent on a group of sites or in a particular sector of the construction industry. They do not use detailed daily recordings of how the man-hours were spent on site. Generally, the input data for these methods is the total amount of labour (or capital) spent, broken down, at the most, at the level of trades. It is difficult to correlate the labour expenditure with particular operations on site or even with groups of operations; multi-regression models can theoretically overcome this problem, but their reliability was found to be small (see Beamish).

Two different approaches can be used. In the first, labour and construction activity statistics are employed to work out rough guides of labour consumption per unit built, per square meter, or per unit of material. Examples can be found in the Collection of Construction Statistics published by the Building Research Station in 1971. It is interesting to note that the actual time to complete each dwelling was in the range of 10 to 18 months during the 1954-1968 period, depending on the type of dwelling (house or flat) and type of promoter (public or private).

Alternatively, a group of selected sites is examined after its construction. Labour consumption is related to physical quantities of work as specified in the Bills of Quantities. A good example of this technique can be seen on the work being developed by the Building Research Establishment during the last 15 years (Clapp-1965, 1977, 1980, Beamish, Lemessany and Clapp-1975, 1978).

Macro-economic methods are not able to obtain non-productive time spent in building operations. Furthermore, durations are calculated by dividing the number of units being built by the rate of starts per month. The method assumes that units started first will also finish first. A much needed item of information not yet available at the level of general construction statistics is the timely occurrence of the work of each trade in the construction of housing units. Abdulmajid, and Hillebrandt pointed out that policy decisions on the number of houses to be built per year will affect trades within different time-lags: an increase in the number of housing starts will almost immediately increase the demand for the trades involved in early work, but will probably take almost a year to affect the finishing trades.

3.1.3 Micro-studies

Micro-study methods are related to the observation of individual sites or operations while they are under construction. They require the presence of time observers throughout the period of observation, as opposed to the previous methods that rely on historical information. Special emphasis will be given to the description of activity sampling techniques.

3.1.3.1 The Observation of Time as a Continuous Variable

3.1.3.1.1 Work Study

Work Study is quite a well known technique: the reader is referred to the classical books by R. Barnes, and Currie.

This review is concerned only with the appropriateness of using work study on building sites.

Work Study has been quite successfully used to examine building operations under laboratory conditions (Nuttall-1968, Whitehead). The range of variability in the production of individual tradesmen discussed in Chapter Two sets a lower limit for the variability of output that can be expected on construction sites. Relaxation allowances and contingency allowances derived from tables published by Blain, Currie, and Davies and Whattingham are in line with the average idle time in building operations mentioned in the preceding chapter (20 to 30%). Currie recommended a minimum of 10% for relaxation, which is above the non-productive time for some efficient subcontractors (Forbes-1980:1, Woodhead-1976).

The fact that experienced work study practitioners are reckoned to be able to rate the work of individual operatives within an accuracy of ± 5% boosts confidence in subjective human estimating. It is of some concern, though, that this statement can not be verified in practice, simply because it is not possible to define a true absolute rate of working for an operative against which the rating accuracy of experienced work study officers can be checked.

Provided that the crucial importance of accurate rating is understood, and the large variability in the output of different operatives is accepted, there is nothing wrong with the use of work study for building operations under laboratory conditions.

It should be noted that work study measures the labour content of operations in units of time, that is, there is no distinction between labour content and the duration of activities. Furthermore, work study presupposes the existence of an established method of performing the operations: information obtained is valid only for specific methods.

Problems start to arise if work study techniques are applied to actual building sites instead of controlled experimental laboratories. Madden wrote that the problems in

the use of work study on site are enormous: conditions do not repeat themselves as in a factory environment. Krick added that work study looks at the task in isolation, ignoring the interdependence of operations: time lost due to interruptions is not considered. Indeed, the maximum allowed interrupted time in work study is 2%; if interrupted time exceeds this figure, observations should be disregarded (Blain, Currie). Winstaley said that 50% of a total of 32% non-productive time on Swedish building sites was related to interruptions while the operatives were actually engaged in the activities: this gives an indication of the amount of work interruption that can occur.

McNally and Havers, and Whitehead stated that the contractor has little control over the method of work used by the labour force. It can be added that day to day variations in productivity and the probable observation of unbalanced crews (ratios of skilled to unskilled workers) due to absences requires either the acceptance of non-representative values or the extension of the period of observation for a large number of days, in order to even up the calculations. Finally, the number of work study officers needed on site to provide coverage of a substantial number of operations would undoubtedly interfere with the normal flow of work on a construction site (Forbes-1980:2).

It was stated previously that theoretical relaxation and contingency allowances used in work study are in line with non-productive time found in building operations. However, the nature of these allowances and non-productive time are different. Peer and North found an average figure of 2% (maximum of 4%) for non-productive time that could be directly related to personal needs or fatigue relaxation. This is a low figure if compared with the minimum theoretical figures of 10% given by Currie, 9% given by Blain, and 6 to 8% given by Davies and Warrington. Peer and North concluded that operatives could afford this low figure for relaxation because the in-built non-productive time of the operations under

observation was around 30%. On the other hand, Davies and Warrington quoted an average figure of 3 to 5% (maximum of 10%) for contingency allowance, designed to compensate for delays and interruptions. Non-productive time related to discontinuity was much higher, according to the figures produced in the last chapter.

Finally, Duff (1976) argued that a great part of the non-productive time in building is related to events that affect the site as a whole, not individual activities.

3.1.3.1.2 Other Continuous Methods

Production card annotation and the recording of work cycles are 2 other methods that consider time as a continuous variable. Production cards are frequently used in the manufacturing industry. Lately Pigott, and Shanley and Keaney applied this technique to building sites in Ireland. Operatives or external observers can be in charge of recording the total number of hours spent in each operation, hence producing different levels of reliability for the data provided. Both labour usage and the duration of activities can be obtained through the use of production cards, but non-productive time other than that caused by the most obvious reasons (interruptions due to weather, lack of materials) is not recorded.

The production card method is inexpensive, does not disturb the operatives, and has the added advantage of recording the rate of deployment of resources over time. This information will be found extremely important for the analyses of durations in Chapter Five. The major disadvantage of the production card method is the production of information at a low level of detail.

The observation of work-cycles is a technique introduced by Adrian (1974, 1976). Instead of observing work in isolation, a leading cyclical activity is chosen as representative of a series of sub-operations. The cycle-time to repeat the leading

activity is recorded, together with delays, interruptions, and ratings for productivity during the cycle. Average cycle-time and delayed time are calculated after a number of repetitions.

The technique is suitable only for certain cyclical operations, like excavating and concreting, but it is extremely useful for providing duration of activities for simulation programs like Cyclone (Halpin-1973). The major contributions of the concept of cycle-time observation are:

- the recognition that time should be measured at some level of aggregation greater than the basic operations level;
- the acknowledgement that the interactions between activities should be taken into account;
- the acceptance of delayed time as an integral part of the process of building.

3.1.3.2 The Observation of Time as an Instantaneous Variable

The choice of continuous and instantaneous headings to classify the observation techniques is somewhat misleading. For the first category, work is measured continuously, but the higher costs prevent the use of the techniques throughout the construction process (with the exception of production cards). For the second category, work is recorded in the form of discrete instantaneous occurrences, but lower costs allow the techniques to be used continuously during the whole project duration. For example, according to R. Barnes, activity sampling studies cost between 5 and 50% of comparable work study exercises.

3.1.3.2.1 Activity Sampling

The following two paragraphs were extracted from the Building Research Notes No. 143/80 and No. 13/81 (Forbes-1980:2, 1981).

"The activity sampling approach is based on the assumption that a sample taken at random from a large group tends to have the same pattern of distribution as the large group . Thus, what operatives can be observed doing at times chosen at random will reflect how, on average, they spend the whole of their time. In practice, a record is kept of what each operative is observed to be doing at particular moments randomly selected. These observations are known as "snaps". The distribution of observations between the chosen parameters (for example, working at task, relaxing, receiving instructions, etc.) is an approximation to the distribution of the operatives time between these parameters. The greater the number of observations that are made, the greater the accuracy of the approximation, so that the frequency of "snaps" may be arranged to give results of the required accuracy.

Because all men are not being observed all the time the results will be in error to a certain extent. The size of the error will depend on the frequency of the sampling and the labour content of the item being measured. Thus, the sampling error effectively sets a limit on the level of detail that is measurable. There is no hope of ever measuring accurately small amounts of labour input that are not repeated".

The development of the formula relating confidence limits, degree of accuracy, and the number of observations is given by Krick. For 95% confidence limits, this formula is (Stevens-1969):

$$a = 2 * \sqrt{\frac{(1-p)}{N * p}}$$

where:

a = degree of accuracy (in decimal form);
p = percentage of occurrence (in decimal form);
N = total number of observations;

The percentage of occurrence is not available at the time of designing the activity sampling study; indeed this is the information the site analyst is trying to obtain. A pilot study with a small number of observations could indicate an approximation to its value. It is good practice to

constantly reassess the value of "p" and consequently of "N", based on the information that becomes available as the study goes on.

The 95% confidence limit means that there is a 95 in 100 chance that the true percentage of work lies between ± "a"% of the percentage arrived at through the use of activity sampling.

Basically, 2 different methods are used to calculate the number of observations that will be needed. Either the analyst selects a percentage accuracy that he wants to achieve, or he selects an absolute desired accuracy in terms of man-hours. According to Krick, the second method is more reasonable and leads to a reduction in the number of observations for activities with a low probability of occurrence. This advantage is especially important when activity sampling is used to analyse simultaneously a number of activities with different probabilities of occurrence and it is not desired to let the smallest activity to determine the total number of observations needed.

The Building Research Establishment approach represents a compromise between these 2 systems. It has been usual to design the observational exercise to be able to measure a unit of work estimated at 1% of the total man-hour requirement to an accuracy of ± 5% with 95% confidence limits.

The confidence limits and accuracy ought to be carefully selected. It should be borne in mind that the number of observations is the key factor: the confidence limits and the accuracy are only means of expressing how close the percentage of work obtained through activity sampling lies to the true percentage. However, the number of observations is not the only factor determining the accuracy of activity sampling. Three other sources of inaccuracy can be listed:

- influence of observer prejudices in respect of the operatives;
- biased decisions on how to allocate doubtful snap observations;
- non-representative samples (operatives changing their behaviour in the presence of the observer).

The influence of these sources of inaccuracy is not affected by the number of observations and probably will never be known (Krick, Thomas et al.). As there is no procedure for eliminating the influence of the above factors other than careful orientation of observers and cooperation of operatives, Krick suggested 90% confidence limits and 5% accuracy as the parameters for calculating the number of observations: he maintained that it is better to allocate resources to a proper design of the activity sampling study and to measures to reduce the observer bias than to an excessive number of observations. Forbes (1980:2) proposed that in practical applications, at the level of the construction company, the confidence limits can be reduced to 80% with an accuracy of 5%.

Observers should be trained and provided with precise definitions of the observable work categories. Objective means of deciding on dubious observations should be devised. The better the planning and training for activity sampling, the better the reliability of results.

The major criticism of the activity sampling technique is its inherent inefficiency; the observer spends most of his time going to the working places rather than observing actual activity. The information obtained distinguishes only two states, for example active/not active, engaged in one operation/not engaged, available at the work place/not available (Krick). Other techniques like work study provide much more information on the performance of operatives or activities. Thomas concluded that there are many more things that activity sampling can not do than that it can do. The objectives and design of the activity sampling exercise should be carefully thought out, in order to mitigate the effects of the above limitations.

There is no point in using activity sampling to observe just one worker. As the observer will probably be committed throughout the period of study, it would be better to employ a continuous technique, like work study. On the other hand, it is not economical to apply activity sampling to the observation of activities with low probabilities of occurrence, due to the great number of observations needed.

Problems caused by large walking distance and cost per observation can be minimized by conducting various activity sampling studies simultaneously, that is, observing various operatives at the same working place or visiting different working places. These strategies are called the crew approach and the tour approach to activity sampling, respectively. Whatever the approach adopted, one of the major problems is to ensure that a substantial number of workers are seen in each round of observations. Forbes (1980:2), Thomas and Holland, and the NEDO report on industrial plant construction (1976) showed that operatives were not seen at the work place between 25 to 50% of the time. Thomas recommended that at least 75% of the operatives should be seen in each round of observations, and that provision should be made to account for the missing workers.

Moreover, simultaneous observations are not truly independent, as required by the statistical basis of activity sampling: a group of operatives engaged on a particular activity will probably be seen doing the same tasks at each round of observations. Despite this shortcoming, the simultaneous approaches seem a necessary compromise in order to reduce the cost of observation, and hence maintain the major advantage of activity sampling over other techniques, namely its low cost.

Due to its low cost, activity sampling can be used for long periods of time, thus decreasing the effects of day to day variations. It compares well with work study in terms of the need for qualified observers, observer fatigue, likelihood of a change of attitude by the operatives, and need for special equipment.

The use of qualified or non-qualified observers is subject to debate. Krick maintained that the use of non-qualified observers is one of the advantages of activity sampling over work study. On the other hand, Thomas et al. suggested that the observers could be in charge of analysing, correcting, and qualifying the information obtained at the end of each day: having seen the work, they are in a better

position to analyse the results than anyone else. Normally, activity sampling neither provides information on the method of work used nor rates the efficiency of operatives: this extra information can be made available if qualified observers are employed. The use of micro-computers to provide on-the-spot information based on the data gathered during the day, can also be a factor in deciding on the use of more or less qualified observers.

Finally, the decision on levels of breakdown of work for observational purposes plays an important role in the selection and training of observers. Thomas recommended that the work should be divided into 12 to 15 categories, in order to make it easier for the observer to allocate each snap observation to the correct heading. Fine (1974) reported an experiment where cost accountants were asked to allocate time sheets to cost headings. It was observed that:

- with 30 cost headings, about 2% of the items were misallocated;
- with 200 cost headings, about 50% were misallocated;
- with 2000 cost headings, only about 2% of the items were correctly allocated.

The activity sampling method presents specific problems for the evaluation of the duration of activities, especially if the intervals between observation rounds are large. There is no indication of the operatives continuity and intensity of effort in each activity. This aspect will be explored in greater depth in Chapter Five.

3.1.3.2.2 Time-lapse Photography and Video-Recording

Time-lapse photography and video-recording represent a compromise between work study and ordinary activity sampling. At one extreme, they can be used to film continuously the operations, providing the same information as work study, plus the influence of delays and interconnections between activities, with the added advantage of a permanent record of

how time was spent on site. The obvious disadvantage of this approach is the time needed to review the operations and the expenses in terms of lineage of films/tapes. At the other extreme, they can be used to record instantaneous occurrences of work, exactly as with activity sampling.

Fixed and movable cameras reduce the need for observer movement from place to place. Interference with the work of operatives is minimized. The provision of a permanent record of snap observations and the physical separation between observer and operative help to reduce the activity sampling biases mentioned earlier on.

Woodhead (1976) reported Australian experience with video-recording. The major disadvantages of his technique are: the cost of the equipment; the need for a crew of observers to operate it; the difficulty in finding suitable vantage points to place the cameras; and the complex operations needed to extract information from the tapes. Touran went to great lengths to obtain the duration of activities on building sites, using a sophisticated integration between a time-lapse projector and a mini-computer. However, he was unable to devise a method to deal with the influence of discontinuity of work and varying rates of allocation of resource in the measurement of durations.

Woodhead's studies with video-recording can be criticised as just an attempt to distance observers from the work place (in order to reduce interference with the operatives), based on the assumption that by looking at the work through a reduced number of TV sets it would be possible to reproduce reality. However, video recording provides the opportunity for continuous and flexible viewing of operations: when it is used to continuously record the operations, it allows the measurement of durations, rates of allocation of resources, and interference between operations at a cost smaller than comparable continuous filming.

Provided that the expenses of the equipment and the crew of observers can be justified, time-lapse photography can be used to study individual activities. Its use for complete coverage of site operations does not seem to be

economical.

The methods of recording information reviewed in this chapter are not able to satisfy all the requirements for the analyses of work on building sites. Work study looks at the operation in isolation, work cycles is applicable only to the observation of cyclical operations, production cards produce a low level of detail, activity sampling is fundamentally inefficient, and it is difficult to justify why the time-lapse techniques prefer to look at the operations through camera lenses rather than personally. Nevertheless, activity sampling can be singled out as the most suitable for building sites, due to its low cost, flexibility, and almost complete coverage of the time spent at the work place or around the site. Imaginative forms of presentation of activity sampling data could make it possible to depict the interrelationships between operations. Its inefficiency (cost per observation and poor quality of the information provided) can be overcome by the observation of a great number of operatives or work places simultaneously, and by devising a much improved structuring of the categories of work deemed to be observable on site.

These two features are present in the Building Research Establishment Activity Analysis Package described in the next section. The remainder of this thesis shows how the analyses of data gathered by an activity sampling method with an improved structuring of the observable categories of work makes available a wealth of production-related information. Madden claimed that the analytical activity sampling information amassed by the Building Research Establishment lately is of an extent, variety, and detail which is thought to be unique in the world.

3.1.4 The Building Research Establishment Site Activity Analyses Package

The next six paragraphs were taken from the Building Research Establishment Internal Note No. 13/81 (Forbes-1981).

"In the site studies carried out by the BRE the need has generally been to determine time spent on tasks and the pattern of working - in time and in place - so that observations are required annotated in time-related operational and geographical terms. Because of the large amounts of data accumulated, automatic data processing techniques are essential. Therefore observations on site are recorded on special forms, suitably coded, which can be fed directly into an optical reader which transcribes the recordings onto magnetic tape in a form suitable for direct input to a computer.

Normally the BRE employs 2 observers full time on site and experience has shown that they can control up to 100 operatives by going around the site at hourly intervals. But observations made only twice a day, at random, could still give data of sufficient accuracy for many contractors requirements. Decreasing the number of observations by four increases the sampling error by two. Observations at this frequency should not prove an unreasonable expense in return for hard information on resource usage, the pattern of work on site, continuity of effort, performance of different gangs of subcontractors, and realistic measures of the effect of design on productivity. Some simulation studies at BRE of the results which can be obtained with this frequency of observation are showing this to be practicable.

The whole process of site analysis consists of three different phases. The first phase is concerned with the setting up of codes against which observations will be recorded. Two major families of codes are necessary: one defining the units to be constructed and the tasks considered to be observable on site, and another describing the operatives, their trades and skills.

The work to be sampled must be described in an hierarchical, or family-tree type of structure. At the top level there is only one object or parent (usually the site name) and the workings of the computer program require that there must be at least one object in each of the lower levels. The package allows the use of up to eight levels, including the top level. There is no limit to the number of objects in each lower level.

The relationship between the objects in the various levels of the hierarchical structure is "top down", which means that each level is defined in terms of components at the next lower level, until the bottom level is reached. The bottom level is an exception, since it is not necessary to state any relationship with the levels above. Because of this, it can be used to describe what the operative is doing at the moment of "snap" without reference to any other parameter; for example, the observer can record a man as "walking", without the necessity of specifying where he was walking.

The workforce is described in a similar way, with the package catering for a maximum of three characteristics of the operatives, for example, employer, trade, and skill (foreman, skilled, non-skilled, apprentice). Further classification is possible since each operative can be allocated a number in the range 1 to 9999, so that different ranges of numbers can be used to further subdivide the workforce".

The setting up of the site hierarchy is entirely the responsibility of the production analyst. It should be done in accordance with the objectives of the site analysis exercise. It is done before the start of work on site; early discussion on the definition of activities in Chapter Two showed that it is not always easy to define the site hierarchy so as to make sure that it will match the actual building progress on site. As a guide, the production analyst should try to define each operation as broadly as possible in order to encompass a significant proportion of work on site, while ensuring that it will be performed by only one building trade and occur at a unique period of time during construction. Small proportions of man-hours are relatively more inaccurate due to the principles of activity sampling; this inaccuracy can render useless the output tables produced by the Site Activity Analysis Package.

The analyst is usually faced with a dilemma. Better accuracy is achieved by aggregating activities, but later, in the analyses of the information, aggregated data will most certainly be associated with a variety of physical quantities of work done. Most of the possible analyses will require the

use of multi-regression techniques. The meaningfulness and accuracy of multi-regression parameters decrease with greater number of independent variables.

An example of the categorisation of work on site according to the hierarchical structure discussed above can be seen in the appendix to this thesis.

The second phase of the process of site analysis uses a package facility to check the consistency of observations: such errors as non-existent operatives, dates, daily working hours, and non-conformity to the codes previously set are detected by the program: the user can correct or delete such observations.

In the last phase, instructions are given to the computer in order to produce the desired printouts. The system currently available at the BRE is very flexible and allows the user to specify the parameters (headings) under which the data is to be presented. Each individual snap observation contains six basic pieces of information:

a) date;
b) hour;
c) observer number;
d) operative number;
e) geographical location (building unit: block, house, storey, etc.);
f) task (stage of work, operation, or activity).

Information contained in items "d", "e" and "f" are in fact represented by several codes arranged in the already mentioned hierarchical structure. For example, each site contains a number of blocks; each block contains a number of houses or storeys; each unit of construction requires several stages of work to be completed; each stage of work is made up of different operations, and all observable work on site can be recorded against a set of tasks (handling, working, being idle, walking, etc.).

The maximum total of 14 items of information (item "d" could contribute three different records, and items "e" and

"f" could together contribute up to eight different records) are compared in pairs, giving a combinatorial total of at least 90 different types of data tabulation. Moreover, it is possible to perform all these tabulations using a selected data bank; this data selection is again made using one of the basic pieces of information: it is possible, for example, to select data only for the carpenter trade, or for work performed in the morning. Almost every aspect of the allocation of man-hours on site can be analysed using specific formats of the output of the package.

The package output comprises tables where row and column headings are taken from the 6 basic pieces of information. At the user's choice, the tabulated values can be expressed in man-hours, man-days, percentages or averages. It is also possible to produce histograms.

Some tables are absolutely essential for any construction managerial system, like the ones aggregating the total number of man-hours spent on each house or stage of work; some other tables are useless due to the low level of detail and hence small accuracy they imply; some tables are useful under very specific circumstances, like when checking the performance of each individual observer on site.

Table 01 gives a simple breakdown of the total number of hours spent on the Ladygate Lane site, broken down at the level of stages of work and blocks. The information produced by this table can be used to estimate labour costs for each stage, to assess the stochastic variability in terms of man-hours required per stage per block, or to check if any improvement due to the learning phenomenon has occurred, once the block starting order is known.

Tables 02 and 03 depict the progress of work for the "wiring, conduit and boxes" operation on two different sites. On the first site, Ladygate Lane, the operation was performed as three different and separate sub-operations. On the second site, Pitcoudie 1, design was rationalized in order to allow one single visit by the electrical trade. Table 03 suggests that this was in part achieved. These types of tables are

TABLE 01

Weekly Allocation of Man-hours to the Stages of Work on the Ladygate Lane Site, Broken Down by Blocks.

BRE SITE ACTIVITY ANALYSIS PACKAGE

ROW SELECTION NUMBER 5 STAGE
COLUMN SELECTION NUMBER 3 BLOCK

CLASS CODE	STAGE	BLOCK 0	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B12	TOTAL
0		5504	65	77	168	75	64	105	233	69	95	140	670	7164
ST1	STRIP TOPSOIL		3	12	1	33	13	19	9	5	3	35	40	154
ST2	SET OUT		14	3	29	16	20	4	5	8	1	3	1	104
ST3	EXCAVATE		37	6	118	22	27	59	83	34	69	26	9	469
ST4	CONCRETE FOUNDATIONS		21	18	61	38	26	1	32	30	11	3	6	245
ST5	SHUTTERING		33	50	10	3	1	1	55				71	223
ST6	BRICK PADS		1	18	4	6	0		5			6		48
ST7	FOUNDATION WALLS		132	80	85	77	70	32	25	62		52	52	666
ST8	HARDCORE		94	74	100	32	64	42	129	18	66	46	25	689
ST9	REINFORCEMENT		4	3	6	10	4		36		3	4	5	76
ST10	FLOOR SLAB		60	20	65	25	50	24	15	25	6	15	60	362
ST11	SERVICES			8	16		18	5	54	14	17	1	4	138
ST13	GF PANELS		108	204	131	74	74	151	162	108	71	44	15	1143
ST14	BAND COURSE		4	64	12	3	5	32	7		1		1	128
ST15	FLOOR		104	173	136	109	98	127	193	121	59	119	38	1276
ST16	FF PANELS		123	256	195	163	91	78	183	140	73	80	36	1418
ST17	ROOF		65	138	140	112	131	108	150	68	92	90	28	1121
ST18	TILING		371	470	527	445	317	399	442	267	275	191	193	3800
ST19	SCAFFOLDING		154	151	226	158	149	131	123	98	109	121	336	1755
ST20	DOORS AND WINDOWS		595	818	848	627	510	927	1023	592	542	430	254	7164
ST21	BRICKWORK		308	252	360	181	272	235	294	181	259	140	1042	3524
ST23	PLASTERBOARD		361	487	702	460	405	476	716	410	348	432	115	4914
ST24	PLUMBING		272	384	414	448	252	463	466	299	356	240	87	3680
ST25	ELECTRICAL		269	397	300	234	342	167	505	193	208	195	46	3056
ST26	GAS		9	18	47	22		41	17	90	36	87	3	366
ST27	HEATING		188	194	331	272	296	388	355	284	264	137	46	2756
ST28	DECORATION		489	737	797	543	475	471	813	484	404	376	203	5793
ST29	GLAZING		17	16	18	10	17	9	5	21	11	13	71	203
ST30	FLOOR FINISHES		44	87	85	93	73	102	94	74	130	55	64	900
ST35	GARAGES		116	5	2	13		1		8	8	9	1519	1680
ST36	DRAINS		5	27	16	20	21	1	10	3	4	5	5342	5453
ST37	MAIN SERVICES				2		2		15				68	87
ST38	ROADWORKS			5	1					4	2	3	3277	3293
ST39	GARDENS		8	2	4	4	4	4		1	2		2589	2618
ST40	SITE ESTABLISHMENT		3	3	5	8	3	8	5	4	2	4	2308	2352
TOTAL:		5504	4076	5257	5953	4314	3898	4718	6155	3715	3504	3100	18621	68817

TABLE 02

Weekly Allocation of Man-hours to the Operation "Wiring, Conduit and Boxes", Broken down by Blocks (Ladygate Lane Site).

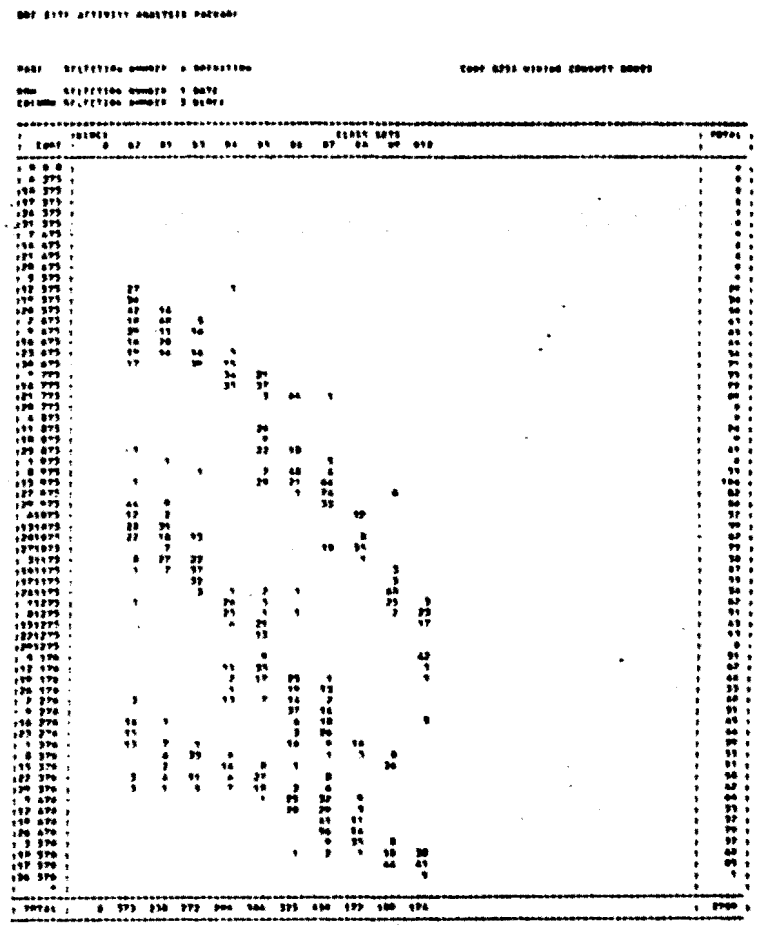
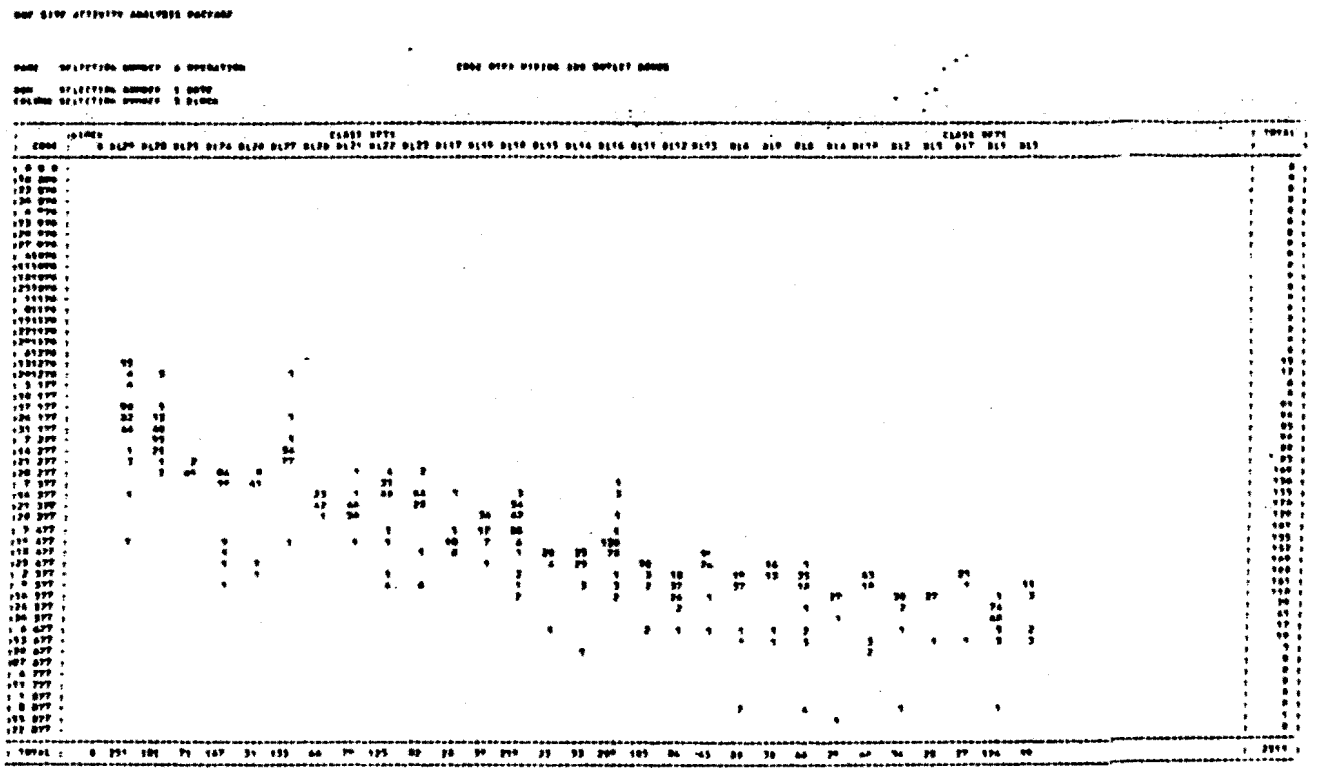


TABLE 03

Weekly Allocation of Man-hours to the Operation "Wiring and Outlet Boxes", Broken down by Blocks (Pitcoudie 1 Site)



especially suited for showing how long each operation took, the distribution of allocations over time, the actual sequence of work, and the continuity of effort.

Further important production-related information can be derived from the examination of tables using as one of the headings the lowest level in the hierarchy (tasks like, walking, idle, handling materials, cleaning up, preparatory work, etc.). For example, the examination of the daily allocation of man-hours on the three sites that constitute the data bank for this research work demonstrated that this allocation varied considerably during the day. Figure 01, taken from the study of the Ladygate Lane site, shows that the daily allocation of resources followed a trapezoidal curve, interrupted by tea and meal breaks. The labour effort was not deployed on a constant basis throughout the day. The majority of effort in the early morning period was devoted to materials handling and work preparation. Cleaning tools and the work place occupied a significant proportion of the allocation in the late afternoon. The morning period showed greater concentration of work than the afternoon period. Tea and meal breaks did not occur at sharply defined intervals.

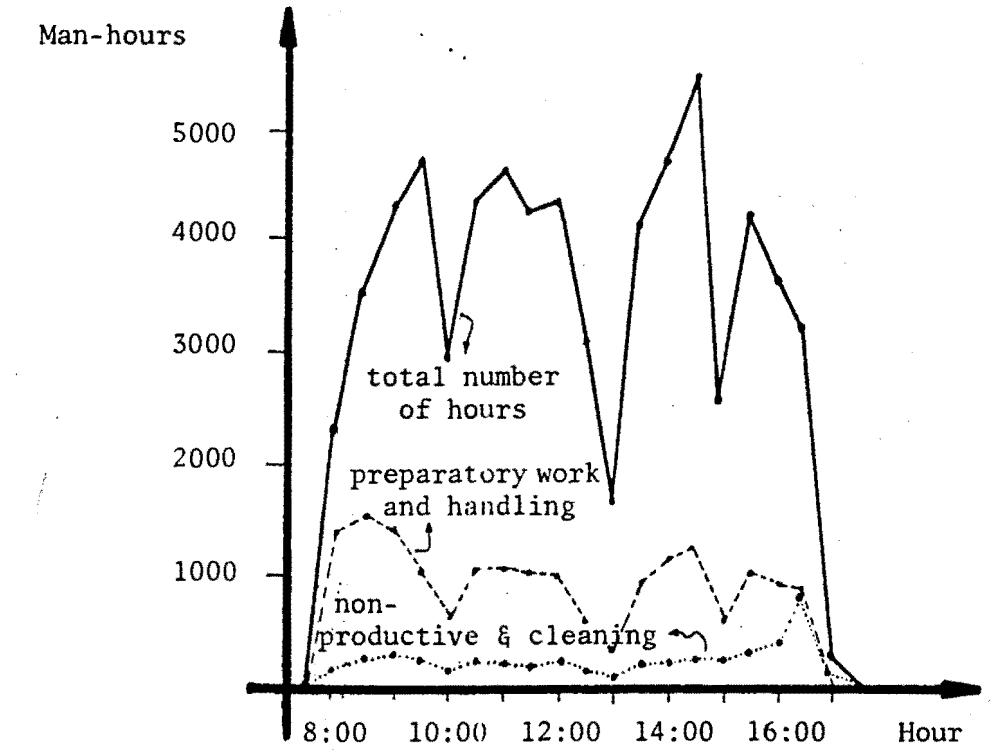
The building sites analysed during the course of this research work and the author's experience in using the Site Activity Analyses Package are described in the next sections.

3.2 The Collection of Data from the Three House Building Sites

3.2.1 Description of the Sites

3.2.1.1 The Ladygate Lane Site

The site layout (figure 02) provides a total of 35 houses, 36 flats, and 32 garages at a density of 150 persons per hectare. The 71 dwellings are arranged in 10 blocks as can be seen in figure 02 and table 04.



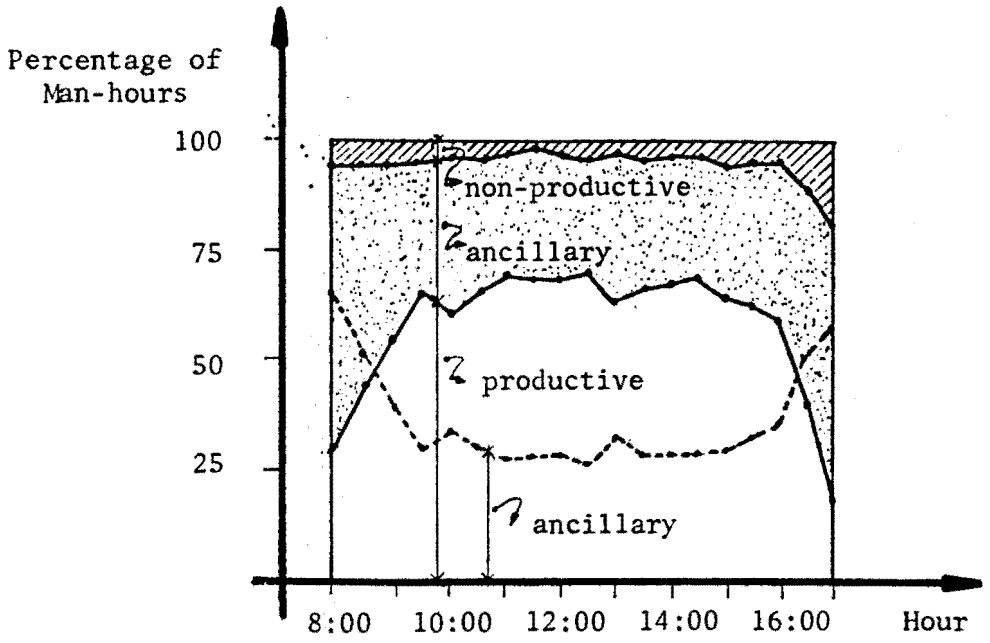


Figure 01

Distribution of Productive, Ancillary and Non-Productive Times During the Day, Ladygate Lane Site

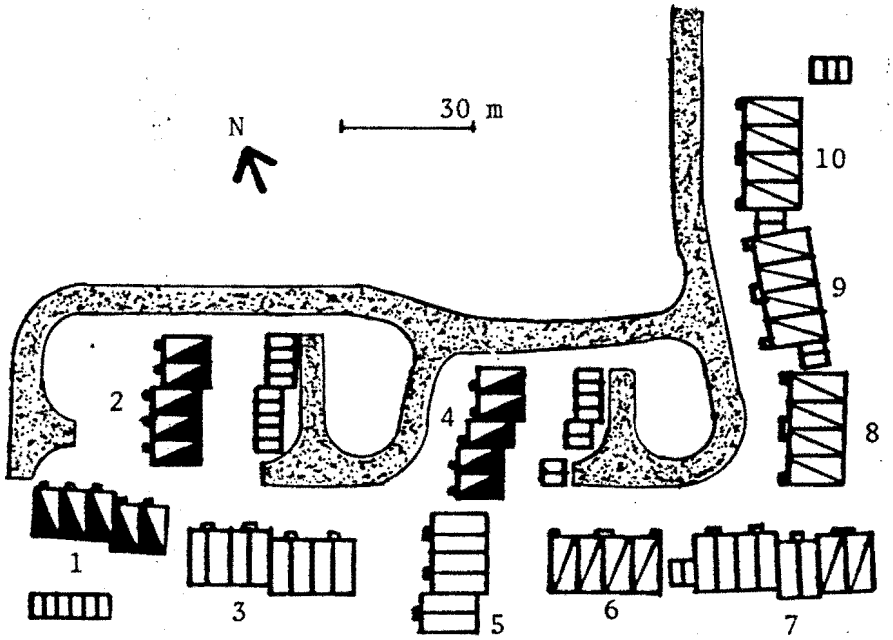


Figure 02

Ladygate Lane Site Layout and Dwelling Mix

TABLE 04

Ladygate Lane Dwelling Mix

and Total Internal Area of Blocks

Block	Number of Houses per Dwelling Type				Internal Area	Area of Porches	Total Internal Area + Porches
	2 person Area = 53.6 sq.m.		4 person Area = 75.6 sq.m.	5 person Area = 86.4 sq.m.	sq.m.	sq.m.	sq.m.
	Ground Floor	First Floor					
1				5	432	10	442
2				5	432	10	442
3			8		605	14	619
4				5	432	10	442
5			6		454	11	465
6	4	4			429	14	443
7	2	2	6		668	18	686
8	4	4			429	14	443
9	4	4			429	14	443
10	4	4			429	14	443
TOTAL	18	18	20	15	4739	129	4868

The 18 two-person ground-floor flats for old people have a living-dining room, working kitchen, bathroom, and a bedroom. The 18 two-person first-floor flats are reached by a shallow pitch private staircase from the front door at ground level; in addition to the accommodation provided for the ground-floor flat, there is a private balcony and a store room with window.

The 20 four-person houses have an interconnected dining kitchen and living room downstairs, and 2 double bedrooms, a separate bathroom, and WC upstairs. The 15 five-person houses have an interconnected dining kitchen and living room, and a WC downstairs. Upstairs there are 2 double bedrooms, one single bedroom, and a bathroom.

The construction is generally timber-framed panels with a brick outer skin on the ground-floor and concrete tile hanging on the first-floor. The timber roof is finished with concrete roof tiles. Plasterboard linings, plumbing, and electrical installations are conventional. The heating system is gas-fired, wall-mounted boilers with balanced flue outlets supplying pumped hot water to radiators in the ground-floor rooms of houses and in all rooms of flats. About half the blocks have foundations of conventional trench fill and brick-work. The remainder have special pad and precast beam foundat-ions.

Contacts with prospective tenders were made in order to integrate design and production methods. The Ladygate Lane site was an experimental project supported by the National Building Agency and monitored by the Building Research Establish-ment, with the intention of analysing possible savings due to a rationalised design.

Previous analyses by Forbes (1980:1) for this site indicated that:

- the concentration of effort on individual activities was smaller than for the Finchampstead Project, a similar site studies by the BRE (Forbes and Stjernsted);
- the sequence of work was from southwest to northeast, that is, from block No. 2 to No. 10;

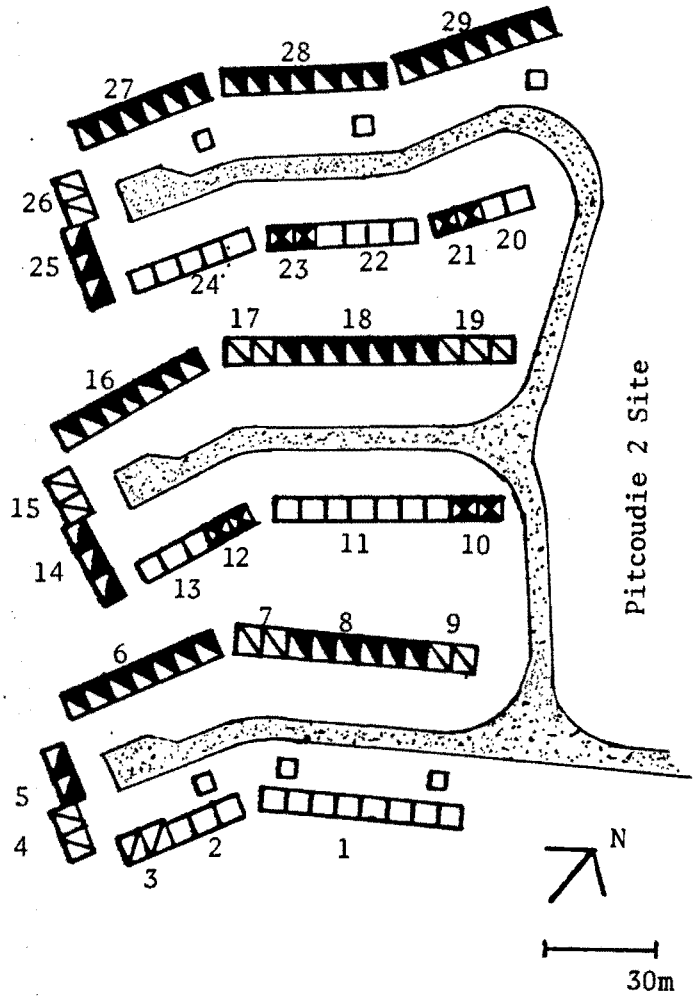
- the average number of man-hours per house was 970, comparing well with the national average for this type of construction of 1100 man-hours, quoted by Lemessany and Clapp. A total of 69,000 man-hours were spent on this site, with an average of 14 man-hours per sq. m. (not including the area of garages);
- non-productive time was 10%, a low figure, that probably reflected the adequacy of labour motivation and the spreading of work to the whole site. The majority of the work-force was subcontracted.

3.2.1.2 The Pitcoudie Project

Pitcoudie 1 and Pitcoudie 2 were projects designed by the Scottish Development Department in association with the National Building Agency. Their aim was to study possible savings of time and money by rationalizing the process of traditional house building construction. Pitcoudie 1 corresponds to the first phase of the project. Pitcoudie 2 corresponds to the second phase and it was built on a site adjacent to Pitcoudie 1. The 2 projects are similar, with minor differences in design and construction technique. The internal lay-out of the various dwelling types are identical and so are the internal areas of construction. A complete description of the Pitcoudie 2 site is given in the appendix. This section reviews briefly some of the characteristics of the individual sites.

3.2.1.2.1 The Pitcoudie 1 Site

The site provides 112 dwellings divided into 17 two-person, 32 four-person, 55 five-person, and 8 seven-person houses, with a density of 157 persons per hectare. Dwellings are arranged in 29 blocks as can be seen in figure 03 and table 05. Twelve isolated garages are also included. It is worth pointing out that sets of houses of different dwelling



2 Persons House - South Aspect
2 Persons House - North Aspect
4 Persons House
5 Persons House - South Aspect
5 Persons House - North Aspect
7 Persons House
Garage

Figure 03

Pitcoudie 1 Site Layout and Dwelling Mix

TABLE 05

PITCOUDIE 1 Dwelling Mix

and Total Internal Area of Blocks

Block	Number of Houses per Dwelling Type				Total Internal Area sq.m.
	2 person Area = 49.5 sq.m.	4 person Area = 79.2 sq.m.	5 person Area = 118.8 sq.m.	7 person Area = 118.8 sq.m.	
1		8			634
2		3			238
3	2				99
4	2				99
5			2		180
6			7		630
7	2				99
8			6		540
9	2				99
10				2	238
11		7			554
12				2	238
13		3			238
14			3		270
15	2				99
16			7		630
17	2				99
18			7		630
19	3				149
20		2			158
21				2	238
22		4			317
23				2	238
24		5			396
25			3		270
26	2				99
27			6		540
28			7		630
29			7		630
TOTAL	17	32	55	8	9279

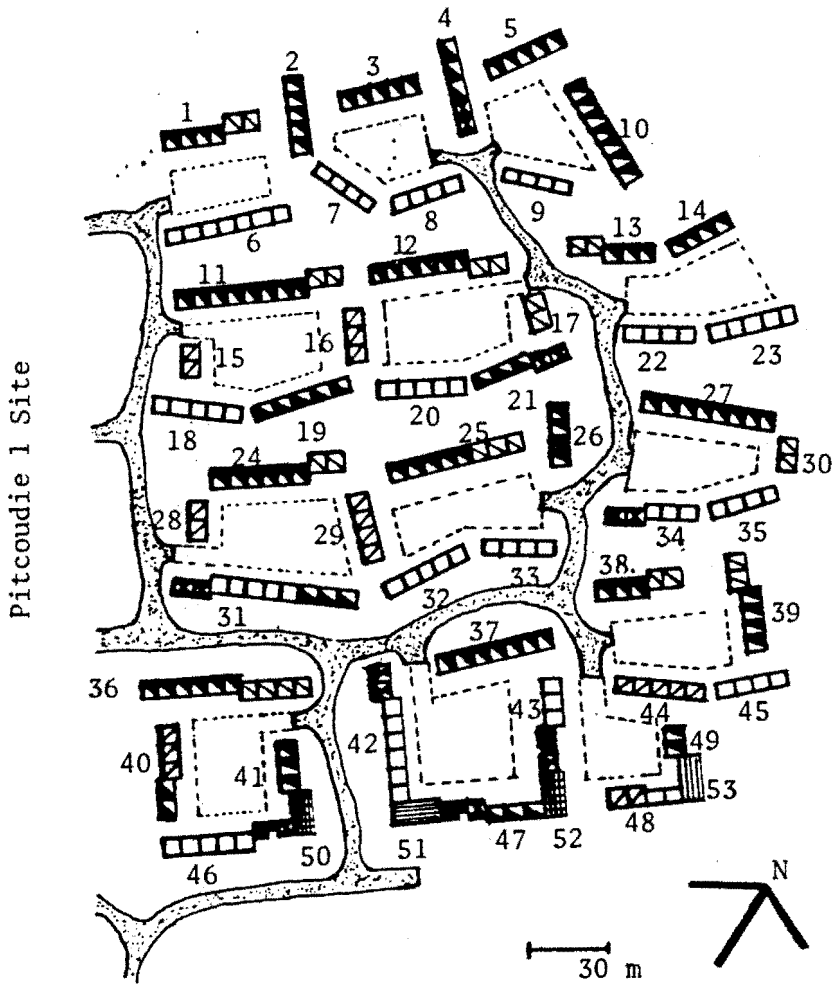
types are defined as different blocks, even if contained inside the same external walls.

Construction is similar for all types of houses, featuring not only identical components but also unified site assemblies. External walls are in a rendered single skin of autoclaved concrete blocks with internal separated lining. The ground-floor slab is finished smooth, without a screed. Electrical and plumbing layouts have been designed to lessen the number of visits to each house by the fitters. Foundations are of the conventional trench fill method, with underbuilding in a thick single block. Intermediate floors have timber joists resting on metal supports fixed to the blockwork walls. Internal partitions use the Patent Plasterboard System with holes for rapid wiring of sockets and switches.

A brief analysis by the author of some of the tables produced for this site showed that a total of 109,000 man-hours were spent, giving an average of 970 man-hours per dwelling, which compares well with the average of 1150 man-hours found by Fraser and Evans for this type of houses in Scotland. An average of 11.7 man-hours per sq. m. was found, not including the area of garages. Non-productive time was around 35%, with a particularly high percentage of non-productive time due to weather (7.8%). The planned sequence of work was from northeast to southwest, that is, from block No. 29 to block No. 1.

3.2.1.2.2 The Pitcoudie 2 Site

This is the largest of the 3 sites, with a total of 283 dwellings, comprising 46 two-person, 79 four-person, 114 five-person, 13 seven-person, and 3 nine-person houses, apart from 4 blocks of 3 and 4 storeys containing 28 flats that were not considered in this research work. Houses and flats are arranged in 53 blocks in accordance with figure 04 and table 06. In contrast to Pitcoudie 1, blocks include non-similar types of houses.



2 Persons House - South Aspect
2 Persons House - North Aspect
4 Persons House
5 Persons House - South Aspect
5 Persons House - North Aspect
7 Persons House
9 Persons House
3 Storey Flats
4 Storey Flats

Figure 04

Pitcoudie 2 Site Layout and Dwelling Mix

TABLE 06

PITCOUDIE 2 Dwelling Mix

and Total Internal Area of Blocks

Block	Number of Houses per Dwelling Type					Total Internal Area sq. m.
	2 Person Area 49.5 sq. m.	4 Person Area 79.2 sq. m.	5 Person Area 90.0 sq. m.	7 Person Area 118.8 sq. m.	9 Person Area 142.2 sq. m.	
Housing Blocks						
1	2		4			459
2			5			450
3			5			450
4			3	2		508
5			5			450
6		7				554
7		4				317
8		4				317
9		4				317
10			7			630
11	2		8			819
12	2		6			639
13	2		3			369
14			4			360
15	2					99
16	3					148
17	2					99
18		5				396
19			5			450
20		5				396
21			3	2		508
22		4				317
23		5				396
24	2		6			639
25	3		5			599
26			4			360
27			8			720
28	2					99
29	4					198
30	2					99
31		5	3	2		904
32		5				396
33		4				317
34		3		2		475
35		4				317
36	4		6			738
37			7			630
38	2		3			369
39	2		4			459
40	3		2			328
41			3			270
42		6		2		713
43		3		1	1	499
44	5					247
45		4				317
46		5		1	1	657
47			3	1	1	531
48	2	2				257
49			2			180
Number of Houses	46	79	114	13	3	255 Houses
Total area of Housing Blocks						20.766
Flats						
50	4*	4*				604
51	3*	3*				453
52	4*	4*				604
53	3*	3*				453
Number of Flats	14*	14*				28 Flats
Total area of Flats						2.114
Total No. of Units	60	93	114	13	3	283
Total area of the Site						22.880

* 2 person and 4 person flats have a different area than 2 person and 4 person houses.

Pitcoudie 2 was a continuation of the Pitcoudie 1 scheme with a bigger scale of operations. The major difference is the change back to traditional cavity-wall construction, with the outer face in brickwork and the inner face in blockwork and thermal lining board. Pitcoudie 2 also differs from Pitcoudie 1 in the bigger variety of housing types: 3 nine-person houses are added to the dwelling mix; dwellings especially designed for the disabled are included amongst the seven-person houses; the placing of windows and doors on four-person and five-person houses is used to break design monotony.

Analyses by the author indicated that a total of 287,000 man-hours were used, giving an average of 1013 man-hours per dwelling, which again compares well with the average of 1150 man-hours given by Fraser and Evans. Labour consumption was 12.5 man-hours per sq. m. Non-productive time was 28% with 7.4% due to bad weather. As for Pitcoudie 1, this is a high figure and could be explained by the harsh weather conditions in Scotland. The total area of the site was made available to the contractor in 2 phases. The first area comprises blocks No. 1, 6, 11, 15, 18, 19, 24, 28, 29, and 31; the second area contains the rest of the blocks. The sequence of work followed a complicated pattern and will be examined in Chapter Four.

3.2.2 Data Retrieval - Objectives and Level of Detail

Data from these three building sites was readily available at the Building Research Establishment. This research work intended to use information obtained from these sites to analyse the following production characteristics of activities:

a) stochastic duration;
b) stochastic resource consumption;
c) progress pattern (rate of progress);
d) precedence;
e) sequence of work.

The family of tables with time periods (months, weeks, or days) as row headings and tasks (stages of work or operations) as column headings was found particularly useful, since it provided data by which to examine the 5 items above.

First of all, it was necessary to define the level of detail to which the tables were to be built. Each block contained a varying number of houses. Each stage of work was further subdivided into operations like:

stage of work	operations
electrical installation	- wiring and conduits; - socket outlets, switches, and fittings; - conduit and meters; - apportionable to stage only (heading used when it was not possible to allocate the task being performed to one of the 3 preceding operations)

Operations were further split into elemental activities like handling, cleaning tools, measuring, remedial work, working productively at the task itself, etc. With a view to reducing the bulk of computer printouts, establishing a level of detail likely to be meaningful to management feedback information systems, and bearing in mind that the accuracy of any activity sampling method increases with data aggregation, it was decided to build tables at the level of blocks instead houses, weeks instead of days or months, and stages instead of operations.

Observations were not available at the level of houses for the Ladygate Lane site. Some preliminary tables were obtained at the level of houses for the Pitcoudie 1 and Pitcoudie 2 sites, but the small number of man-hours per stage per house did not encourage further investigation at this level of breakdown. Similarly, preliminary tables for the Ladygate Lane site were at the level of blocks, days, and operations. The need for more statistically significant allocations of

man-hours called for the aggregation of time at the level of weeks. It was decided, though, to maintain the operations level of breakdown, in order to investigate if this would lead to conclusions different from those for the stage of work level of breakdown in Pictoudie 1 and 2.

There was also the possibility of constructing the tables using a particular set of elemental tasks; man-hours presented in each table would refer only to handling, truly productive work ("making the building grow"), etc. It was decided, however, to use the aggregated value of all elemental tasks. As a result, man-hours recorded against each pair of row and column headings contained productive, ancillary, and non-productive time.

3.2.3 The Suitability of the Data for the proposed Research Work

The suitability of the data for the research work was appraised after the activity sampling data was retrieved and the tables produced. The opportunity to examine activity sampling at this level of detail was unique and not available elsewhere; however, some problems were noted, stemming from the areas discussed below.

3.2.3.1 The Shortcomings of the Site Activity Analyses Package Output

In the past the BRE has used activity sampling computer programs on a specific basis, tailoring each program to the especial requirements of each site and the research work being carried out. This new Site Activity Analysis Package was intended as a general package, applicable to any foreseeable size and type of building site.

A rather generous layout was devised in order to simplify the commands for creating the printouts; for example,

man-hours presented in the tables can vary from 0 to 9999, which implies that a maximum of 18 columns are produced in each computer page. Similarly, not more than 30 rows will appear per page. The consequence of this decision is that computer printouts are in general bulky, and it is necessary to do a lot of clerical work before the tables can be properly analysed. For example, the largest of the 3 sites, Pitcoudie 2, involved 42 stages of work and 53 blocks. The whole work on site took 94 weeks to be completed. The author produced one table giving weeks as row headings and stages of work as column headings for each of the 53 blocks. The total number of computer pages output was:

94 weeks at a maximum of 32 weeks/page	=	3 pages
42 stages at a maximum of 18 stages/page	=	3 pages
Total number of pages = 53 blocks * 3 * 3	=	477 pages

If an analysis in terms of days rather than weeks was chosen, the number of pages would be 7 * 477 = 3239 pages.

All the 477 pages were separated, cut, and glued together in order to produce a clear picture of the progress of work in each block. Moreover, reductions using xerox or photography might be necessary in order to arrive at workable sizes of tables, with inevitable losses in printing clarity.

A second problem with the output of the package is that whatever rows and columns are chosen, the information conveyed by the tables is always man-hours, man-days, percentages of man-hours, or histograms representing one of these values. There is no facility to include a third variable in the tables. For example, if it is intended to follow the movement of operatives from block to block during the period of construction, 3 variables are involved: time, location, and operatives. Several tables would be required to conduct this analysis, one per block, per operative, or per time period, with rows and columns corresponding to the remaining 2 variables. It is not possible to include the 3 variables in one unique 2 dimensional table.

3.2.3.2 The Proportion of Work allocated to Individual Blocks

This research work aimed to study durations and the allocation of resources in connection with the repetitive work involved in the construction of each block: the non-repetitive part of the job related to site works (drainage, gardens, landscaping, garages, road works, etc.) was of only passing interest.

Unexpectedly, it was found that on average only 50% of the observations were related to work on individual construction units. Site works took an average of 25% of the total number of man-hours, while the remaining 25% were neither related to geographical locations (blocks or site works) nor to specific stages. This high proportion of non-identified consumption of labour resources was probably related to non-productive time outside the working place (idle around the site, walking, interruptions due to rain, etc.). The Ladygate Lane site, with the lowest non-productive time, showed the lowest proportion of non-identified work, while the Pitcoudie 1, with the highest non-productive time, produced the highest proportion for this parameter. This could also reflect difficulties experienced by the observers in classifying work according to the site hierarchy previously selected.

The high proportion of time spent in connection with site works reaffirmed the importance of programming and costing this part of the job. This view was also expressed by Madden, after finding that site works represented nearly 40% of the total number of hours needed to build a house in the Finchampstedt Project.

The fact that only 50% of the observations were associated with block-related stages of work should not be viewed as detrimental to the use of activity sampling, or as a shortcoming of the particular implementation of this data recording tool on the 3 sites. To the contrary, this would recommend the use of activity sampling over work study. However, the low proportion of man-hours consumed by the repetitive activities implies that the accuracy of the data was less than expected, as will be explained in the next section.

3.2.3.3 The Statistical Accuracy of the Data

Only the 500 block-related man-hours of the 1000 man-hour total for each house were of direct interest for this research work. The actual number of hours taken by the block-related work would be the key factor to decide the accuracy required for the activity sampling exercise. The smaller than expected proportion of work under this category means that the number of observations should have been greater. For each site an average of 20 to 25 block-related stages were defined, thus giving an average use of resources per block per stage of around 25 man-hours. The distribution of man-hours to the various stages showed a typical Pareto's curve, with the 20% more important stages taking 50% of the resources. Nevertheless, the largest stage in each house took less than 100 man-hours, that is, less than 10% of the total number of hours needed to build a house.

The accuracy associated with 25 man-hours is approximately ± 40% (i.e. a range of 15 to 35 man-hours), while the accuracy for 100 man-hours is ± 20% (i.e. a range of 80 to 120 man-hours). Tables were done at the level of blocks rather than houses, in order to overcome these low accuracies, but the results were not much better. The Ladygate Lane site showed an average of 200 man-hours per block per stage, while the Pitcoudie 1 and 2 sites had an average of 100 man-hours. Due to the mechanics of the accuracy formula, a twofold increase in the number of hours allocated, for example from 100 to 200 man-hours, produces an increase in accuracy of only a quarter (from ± 20% for 100 man-hours to ± 15% for 200 man-hours).

The low accuracy even at the level of blocks led to a further aggregation: the average total allocation of resources to the stages for all blocks was 2000 man-hours for the Ladygate Lane site, 2600 man-hours for the Pitcoudie 1, and 6000 man-hours for the Pitcoudie 2 site, with respective accuracies of ± 3.6%, ± 3.9%, and ± 2.6%.

These accuracy values were obtained through the use of equation 4. The number of observations was taken as the

total number of hours spent on site for the Pitcoudie 1 and 2 sites, and as the total number of hours multiplied by 1.5 for the Ladygate Lane site. On the former sites, observations were done at hourly intervals; on the latter, observation rounds took only 40 minutes. The use of these values for the total number of observations is an overestimate of the true number of occasions when the activities, operatives, or construction units were observable.

The argument behind this assertion is complicated and can be best explained through the use of an example. Consider the calculation of the accuracy for the number of hours worked by a particular operative: he would not have had the chance of being spotted in every observation throughout the construction duration: during several weeks his trade may not even have been present on site. Similar arguments can be extended to the calculation of the accuracy related to the work content of activities or blocks. It should be realised that the tour approach to activity sampling corresponds to various theoretically independent studies conducted simultaneously. The overestimation of "n" (the total number of observations) leads to a decrease in the apparent probability of occurrence of each category of work and consequently to smaller accuracy. The correction of this bias is not easy, because it would be necessary to quantify the true number of observations for every type of output table to be produced by the package. Moreover, a study by the author showed that even if the true number of observations for the 3 sites is 10 times less than the total number of man-hours (total number of observations), no improvement in accuracy is noted for allocations smaller than 4000 man-hours.

3.2.3.4 Other Sources of Inaccuracy and Bias

The statistical accuracy is not the only source of possible errors in the analysis of activity sampling data. It is necessary also to investigate the reliability of data as far as the performance of observers and the cooperation of the operatives is concerned.

The author used tables at the level of operations rather than stages for the Ladygate Lane site. As already mentioned, each stage was formed by a group of operations plus a general category "apportionable to stage only": this category was used by the observer whenever he reckoned that the task being performed was connected with the stage, but he was unable to further classify it as one of the stage-related operations. Approximately 7% of the total work for the Ladygate Lane site was classified under this heading. The pattern of allocations reflected the uncertainties of the observer during the initial periods of the activity sampling exercise: almost the majority of observations were assigned to this category for the stages and blocks initially carried out on site. A careful reassignment of such observations was undertaken by the author, in order to make it possible to analyse these initial operations.

Indications of other possible sources of inaccuracy and bias were not available. There is nothing to suggest that their effect was significant. In particular, the observers for the Pitcoudie 2 site provided a very well organized and comprehensive report on events on site, which led the author to believe that observations were made with great care.

3.2.3.5 Physical Differences Within and Between Sites

The physical differences within and between sites were seen as potential difficulties for the analyses of the data. It is always desirable to have as many repetitions as possible of identical experiments from which to draw conclusions. This is an ideal situation: the research worker in the area of building management must content himself with whatever data might be available.

Sites were not directly comparable due to the different rationalized technologies employed in the Ladygate Lane and Pitcoudie projects, and the different site hierarchies used for activity sampling. For example, the substructure

work in Ladygate Lane comprised 11 operations, while only 2 stages of work were used to record this type of work for the Pitcoudie 2 Site; observations started late on the Pitcoudie 1 site and substructure was not recorded.

Total area of construction and total consumption of labour resources were in a 4:1 ratio between the Pitcoudie 2 and the Ladygate Lane site; the number of blocks was in a 5:1 ratio, and the number of dwellings in a 4:1 ratio. Non-productive time was at its lowest in Ladygate Lane at 10%, and at its highest in Pitcoudie 1 at 35%: non-productive time due to bad weather alone in Pitcoudie 1 and 2 was almost as high as the total non-productive time in Ladygate Lane. Houses were smaller in Ladygate Lane, with an average of 63 sq. m. per dwelling, against an average of 82 sq. m. in the Pitcoudie project. The area per block was 487 sq. m. in Ladygate Lane, against 320 and 424 sq. m. in Pitcoudie 1 and 2. This reflects the fact that Ladygate Lane had more houses per block (an average of 7 houses) than Pitcoudie 1 (4 houses) and Pitcoudie 2 (5 houses). Consequently, the number of hours observed per block was also different, with 6880 man-hours per block in Ladygate Lane, 3700 man-hours in Pitcoudie 1 and 5400 man-hours in Pitcoudie 2. The average number of hours spent per stage (operation) per block was also different, with an average of 200 man-hours for Ladygate and 100 man-hours for Pitcoudie 1 and 2.

Ladygate Lane was more homogeneous in terms of the areas of blocks; the areas of the 10 blocks produced a coefficient of variation of 18%. It is interesting to note that the average coefficient of variation for the allocation of resources to the operations of this site was around 40%, that is, the allocation of resources was more variable than the physical quantities of work (similar results were reported by Reiners and Broughton). The area of blocks on the 2 other sites was much more variable, with a coefficient of variation of 45% for Pitcoudie 1, and 65% for Pitcoudie 2: these values are of the same magnitude as the average coefficients of variation for the resource usage by the stages of work; thus, nothing can be

said, a priori, about the influence of the physical size of blocks in the variability of resource usage.

Man-hours per sq. m. were significantly higher in Ladygate Lane (14.1 man-hours per sq. m.) than in Pitcoudie 1 and 2 (11.7 and 12.5 man-hours per sq. m.), probably due to the fact that the site was smaller. Nonetheless, as the average area of dwellings was smaller in Ladygate Lane, the number of man-hours required per house was similar.

Other common features were: the average number of hours per house similarly better (12 to 16%) than national averages published elsewhere; the average number of hours per stage (operation) per house; the maximum number of hours per stage per house; the distribution of man-hours from the largest to the smallest stage; and the proportion of block-related work to site related work.

On balance, the differences between sites indicated that inter-site comparisons would probably not be profitable. The differences in physical size within each site (see tables 04, 05 and 06) called for an analysis in terms of average results. It was not possible to follow Fine's suggestion (1977:2) to ignore the differences in physical quantities of work in different blocks of house building construction, due to their small influence on the variability of resource usage and durations: examination of the data showed that smaller resource usage was associated with smaller blocks.

3.2.3.6 Discussion

The direct cost of maintaining the observers on site was approximately 9%, 4%, and 3% of the total labour bill for the Ladygate Lane, Pitcoudie 1, and Pitcoudie 2 sites, respectively. This cost is thought to be high in the light of the accuracy achieved for the recording of work in individual stages and blocks. A smaller number of observation rounds per day would have resulted in smaller costs at the expense

of even lower accuracy. However, this reduction in cost is possible if observers are taken from the present building management team, without the burden of this extra administrative involvement affecting their usual activities.

The benefits of in-depth and costly analyses of the progress of work accrue from the accurate knowledge of how money is spent on site at a low level of detail. If activity sampling accuracy can only be achieved in practical terms by data aggregation, it could well be that simplified techniques, like the analyses of the contractor pay-roll, would be able to provide the required information, at the same level of detail, but at a lower cost.

This cost/benefit discussion has no special significance in a research environment. Concern with the accuracy of the data was overlooked by the author, because the observational effort expended was considered as large as it could possibly be in practical terms. More immediate challenges to the suitability of the data were posed by the shortcomings of the package printouts and the differences of block size within each site: it was not possible to derive information by just inspecting the tables. Moreover, certain analyses were virtually impossible to carry out. For example, the BRE was forced to use a photographic technique to analyse the precedence relationship between operations: the computer printouts for each operation were reproduced on a translucent sheet of plastic and superimposed one on the top of the other.

The author has simplified the analysis of the data by creating a number of computer programs to drive the plotting facilities at the research center. The programs were especially developed to make it easier to compare a greater number of variables on the same sheet of paper, mainly for the comparison of the progress of work of different stages. The information made available by the Site Activity Analysis Package is rearranged by the user on an interactive basis and displayed in the form of graphical output, using either Video Display Unit terminals or Calcomp hard copy plotters.

The next chapter describes the set of computer programs developed during the course of this research work, and puts forward some tentative conclusions based solely on the qualitative evidence stemming from the graphs.

CHAPTER FOUR

GRAPHICAL ANALYSES OF THE DURATION OF ACTIVITIES, THEIR PRECEDENCE, SEQUENCE OF WORK AND RATE OF RESOURCE ALLOCATION

4.1 Generalities

Programs developed for the graphical analyses are briefly described, graphical output is presented, and the major findings that stem from each graph are discussed. A complete documentation of each program, comprising the Fortran program itself, input files, and a graphical example, is available from the author.

The majority of examples are taken from the largest site, Pitcoudie 2. The discussion for programs and graphs refer to this site, unless otherwise stated. The same type of graphs were produced for the 3 sites and the following examples are representative of what was found in the 3 separate studies conducted. Conclusions presented in the last section of this chapter are based on the totality of graphs produced for the 3 sites.

The graphs for Pitcoudie 1 and 2 are based on information aggregated at the level of stages of work. Some conclusions taken from the graphs may be criticised because the lower level of detail (operations) was not investigated. However, analyses were carried out at the level of operations for the Ladygate Lane site without significantly different results.

The production tables obtained from the Building Research Establishment contain both productive and non-productive allocations of man-hours. The graphs presented in this report can be redrawn using only productive hours, if so desired.

4.2 Graphical Software

4.2.1 Program "Block Bar Chart"

Information obtained from the Building Research Establishment was in the form of tables showing weeks as the row headings, stages of work as the column headings, and man-hours as the tabulated values, one table for each of the 53 blocks on the Pitcoudie 2 site. This program simply plots the information contained in these tables; the program output is a graphical representation of the tables used as input. Stages of work are arranged in a bar chart format. Only stages 1 to 25 were included; the remaining stages were related to external work.

Weekly totals of man-hours allocated per stage per block are transformed into "colour densities" by the use of the subroutine "Call Thick" (see Carderbank and Prior). This subroutine draws n-1 parallel lines alongside a central line; the length of the lines drawn corresponds to one week of work on site; the value of "n" is given as a parameter for the subroutine; the greater the number of parallel lines drawn the wider and apparently the more colourful becomes the rectangle representing the number of weekly man-hours allocated to the stage of work; a suitable scale is chosen to relate man-hours to colour densities, for example:

Range of man-hours	n	Number of parallel lines drawn
From 1 to less than 5 man-hours	1	1
From 5 to less than 21 man-hours	2	3
From 21 to less than 41 man-hours	3	5
From 41 to less than 81 man-hours	4	7
From 81 to less than 121 man-hours	5	9
More than 120 man-hours	6	11

This scale corresponds roughly to half a man-day, half a man-week, one man-week, 2 man-weeks, up to more than 3 man-weeks' work. Any scale can be rapidly implemented in the program.

Figures 05 is an example of the graphical output produced by this program. The figure conveys a more concise and clearer image of the progress of work than the printed output tables. Information can be analysed in terms of stages of work duration, technical precedence, and weekly intensity of work. For example, the stage "decoration" took nearly 18 weeks to be completed in block 11, and was done in parallel with stages "doors", "joinery", and "stairs".

Four different periods of work can be identified in figure 05. The first one corresponds to substructure (foundations, substructure, and ground-floor concrete slab); the second one relates to what can best be described as building carcassing (first, second and third-storey superstructures, floors, roof carcassing, and roof covering); after that, only the stage dry-linings was carried out; near the completion of this stage, the finishing operations were started, including services (plumbing, heating, and electrical work), woodwork (doors, joinery, and stairs) and decoration. The possibility of dividing the construction process into 4 broad areas is further investigated in the next program.

4.2.2 Program "General Progress Pattern"

This program allows the simultaneous plotting of any number of stages from any number of blocks. Different colours are assigned to each stage of work (up to a maximum of 4 colours - black, red, green, and blue - in accordance with the Calcomp 1012 plotter device). Weekly allocations of man-hours per stage per block are represented by colour densities according to a user selected convention. Different ranges of man-hours allocation were associated with different parameters "n" of the subroutine Call Thick, exactly as in the preceding program. The convention used in figure 06 was:

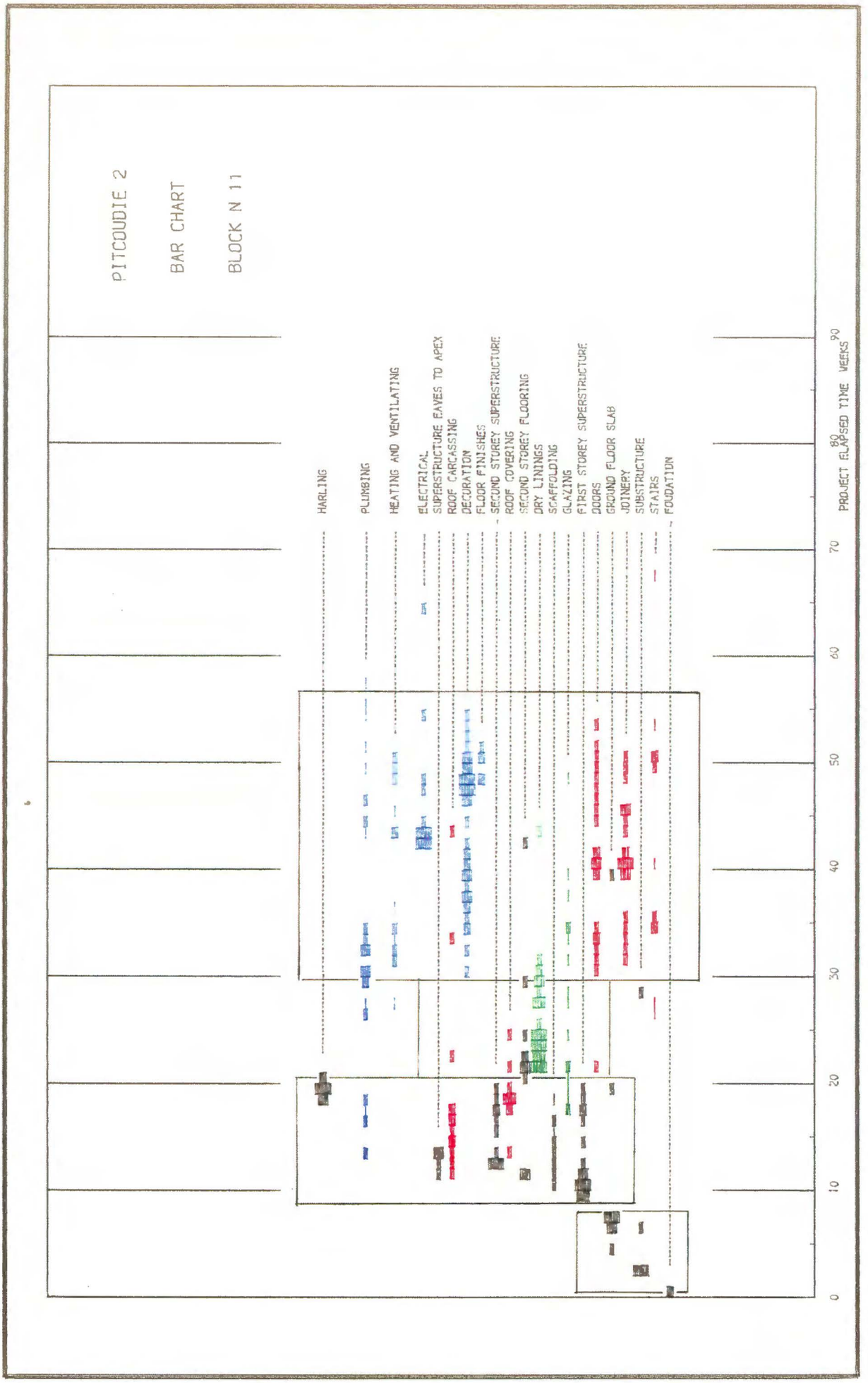

PITCOUDIE 2
BAR CHART
BLOCK N 11
HARLING
PLUMBING
HEATING AND VENTILATING
ELECTRICAL
SUPERSTRUCTURE EAVES TO APEX
ROOF CARCASSING
DECORATION
FLOOR FINISHES
SECOND STOREY SUPERSTRUCTURE
ROOF COVERING
SECOND STOREY FLOORING
DRY LININGS
SCAFFOLDING
GLAZING
FIRST STOREY SUPERSTRUCTURE
DOORS
GROUND FLOOR SLAB
JOINERY
SUBSTRUCTURE
STAIRS
FOUDATION
0
10
20
30
40
50
60
70
80
90
PROJECT ELAPSED TIME WEEKS

Figure 05

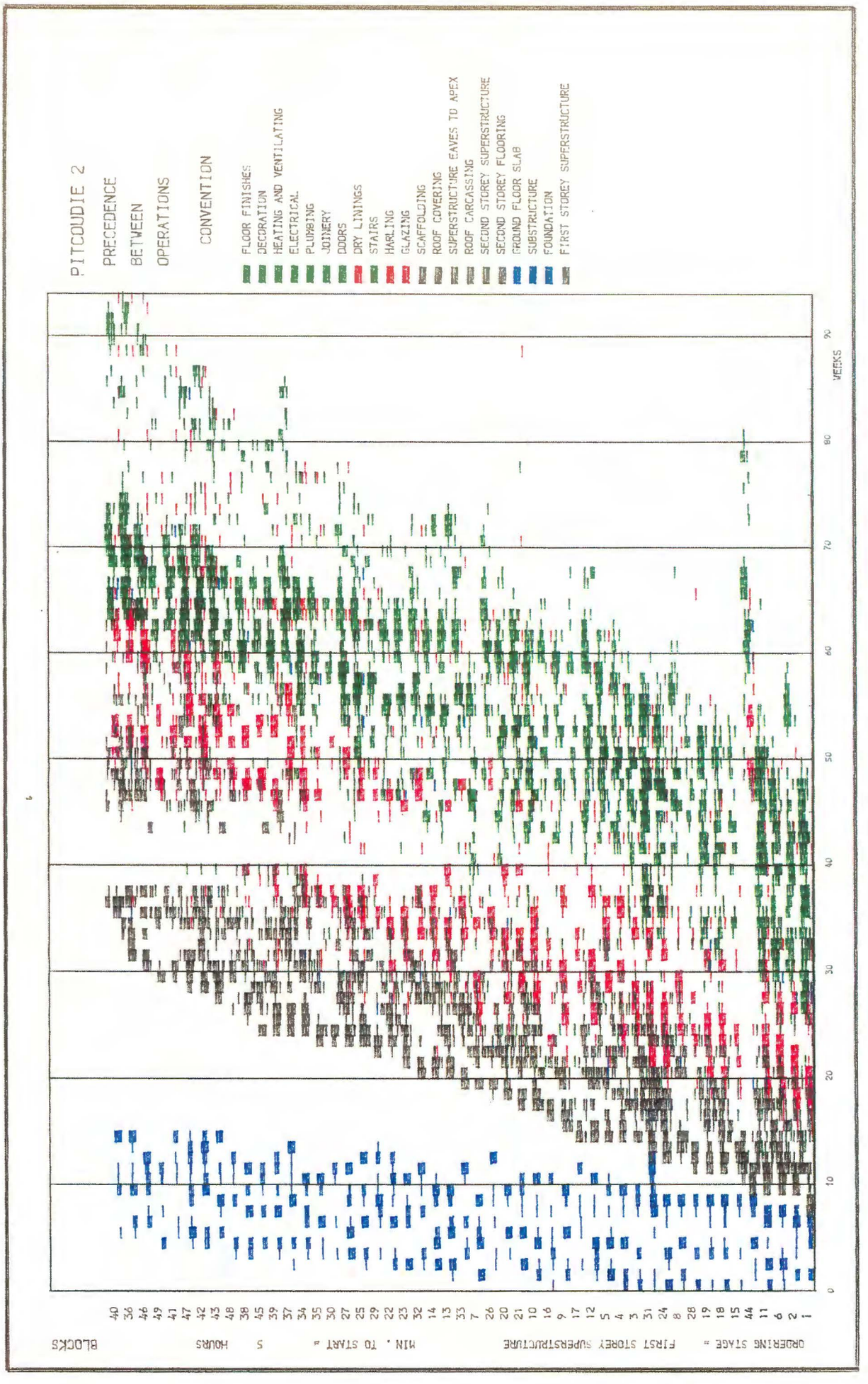


FIG. 22

Figure 06

Range of man-hours	Parameter for the subroutine	Number of parallel lines drawn
From 1 to 20 man-hours	1	1
From 21 to 40 man-hours	2	3
More than 41 man-hours	3	5

This graph corroborates the contention that the stages of work were performed in 4 different groups with respect to time. Various combinations of colour assignments to the stages of work were tried but the clearest picture emerged with the colour convention appearing in the right hand side of figure 06.

It is worth noting that:

- the stages of work foundation, substructure, and ground-floor slab were performed at a much quicker pace than the others;
- the stages of work corresponding to carcassing and dry-linings were interrupted by holidays between the 40th and 45th week, but the finishing stages were not so interrupted;
- block No. 44 did not follow the building sequence after the carcassing period;
- the y axis gives an approximate order for the starts and completions of the stages of work.

In fact, the y axis for this figure was organized according to the starting order observed for the stage first-storey superstructure. This is not to say that all stages of work had the same starting order as the first-storey superstructure. Any stage of work could have been used to organize the y axis.

The main feature of this type of graph is its capability of conveying at a glance the amount of interference between stages of work and the production characteristics (duration, precedence, and intensity of work) of these newly identified groups of stages like substructure, carcassing, etc.

4.2.3 Program "Site Bar Chart"

The basic idea behind the program "Site Bar Chart" was to obtain a pictorial representation of the average duration of each stage, its precedence relationships, and the intensity of effort by the operatives, that is, an average bar chart for a number of blocks.

The program superimposes any number of graphs produced by program "Block Bar Chart". This is not straightforward because each block had different total durations and different durations of the stages of work; for example, some stages of work took much longer for some blocks than for others simply because they were interrupted by holidays. Superimposition requires the bar charts of each block to be as similar as possible with respect to time.

From the analyses of graphs produced by the previous programs it became clear that it was possible to differentiate stages of work into well defined groups. The bar charts for each individual block on the Pitcoudie 2 site were divided into 4 groups: substructure, carcassing, dry-linings, and finishings. The graphs produced by program "Block Bar Chart" were used to determine the practical start and completion dates for each of these groups of stages within a block. An average duration for each group was calculated. The average group duration was then used to establish a standard bar chart framework. The standard bar chart framework developed for figure 07 had the following characteristics:

Pitcoudie 2 Site		
groups of stages	duration	accumulated duration (milestones)
substructure	9 weeks	week 0 to the end of week 9
carcassing	13 weeks	week 10 to the end of week 22
dry-linings	11 weeks	week 23 to the end of week 33
finishings	-	week 34 onwards

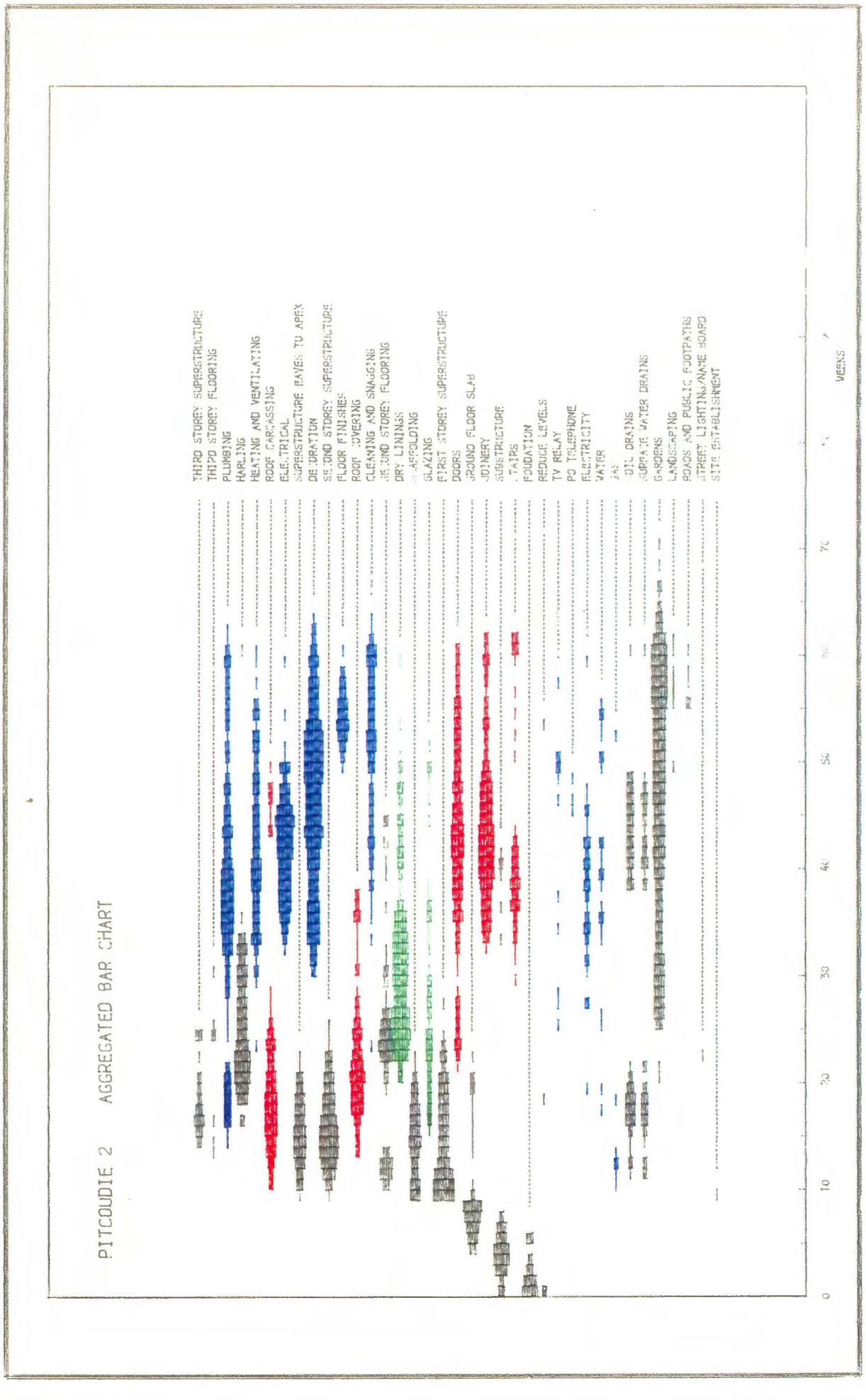

PITCOUDIE 2 AGGREGATED BAR CHART
THIRD STOREY SUPERSTRUCTURE
THIRD STOREY FLOORING
PLUMBING
HARLING
HEATING AND VENTILATING
ROOF CARCASSING
ELECTRICAL
SUPERSTRUCTURE RAYES TO APEX
DECORATION
SECOND STOREY SUPERSTRUCTURE
FLOOR FINISHES
ROOF COVERING
CLEANING AND SNAGGING
SECOND STOREY FLOORING
DRY LININGS
SCAFFOLDING
GLAZING
FIRST STOREY SUPERSTRUCTURE
DOORS
GROUND FLOOR SLAB
JOINERY
SUBSTRUCTURE
STAIRS
FOUNDATION
REDUCE LEVELS
TV RELAY
PO TELEPHONE
ELECTRICITY
WATER
GAS
OIL DRAINS
SURFACE WATER DRAINS
GARDENS
LANDSCAPING
ROADS AND PUBLIC FOOTPATHS
STREET LIGHTING/NAME BOARD
SITE ESTABLISHMENT
0
10
20
30
40
50
70
WEEKS

Figure 07

Each group duration was compressed or decompressed to fit this time structure. Finishing stages were left unchanged, but in all blocks they were made to start in the 34th week. After this exercise of fitting each individual block bar chart into the standard bar chart framework, man-hours allocated to each block were aggregated and plotted, stage of work by stage of work and week by week. The exact procedure is fully explained in the source copy of the Fortran program "Site Bar Chart".

A geometrical scale was used to represent the aggregated amount of man-hours allocated per week. The scale below was used to provide the parameters for the subroutine Call Thick:

Range of man-hours	Parameter for the subroutine call thick	Number of parallel lines drawn
From 1 to 40 man-hours	1	1
From 41 to 80 man-hours	2	3
From 81 to 160 man-hours	3	5
From 161 to 320 man-hours	4	7
From 321 to 640 man-hours	5	9
From 641 to 1280 man-hours	6	11
From 1281 to 2560 man-hours	7	13
From 2561 to 5120 man-hours	8	15
From 5121 to 9999 man-hours	9	17

The absolute amount of aggregated man-hours depicted on the graph has no special meaning because it is a function of the subjective standardization procedure used. It can be used only on a relative basis, comparing the allocation of effort within or between stages.

Figure 07 shows the aggregated bar chart drawn by this program. It gives a rough idea of the precedence relationships between stages of work, their durations, and their ocurrences during the construction process. This figure provides evidence that:

- average durations per block were very large; for example, doors and joinery work took more than 30 weeks to be completed; decoration took even more than this; the electrical stage of work that was carefully designed to require only one visit by the electrical trade took on average nearly 15 weeks to be completed;
- the technical precedence between stages did not require the completion of a supposedly preceding stage of work to allow the succeeding one to start. Stages of work overlapped, they were done in parallel rather than in sequence. The planned flow of work is presented in a report by the Scottish Development Department: observation of figure 07 leads to the inference that progress on site did not follow the planned flow of work, and that the desired sharp separation between the work of various trades did not occur;
- each block took on average 60 weeks to be completed.

Any particular set of blocks and stages of work can be examined by this program. It could be used to investigate, for example, only one-storey blocks or only blocks containing five-person houses.

4.2.4 Program "Trade Bar Chart"

This program simply aggregates and plots the weekly total number of man-hours spent in each stage irrespective of block. Figure 08 was drawn for the Pitcoudie 2 site: not only blocks 1 to 53 are included but also block 60. The heading "block 60" was used whenever the stage of work being observed is related to site works rather than to specific blocks (see the appendix). For the majority of block-related stages of work, i.e., the ones with identification numbers between 1 to 26, the amount of hours recorded under this "block 60" heading was not more than 12%, but for the site works stages, i.e., the ones with identification numbers between 30 to 42, the majority of the work was recorded under this heading.

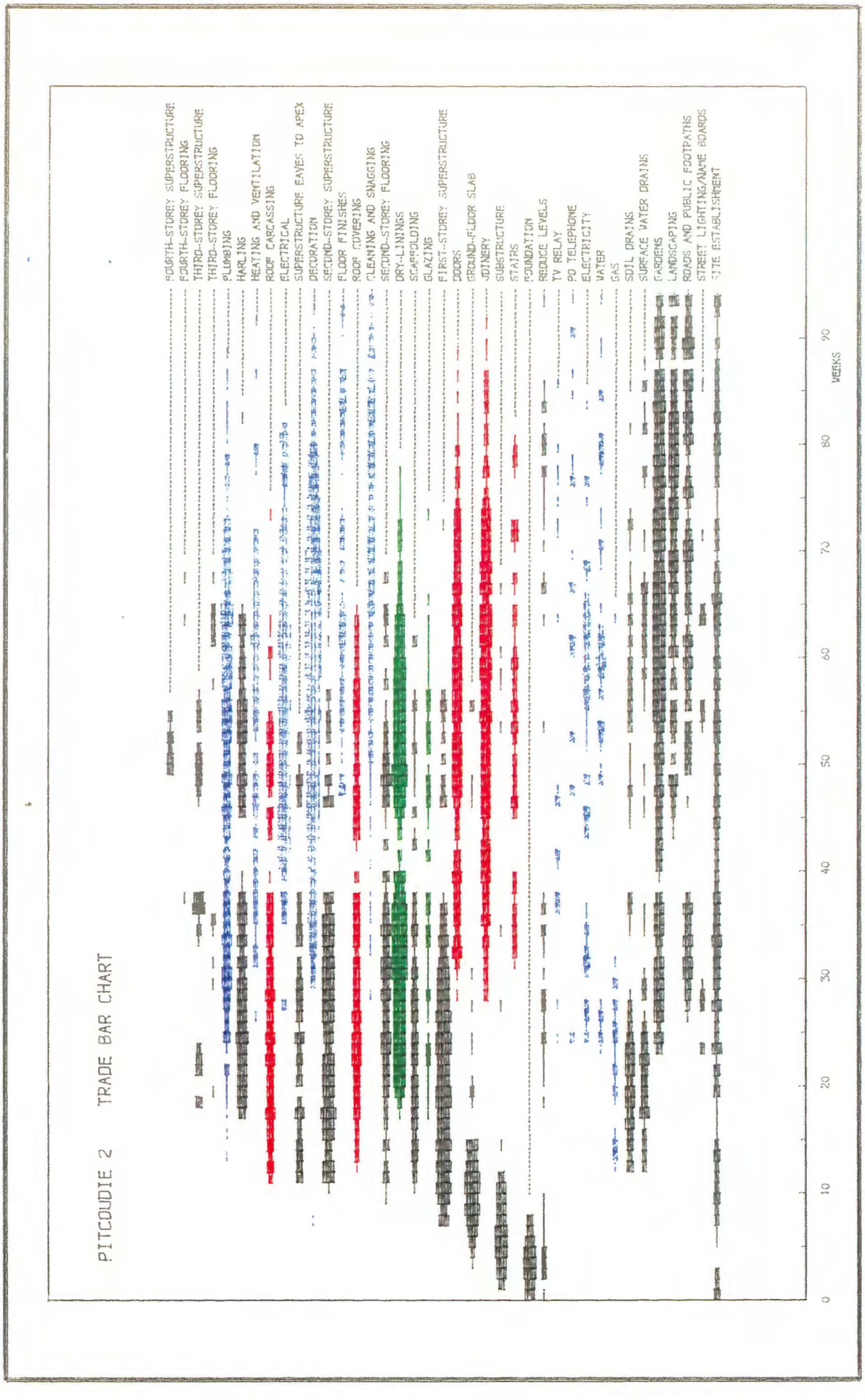

PITCOUDIE 2 TRADE BAR CHART
FOURTH-STOREY SUPERSTRUCTURE
FOURTH-STOREY FLOORING
THIRD-STOREY SUPERSTRUCTURE
THIRD-STOREY FLOORING
PLUMBING
HARLING
HEATING AND VENTILATION
ROOF CARCASSING
ELECTRICAL
SUPERSTRUCTURE EAVES TO APEX
DECORATION
SECOND-STOREY SUPERSTRUCTURE
FLOOR FINISHES
ROOF COVERING
CLEANING AND SNAGGING
SECOND-STOREY FLOORING
DRY-LININGS
SCAFFOLDING
GLAZING
FIRST-STOREY SUPERSTRUCTURE
DOORS
GROUND-FLOOR SLAB
JOINERY
SUBSTRUCTURE
STAIRS
FOUNDATION
REDUCE LEVELS
TV RELAY
PO TELEPHONE
ELECTRICITY
WATER
GAS
SOIL DRAINS
SURFACE WATER DRAINS
GARDENS
LANDSCAPING
ROADS AND PUBLIC FOOTPATHS
STREET LIGHTING/NAME BOARDS
SITE ESTABLISHMENT
0
10
20
30
40
50
60
70
80
90
WEEKS

Figure 08

The scale used to represent the intensity of effort applied to the stages is the same as in program "Site Bar Chart".

This program is useful for providing a general picture of the progress of work on site when used in conjunction with program "General Pattern of Progress". The start and finishing of the work of each trade is clearly marked. Another useful piece of information is the total number of hours worked per trade per week.

The total duration of work on site, not considering the external works like gardens, landscaping, roads, and public footpaths, can be taken as 85 weeks. Comparatively speaking, this is not much greater than the 60 weeks observed in figure 07 depicting the average bar chart of individual blocks. This means that each block took on average 70% of the total time taken to complete the whole site, or in other words, it means that the time taken to complete the individual blocks and the whole site were of the same order of magnitude.

4.2.5 Program "Rate of Progress"

The programs so far described are useful for analysing the progress of work as a whole, and for studying groups of stages of work from subsets of building units (blocks, houses, etc.). Individual stages of work are analysed and compared using the next 2 programs. Both programs enable the user to choose any particular set of blocks using any particular "colour density convention".

The program "Rate of Progress" was the first to be developed. One initial difficulty was finding a suitable arrangement for the y axis, in order to represent the sequence of work from block to block. Blocks were numbered from top to bottom and from left to right as in figure 04. The unique clue found in the drawings was that blocks 1, 6, 11, 15, 18, 19, 24, 28, 29, and 31 were situated in the "first area available for building"; no other information was available about the sequence of work.

Therefore, it was decided to investigate the actual sequence of work using initially a tentative block ordering from 1 to 49. After some graphs it was realized that the stages of work did not follow the ordinal sequence 1 to 49 in terms of start and completion of work. A better procedure was introduced, capable of finding the order in which individual stages of work were started. Whenever the number of man-hours allocated to a stage of work was greater than a given amount, the work in this stage was considered to have started. There is no point in saying, for example, that a stage of work has started because one observation was made of an operative just, say, visiting the work place. For the remainder of the chapter, this minimum number of man-hours chosen by the user as indicative that the stage of work has really started will be called the starting parameter. In some cases a different starting order and a different graphical representation of the progress of work on site was obtained with different starting parameters.

Figure 09 refers to the first-storey superstructure stage of work: even with 1 man-hour as the starting parameter, the pattern of work is clearly set; the stage occupied a band of some 10 weeks from start to completion, with the majority of the work concentrated in the 2 initial weeks. The aggregated total amount of man-hours allocated weekly to the stage for the particular set of blocks under examination is plotted at the bottom of the figure.

Figures 10 and 11 refer to the joinery stage of work. A completely different pattern of work emerges with each starting parameter. For example, no clear pattern of progress for this stage appears in figure 10 using 1 man-hour as the starting parameters; however, with a 40 man-hours parameter (figure 11) it becomes apparent that the major concentration of effort for this stage took a relatively small proportion of the total stage duration per block (between 2 and 3 weeks). It is also apparent that the major concentration of effort followed a steady line of progress from block to block. The relative position of the major effort changed as new blocks were tackled: in the first blocks, the major effort occurred

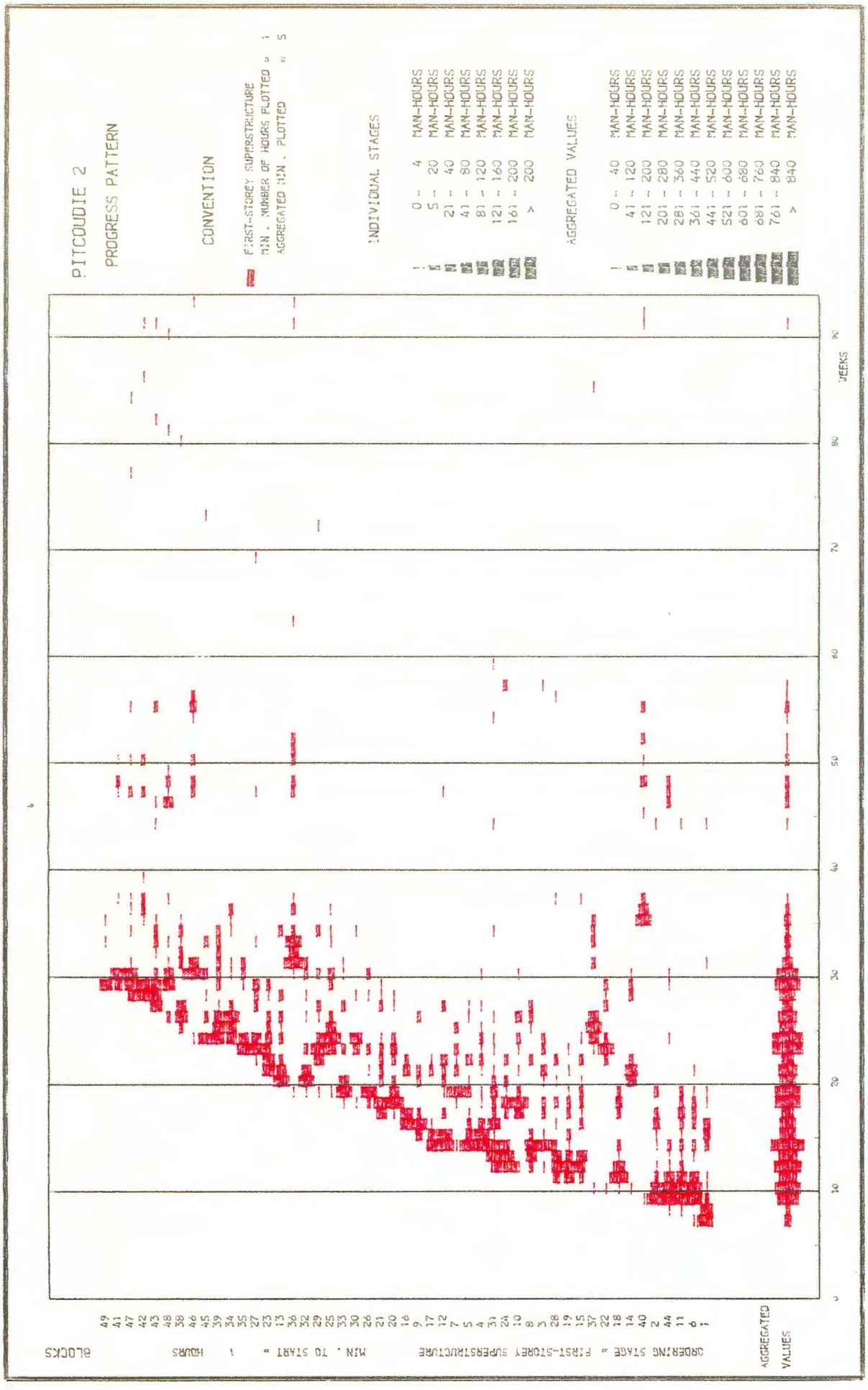

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
FIRST-STOREY SUPERSTRUCTURE
MIN. NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN. PLOTTED = 5
INDIVIDUAL STAGES
0 - 4 MAN-HOURS
5 - 20 MAN-HOURS
21 - 40 MAN-HOURS
41 - 80 MAN-HOURS
81 - 120 MAN-HOURS
121 - 160 MAN-HOURS
161 - 200 MAN-HOURS
> 200 MAN-HOURS
AGGREGATED VALUES
0 - 40 MAN-HOURS
41 - 120 MAN-HOURS
121 - 200 MAN-HOURS
201 - 280 MAN-HOURS
281 - 360 MAN-HOURS
361 - 440 MAN-HOURS
441 - 520 MAN-HOURS
521 - 600 MAN-HOURS
601 - 680 MAN-HOURS
681 - 760 MAN-HOURS
761 - 840 MAN-HOURS
> 840 MAN-HOURS
WEEKS
ORDERING STAGE = FIRST-STOREY SUPERSTRUCTURE
MIN. TO START = 1 HOURS
BLOCKS
AGGREGATED VALUES

Figure 09

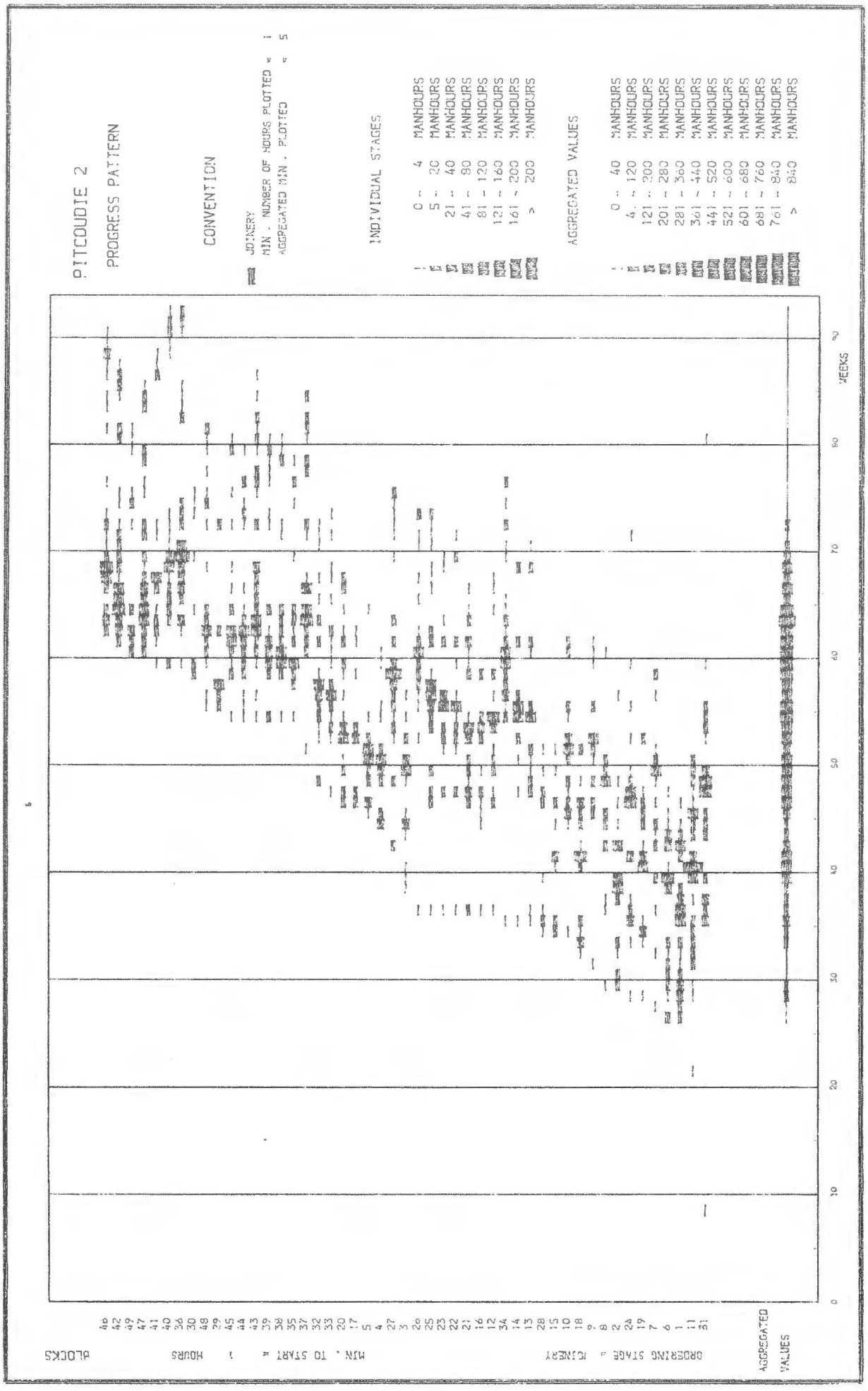

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
JOINERY
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
0 - 4 MANHOURS
5 - 20 MANHOURS
21 - 40 MANHOURS
41 - 80 MANHOURS
81 - 120 MANHOURS
121 - 160 MANHOURS
161 - 200 MANHOURS
> 200 MANHOURS
AGGREGATED VALUES
0 - 40 MANHOURS
41 - 120 MANHOURS
121 - 200 MANHOURS
201 - 280 MANHOURS
281 - 360 MANHOURS
361 - 440 MANHOURS
441 - 520 MANHOURS
521 - 600 MANHOURS
601 - 680 MANHOURS
681 - 760 MANHOURS
761 - 840 MANHOURS
> 840 MANHOURS
WEEKS
BLOCKS
HOURS
MIN . TO START =
BOARDING STAGE = JOINERY
AGGREGATED VALUES

Figure 10

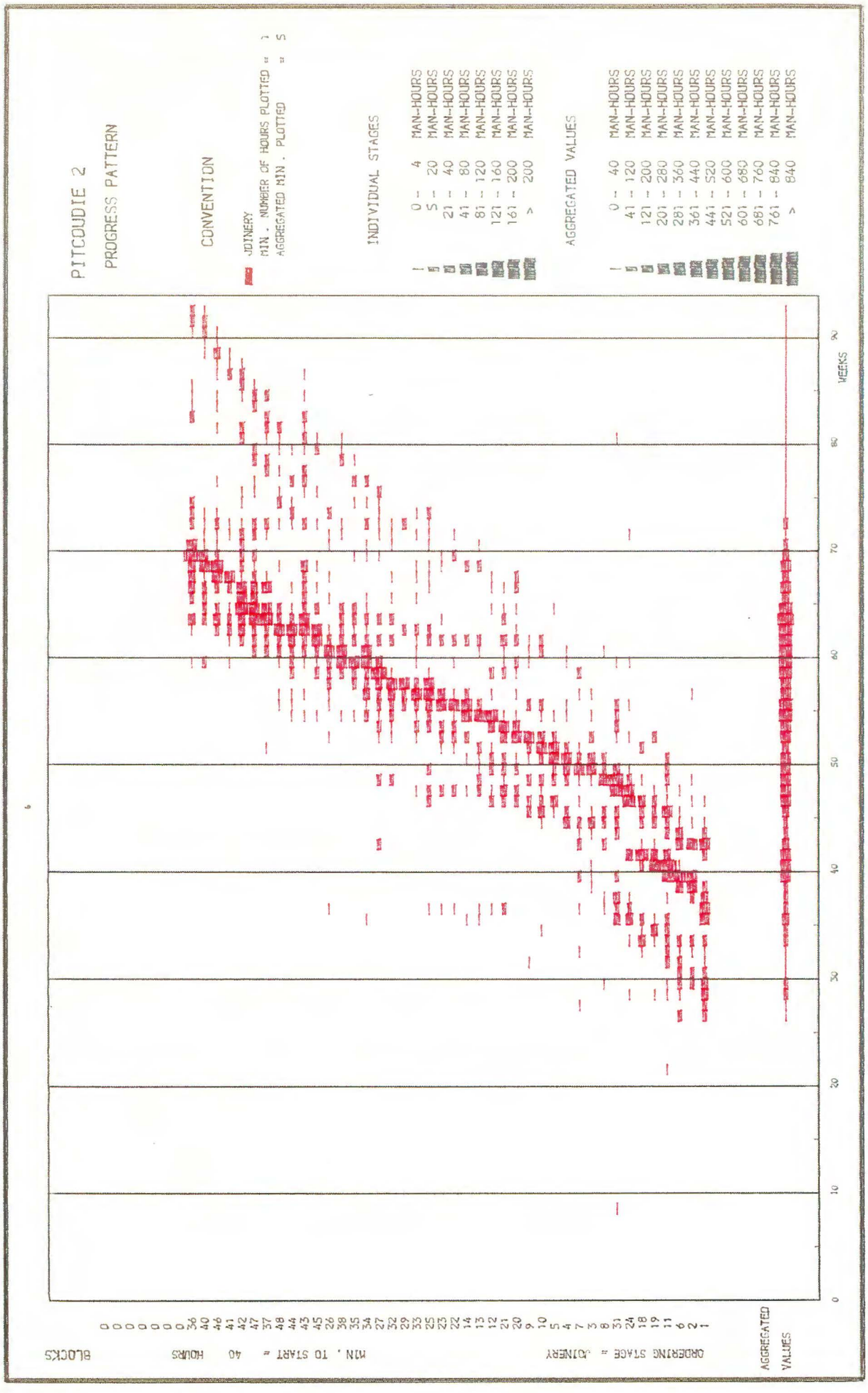

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
JOINERY
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
0 - 4 MAN-HOURS
5 - 20 MAN-HOURS
21 - 40 MAN-HOURS
41 - 80 MAN-HOURS
81 - 120 MAN-HOURS
121 - 160 MAN-HOURS
161 - 200 MAN-HOURS
> 200 MAN-HOURS
AGGREGATED VALUES
0 - 40 MAN-HOURS
41 - 120 MAN-HOURS
121 - 200 MAN-HOURS
201 - 280 MAN-HOURS
281 - 360 MAN-HOURS
361 - 440 MAN-HOURS
441 - 520 MAN-HOURS
521 - 600 MAN-HOURS
601 - 680 MAN-HOURS
681 - 760 MAN-HOURS
761 - 840 MAN-HOURS
> 840 MAN-HOURS
WEEKS
0
10
20
30
40
50
60
70
80
90
AGGREGATED VALUES
ORDERING STAGE = JOINERY
MIN . TO START = 40 HOURS
BLOCKS

Figure 11

at the end of the stage duration, while in the last blocks it was applied right at the beginning.

This program is useful for determining the progress pattern of single stages; it can also be used to give a rough idea about average stage durations, levels of resources available on site, and precedence relationships between different stages. Figure 12 compares the progress of work of second-storey flooring and second-storey superstructure; the first part of second-storey flooring preceded second-storey superstructure, but the last part of flooring came just after the latter had finished. Figure 12 shows that the stage second-storey flooring comprised in fact 3 operations. The site hierarchy set by the Building Research Establishment analyst assumed that only 2 operations would be performed under the heading "second-storey flooring", that is, floor structure (ties and joists), and flooring. The other operations shown under this heading in the appendix refer to the flats, where concrete floors and concrete staircases were used.

The comparison between the progress of work in 2 stages could be complicated by the presence of large amounts of overlapping. The next program evolved from this one: the author tried to develop a better way of qualitatively analysing the degree of overlapping between 2 stages of work, and obtaining a clearer indication on the duration of activities.

4.2.6 Program "Duration Band"

This program aligns vertically the stage of work starting dates for a number of blocks. In other words, it brings to the vertical the inclined band of progress that the stages of work normally show; all blocks are depicted as having started simultaneously. The starting order that appears on the y axis is fixed by a minimum number of man-hours allocated, the starting parameter previously discussed. In the case of 2 stages being compared, the starting order is given by the stage first input while replying to the program

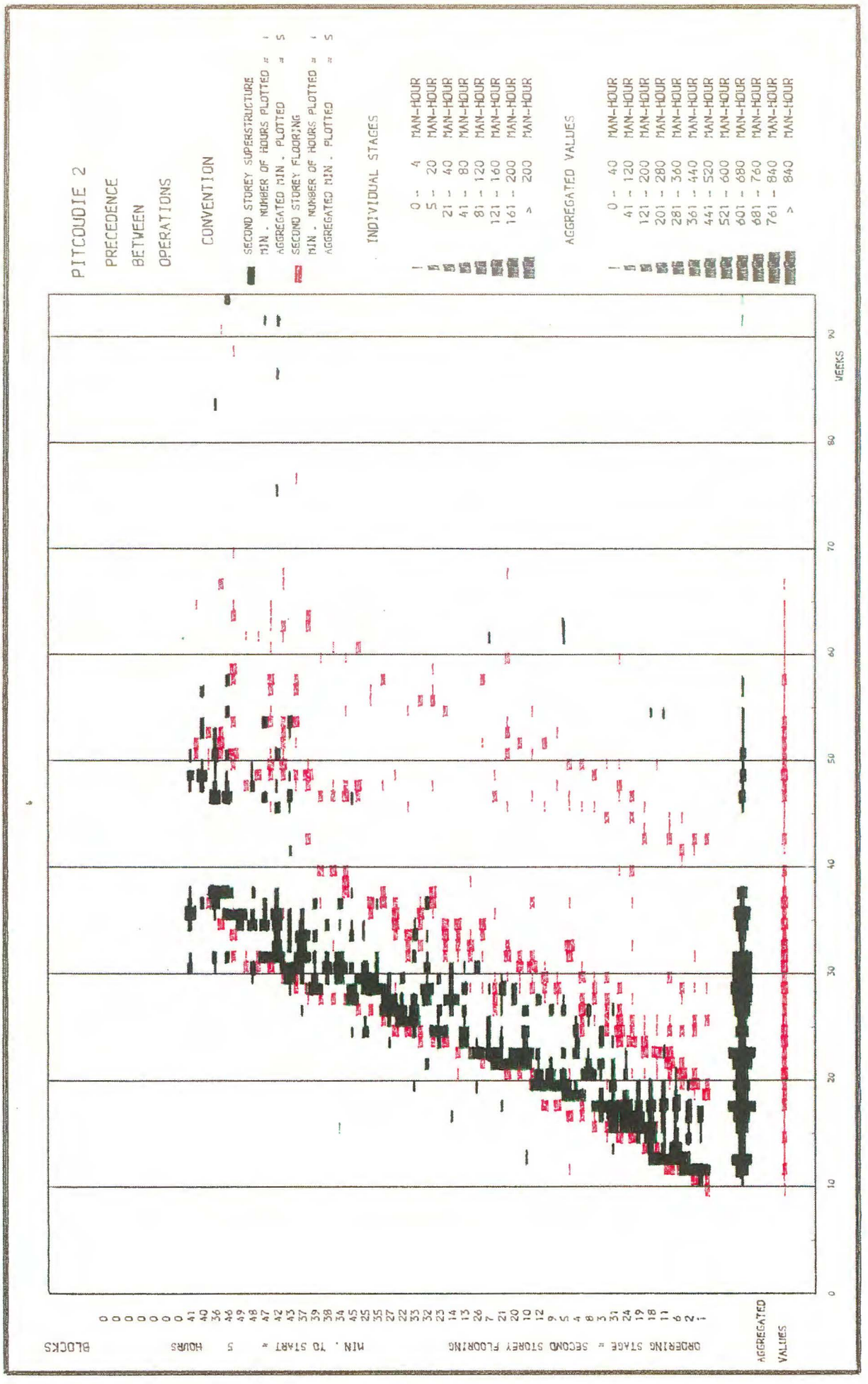


FIG. 51

Figure 12

queries. Horizontal shifts to the left given to the first stage are equally given to the second stage of work, block by block.

This program is not able to show the progress of work throughout the project duration as program "Rate of Progress" does, but it produces a clearer picture in terms of stage of work duration and precedence. Figure 13 demonstrates that the majority of work associated with the dry-linings stage took an average of 13 weeks (total duration was more than 30 weeks). Dry-linings was preceded by second-storey superstructure, but the pace of work of the 2 stages was different: the time gap between them increased as the final blocks were reached. The aggregated plots at the bottom of the figure give some rough qualitative indication on the precedence relationship between the stages.

Figure 14 compares roof covering and dry-linings. While it is clear that substantial roof covering was needed before dry-linings would start, the amount of overlapping was significant; it was not necessary to complete roof covering in order to start dry-linings. This form of progress presentation makes it impossible to detect the interruption due to holidays seen in figure 06.

Figure 15 investigates the precedence relationship between first-storey superstructure and second-storey flooring; a small proportion of the second-storey flooring work was done just after the major proportion of first-storey superstructure work. Likewise, it is apparent from figure 16 that second-storey superstructure had started only after this small proportion of second-storey flooring work was done. Only block 41 did not follow this precedence arrangement. Both figures show that the majority of work in connection with second-storey flooring was done after first and second-storey superstructure were virtually completed. This construction pattern is what can be expected in this type of house construction, where external first-storey and second-storey brickwork are operationally split by floor joisting.

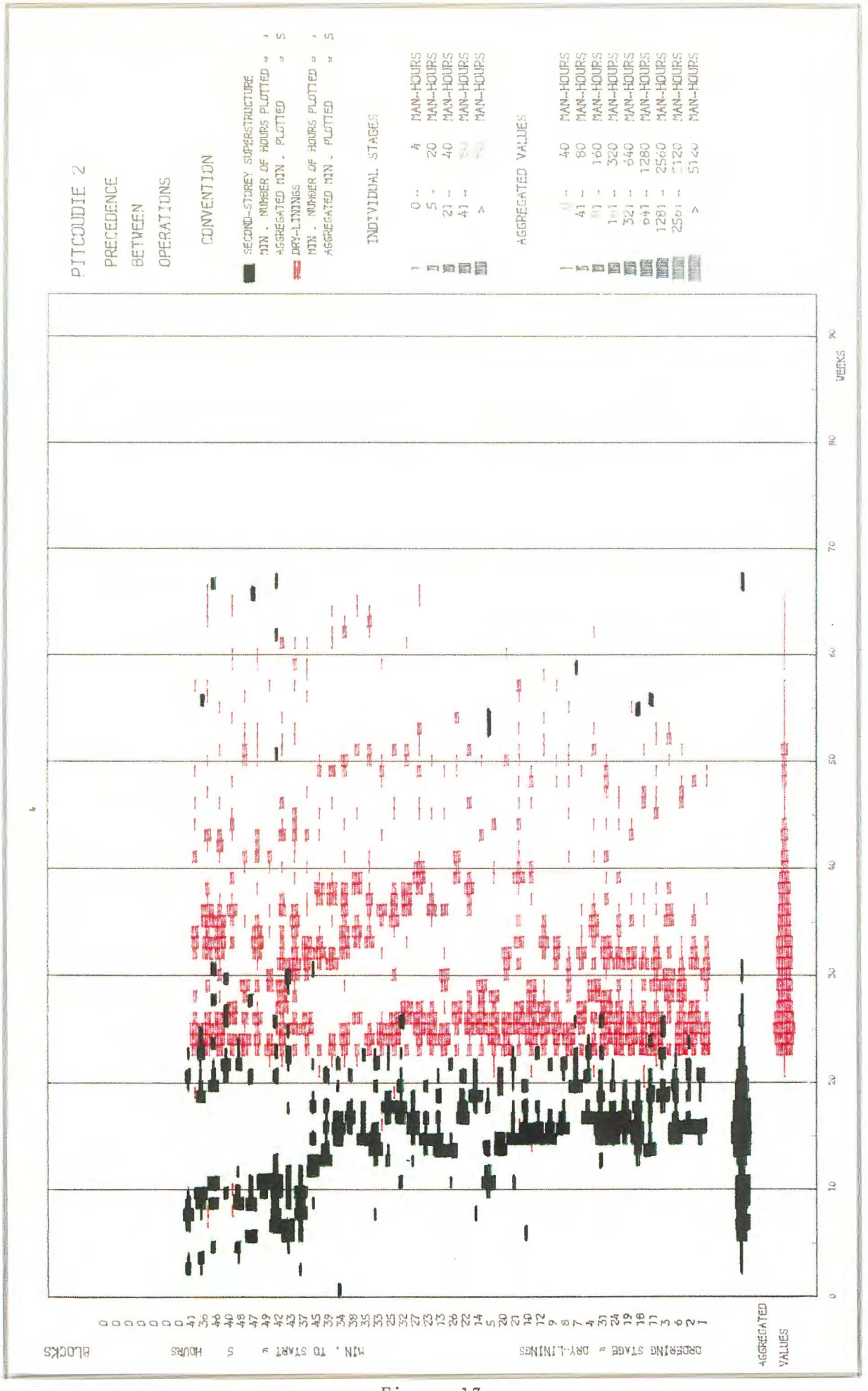

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
SECOND-STOREY SUPERSTRUCTURE
MIN . NUMBER OF HOURS PLOTTED =
AGGREGATED MIN . PLOTTED =
DRY-LININGS
MIN . NUMBER OF HOURS PLOTTED =
AGGREGATED MIN . PLOTTED =
INDIVIDUAL STAGES
1 0 -- 4 MAN-HOURS
2 5 -- 20 MAN-HOURS
3 21 -- 40 MAN-HOURS
4 41 -- 80 MAN-HOURS
5 > 80 MAN-HOURS
AGGREGATED VALUES
1 0 -- 40 MAN-HOURS
2 41 -- 80 MAN-HOURS
3 81 -- 160 MAN-HOURS
4 161 -- 320 MAN-HOURS
5 321 -- 640 MAN-HOURS
6 641 -- 1280 MAN-HOURS
7 1281 -- 2560 MAN-HOURS
8 2561 -- 5120 MAN-HOURS
9 > 5120 MAN-HOURS
WEEKS
0 10 20 30 40 50 60 70 80 90
AGGREGATED VALUES
ORDERING STAGE = DRY-LININGS
MIN . TO START = 5 HOURS
BLOCKS

Figure 13

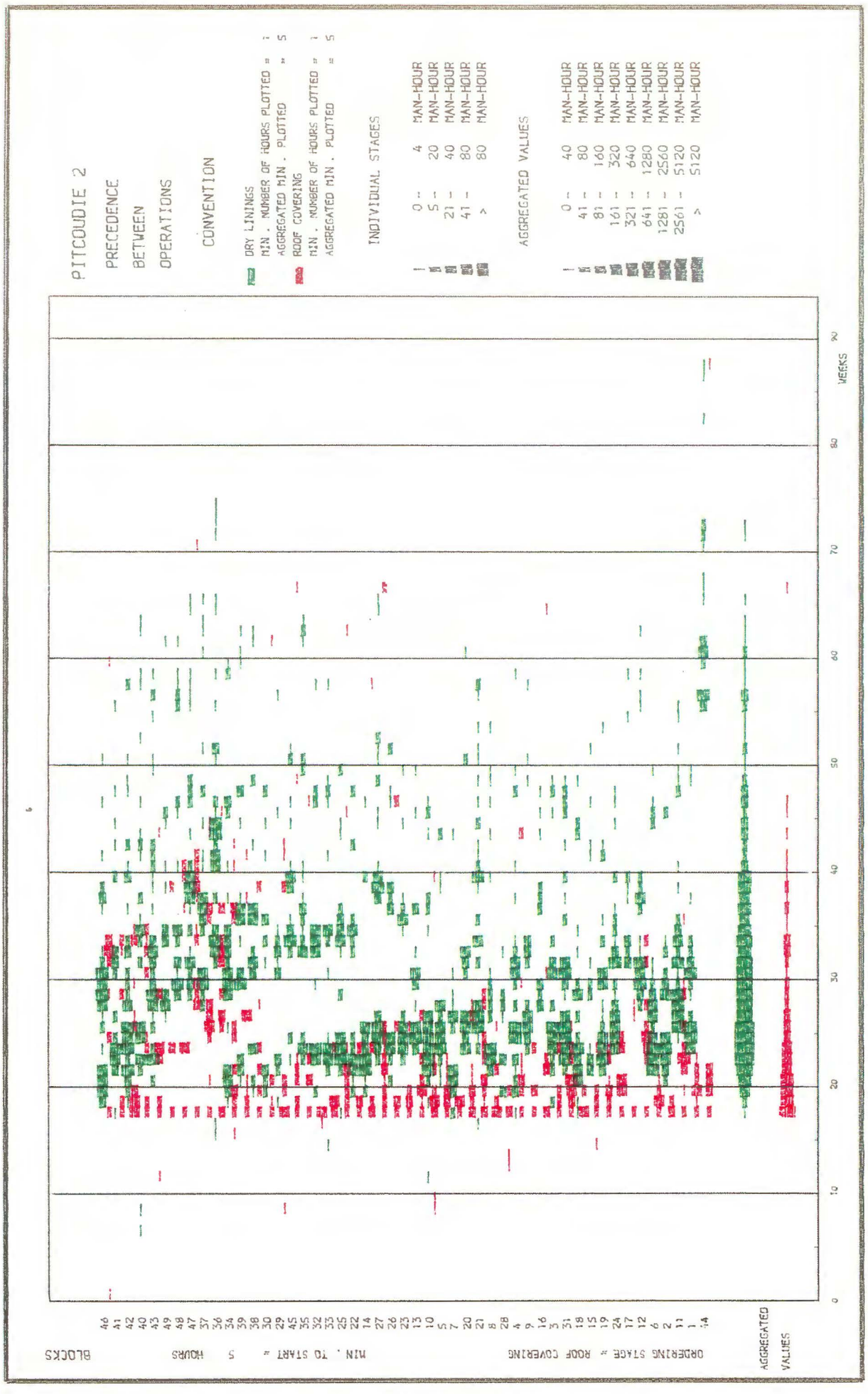


FIG. 55

Figure 14

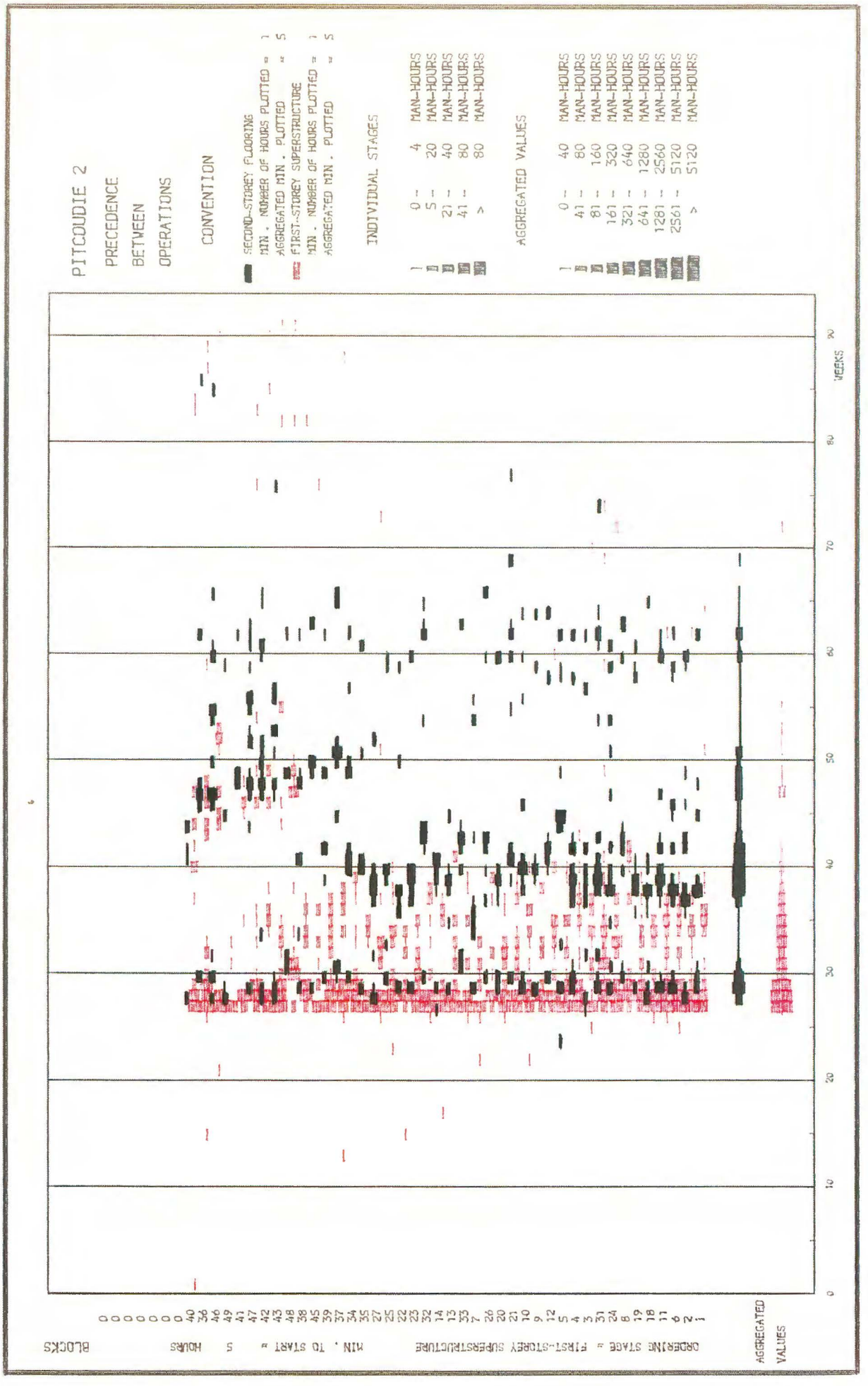

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
SECOND-STOREY FLOORING
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
FIRST-STOREY SUPERSTRUCTURE
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
1 0 - 4 MAN-HOURS
2 5 - 20 MAN-HOURS
3 21 - 40 MAN-HOURS
4 41 - 80 MAN-HOURS
5 > 80 MAN-HOURS
AGGREGATED VALUES
1 0 - 40 MAN-HOURS
2 41 - 80 MAN-HOURS
3 81 - 160 MAN-HOURS
4 161 - 320 MAN-HOURS
5 321 - 640 MAN-HOURS
6 641 - 1280 MAN-HOURS
7 1281 - 2560 MAN-HOURS
8 2561 - 5120 MAN-HOURS
9 > 5120 MAN-HOURS
WEEKS
ORDERING STAGE = FIRST-STOREY SUPERSTRUCTURE
MIN . TO START = 5 HOURS
BLOCKS
AGGREGATED VALUES

Figure 15

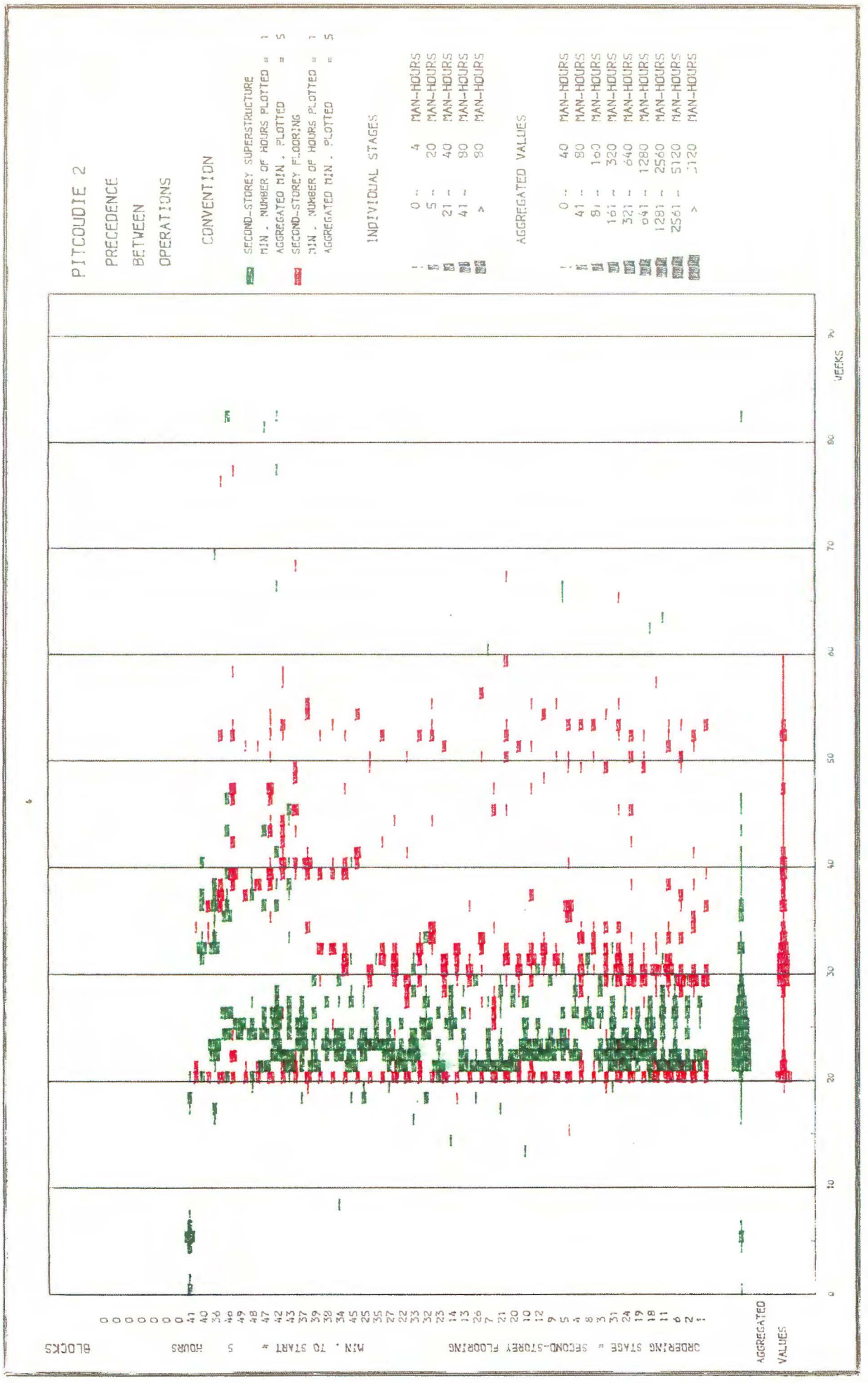

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
SECOND-STOREY SUPERSTRUCTURE
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
SECOND-STOREY FLOORING
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
0 -- 4 MAN-HOURS
5 -- 20 MAN-HOURS
21 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
> 80 MAN-HOURS
AGGREGATED VALUES
0 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
81 -- 160 MAN-HOURS
161 -- 320 MAN-HOURS
321 -- 640 MAN-HOURS
641 -- 1280 MAN-HOURS
1281 -- 2560 MAN-HOURS
2561 -- 5120 MAN-HOURS
> 5120 MAN-HOURS
WEEKS
0
10
20
30
40
50
60
70
80
90
ORDERING STAGE = SECOND-STOREY FLOORING
MIN . TO START = 5 HOURS
BLOCKS
AGGREGATED VALUES

Figure 16

Figure 17 illustrates a case of total overlapping between stages of work: roof carcassing marginally preceded roof covering, but apart from this initial lag, both stages proceeded in parallel until their completion. Figure 18 exemplifies the overlapping tendency found within the finishing stages. Decoration is compared with joinery work: from the set of graphs comparing decoration with the finishing stages (joinery, plumbing, electrical work, heating and ventilation, and floor finishes) it seems that only the electrical stage had occupied a well defined relative position in time, always before the decoration major effort.

Program "Site Bar Chart" provides a rough indication on the stages that should be compared using program "Duration Band", if an analyses of precedence is required; it is obvious that decoration should succeed foundation or first-storey superstructure, but, unexpectedly, the author found that decoration was performed in parallel with stages like doors, joinery, and services.

The uncertainty regarding the precedence relationships, created by the observed tendency for overlapping between stages, dictates that a large number of stage comparisons is needed. The maximum number of comparisons for this site with a total of 42 stages is $42 \times 41 = 1722$, or 861 if the user does not want to compare each pair of stages twice, each time with one of them as the leading stage responsible for the starting order. The author was able to cut down this number to some 150 comparisons. Although this large number of graphs provided a very good qualitative understanding of the real precedence relationships between stages of work, it proved to be an expensive exercise in terms of computer time and plotting resources.

This program allowed the study of particular characteristics of the duration of stages. Figure 19 depicts the change in the relative position of the major effort part of the work for the decoration stage. The total duration of this stage of work remained roughly the same, block after

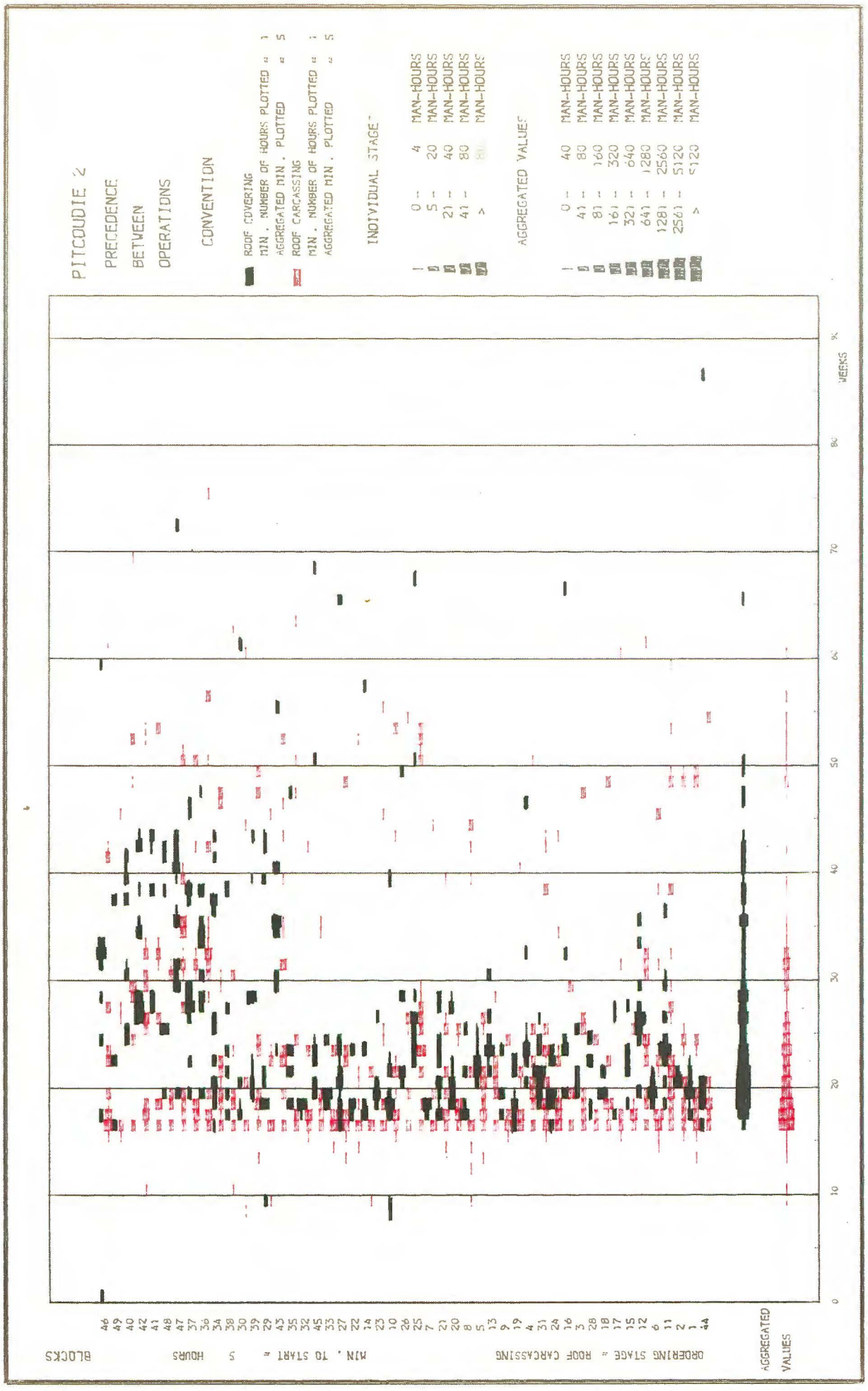

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
ROOF COVERING
MIN . NUMBER OF HOURS PLOTTED =
AGGREGATED MIN . PLOTTED
ROOF CARCASSING
MIN . NUMBER OF HOURS PLOTTED =
AGGREGATED MIN . PLOTTED
INDIVIDUAL STAGE
AGGREGATED VALUES
MAN-HOURS
WEEKS
BLOCKS
HOURS
MIN . TO START =
ORDERING STAGE = ROOF CARCASSING
AGGREGATED VALUES

Figure 17

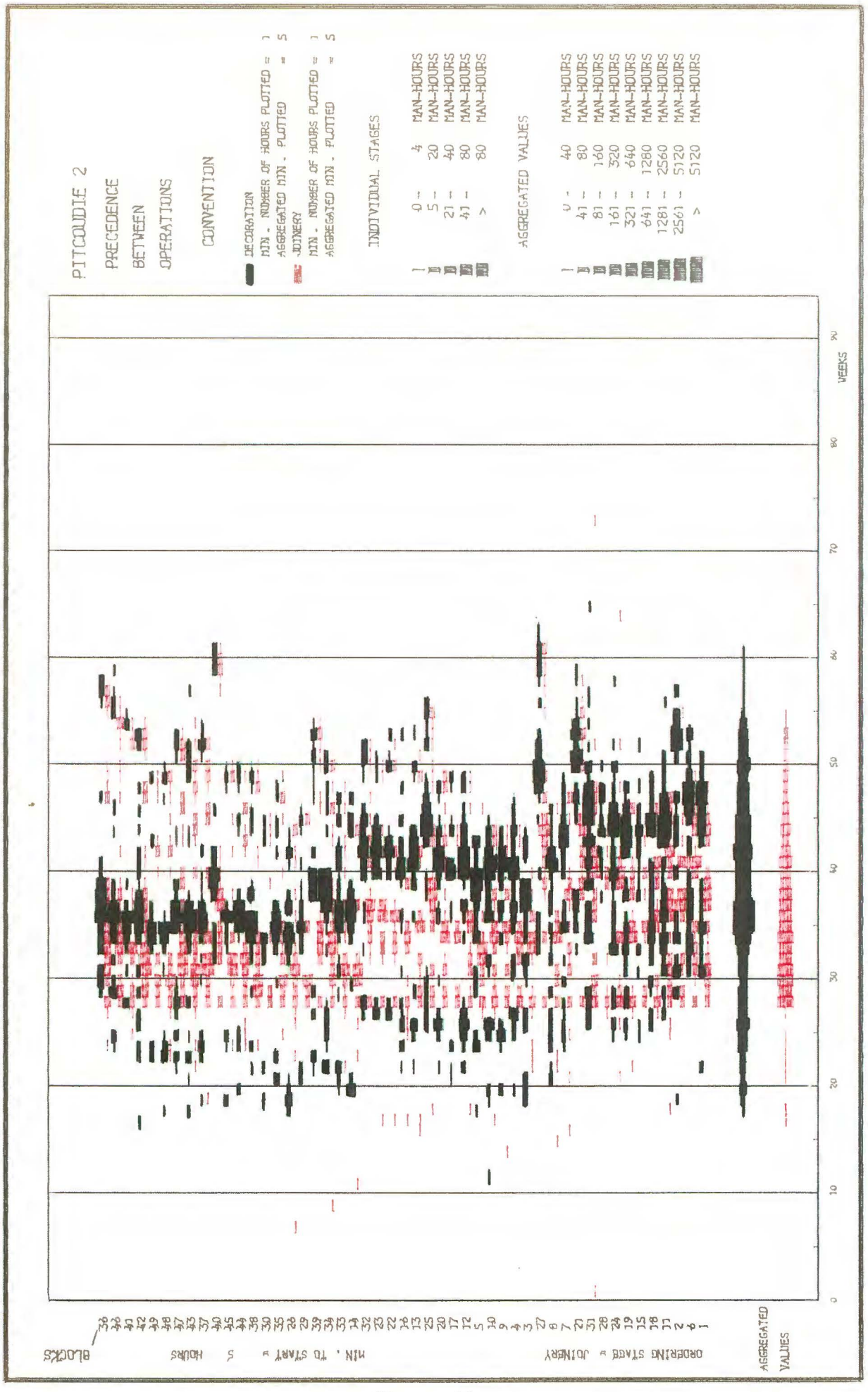

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
DECORATION
MIN. NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN. PLOTTED = 5
JOINERY
MIN. NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN. PLOTTED = 5
INDIVIDUAL STAGES
1 0 - 4 MAN-HOURS
2 5 - 20 MAN-HOURS
3 21 - 40 MAN-HOURS
4 41 - 80 MAN-HOURS
5 > 80 MAN-HOURS
AGGREGATED VALUES
1 0 - 40 MAN-HOURS
2 41 - 80 MAN-HOURS
3 81 - 160 MAN-HOURS
4 161 - 320 MAN-HOURS
5 321 - 640 MAN-HOURS
6 641 - 1280 MAN-HOURS
7 1281 - 2560 MAN-HOURS
8 2561 - 5120 MAN-HOURS
9 > 5120 MAN-HOURS
WEEKS
0 10 20 30 40 50 60 70 80
BLOCKS
MIN. TO START = 5 HOURS
ORDERING STAGE = JOINERY
AGGREGATED VALUES

Figure 18

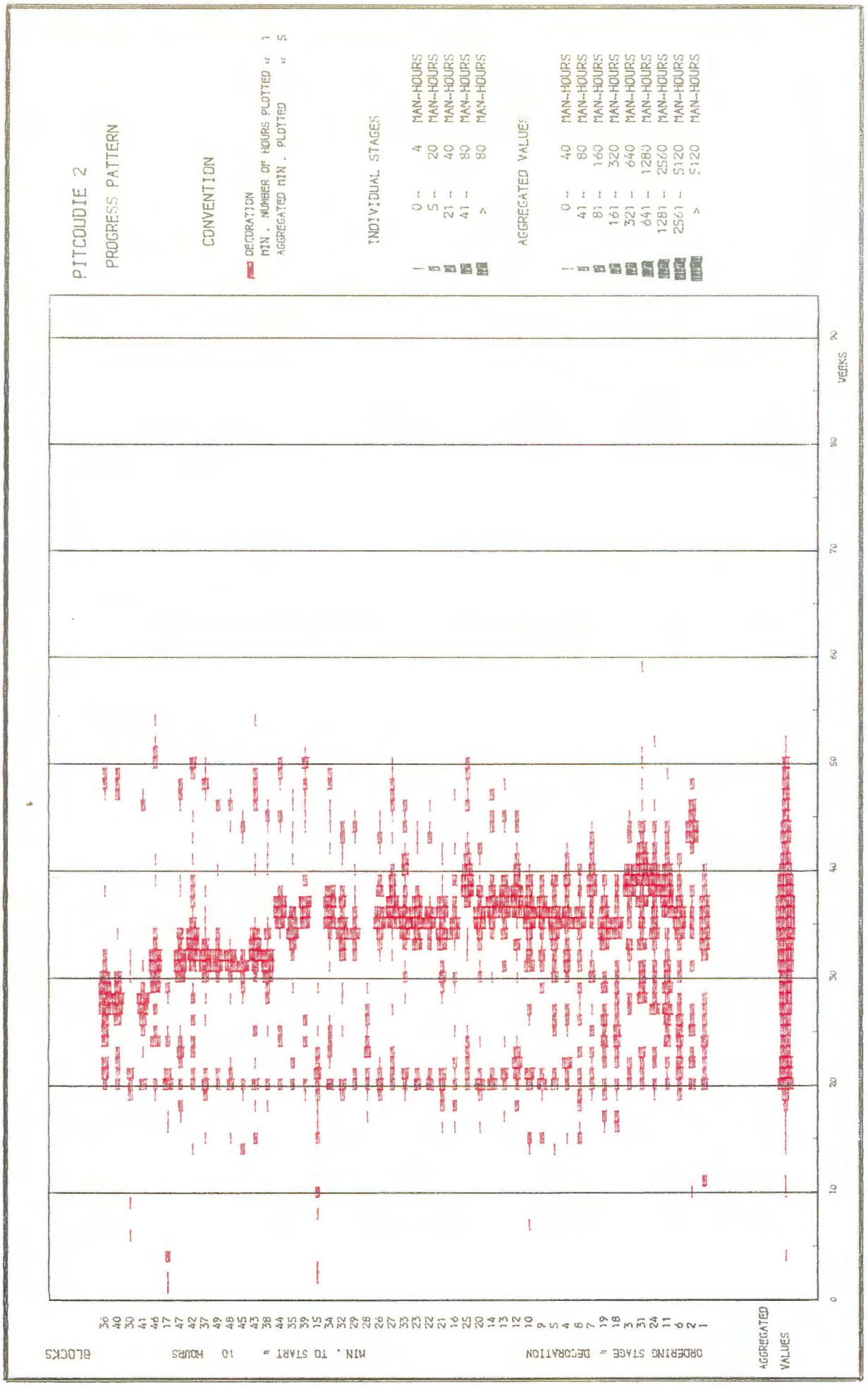

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
DECORATION
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
0 -- 4 MAN-HOURS
5 -- 20 MAN-HOURS
21 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
> 80 MAN-HOURS
AGGREGATED VALUES
0 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
81 -- 160 MAN-HOURS
161 -- 320 MAN-HOURS
321 -- 640 MAN-HOURS
641 -- 1280 MAN-HOURS
1281 -- 2560 MAN-HOURS
2561 -- 5120 MAN-HOURS
> 5120 MAN-HOURS
WEEKS
0 10 20 30 40 50 60 70 80 90
AGGREGATED VALUES
ORDERING STAGE = DECORATION
MIN . TO START = 10 HOURS
BLOCKS

Figure 19

block. However, figure 19 indicates that the practical duration of the decoration stage decreased as the operatives progressed through the site; the major effort occurred closer to the start of the stage, and the remaining allocations were less and less significant.

Figure 20 relates to the plumbing stage of work. The actual number of man-hours allocated per block was between 55 and 407, with an average of 138 man-hours. The graph indicates that the average total duration can be taken as 45 weeks. The following operations were recorded under the plumbing stage of work heading:

- gutters, downpipes, and roof flashings;
- soil and ventilation pipes;
- hot and cold water pipes, tank, cistern, and lagging;
- basin, bath, and w.c.;
- radiators and pipes;
- gas pipes.

It is possible to count an average of 8 interruptions for the work in each block. The dispersed aspect of the figure could have been determined by the fact that it actually represents 6 different operations; each operation could have been performed in a shorter duration, with a higher relative density of man-hours. Only analysis at the level of operations rather than stages will show if this was so. For the moment it is worth mentioning that the notes and specifications for Pitcoudie 2 said that (see Appendix):

> "Rationalization of house building construction was achieved by careful attention to plumbing, electrical, and joinery work, forming fewer, larger, and more independent trade operations".

The electrical installation had been the object of special concern in the Pitcoudie project. Previous Building Research Establishment experience on the observation of actual progress of electrical installation work was applied to the projects, making this stage a one visit job. The site hierarchy divided the stage in 3 operations:

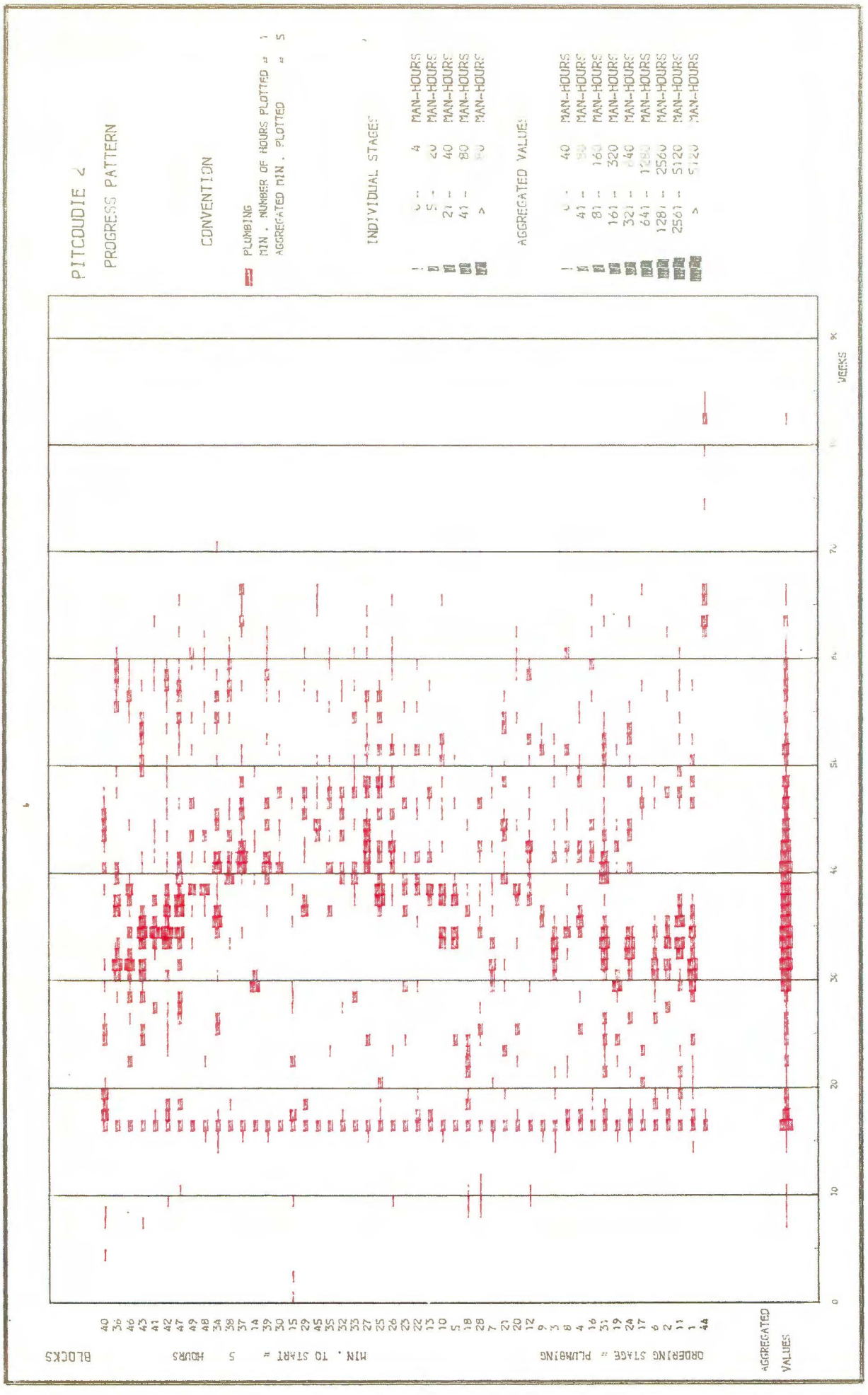

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
PLUMBING
MIN . NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN . PLOTTED = 5
INDIVIDUAL STAGES
1 -- 4 MAN-HOURS
5 -- 20 MAN-HOURS
21 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
> 80 MAN-HOURS
AGGREGATED VALUES
1 -- 40 MAN-HOURS
41 -- 80 MAN-HOURS
81 -- 160 MAN-HOURS
161 -- 320 MAN-HOURS
321 -- 640 MAN-HOURS
641 -- 1280 MAN-HOURS
1281 -- 2560 MAN-HOURS
2561 -- 5120 MAN-HOURS
> 5120 MAN-HOURS
WEEKS
0
10
20
30
40
50
60
70
80
40 36 46 43 41 42 47 49 48 34 38 37 14 39 30 15 29 45 35 32 33 27 25 26 23 22 13 10 5 18 28 7 21 20 12 9 3 8 4 16 31 19 24 17 6 2 11 1 44
BLOCKS
MIN . TO START = 5 HOURS
ORDERING STAGE = PLUMBING
AGGREGATED VALUES

Figure 20

- wiring;
- socket outlets, switches, and fittings;
- conduit and meters.

Under traditional design practices this stage would correspond to at least 2 visits, first fixings and second fixings. Figure 21 confirms that the one visit aim was partially achieved: the majority of the work was done in the 2 or 3 initial weeks, but the actual total duration was still in the region of 10 to 12 weeks. The total number of man-hours allocated per block ranged from 36 to 482 with an average of 164 man-hours: the average intensity of work was, thus, around 16 man-hours per week.

High intensities of work were apparent only for foundations, substructure, ground-floor slab, harling, and floor finishes. Figure 22 refers to the harling stage of work. However, Chapter Five will show that even for the apparent high intensity of work depicted in this figure, the allocation of resources did not exceed 30 man-hours per week. This figure was obtained excluding weeks with no occurrence of work: if these weeks are included in the calculations, the average intensity of work decreased to 12 man-hours per week.

The last 2 programs highlighted the need for a better understanding of the sequence of work on site. The rate of progress and precedence comparisons made with the previous programs took the starting order from just one of the stages being analysed: the second stage was forced to follow this arrangement of the y axis. Furthermore, just one starting parameter was used per graph. The next 2 programs feature the possibility of analysing simultaneously different starting parameters and using a particular starting order for each of the stages being compared.

4.2.7 Program "Starting Order"

The various examples of graphs produced using program "Rate of Progress" attested to the fact that each stage of

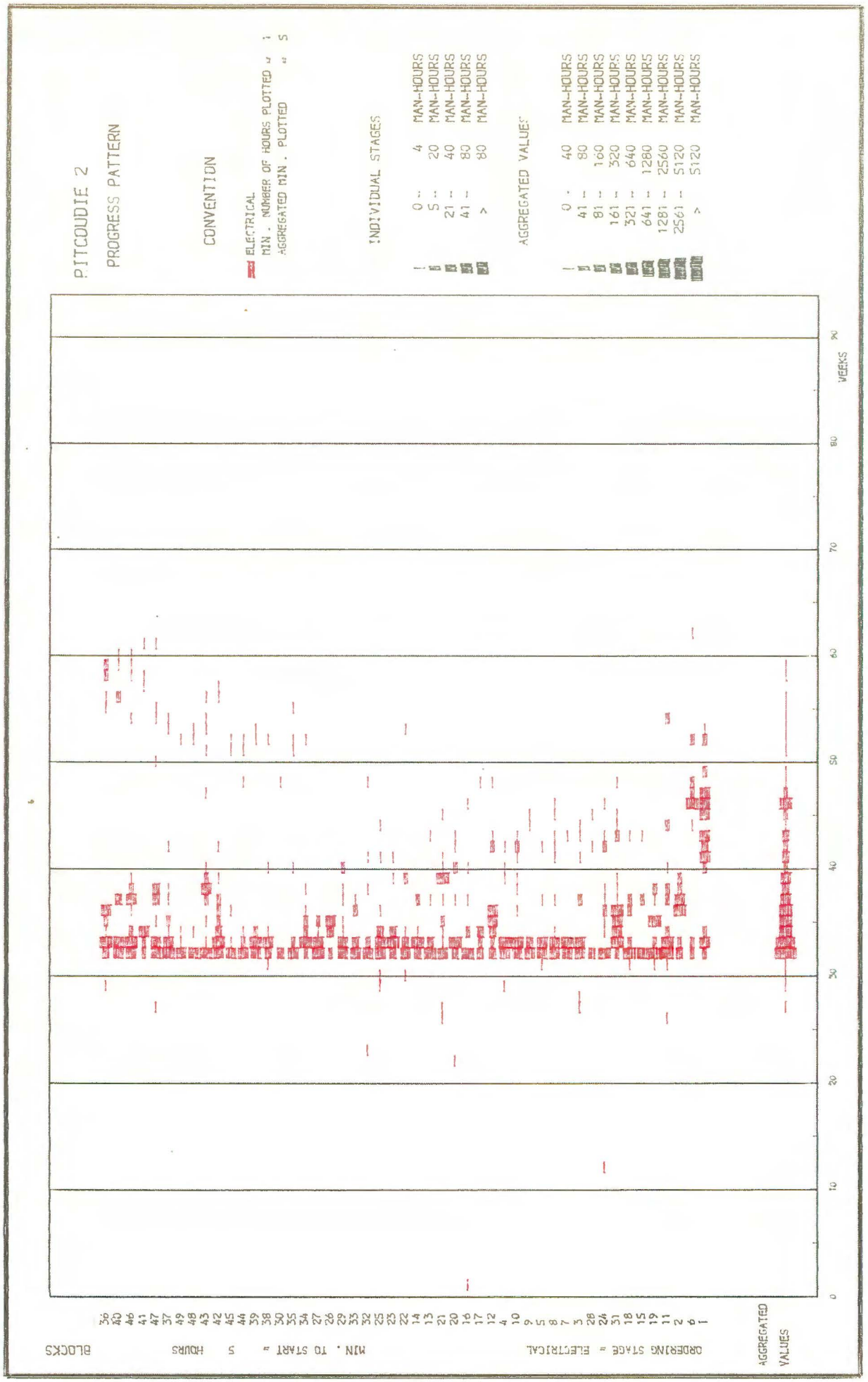

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
ELECTRICAL
MIN. NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN. PLOTTED = 5
INDIVIDUAL STAGES
1 0 - 4 MAN-HOURS
5 5 - 20 MAN-HOURS
21 21 - 40 MAN-HOURS
41 41 - 80 MAN-HOURS
> 80 MAN-HOURS
AGGREGATED VALUES
1 0 - 40 MAN-HOURS
41 41 - 80 MAN-HOURS
81 81 - 160 MAN-HOURS
161 161 - 320 MAN-HOURS
321 321 - 640 MAN-HOURS
641 641 - 1280 MAN-HOURS
1281 1281 - 2560 MAN-HOURS
2561 2561 - 5120 MAN-HOURS
> 5120 MAN-HOURS
WEEKS
ORDERING STAGE = ELECTRICAL
MIN. TO START = 5 HOURS
BLOCKS
AGGREGATED VALUES

Figure 21

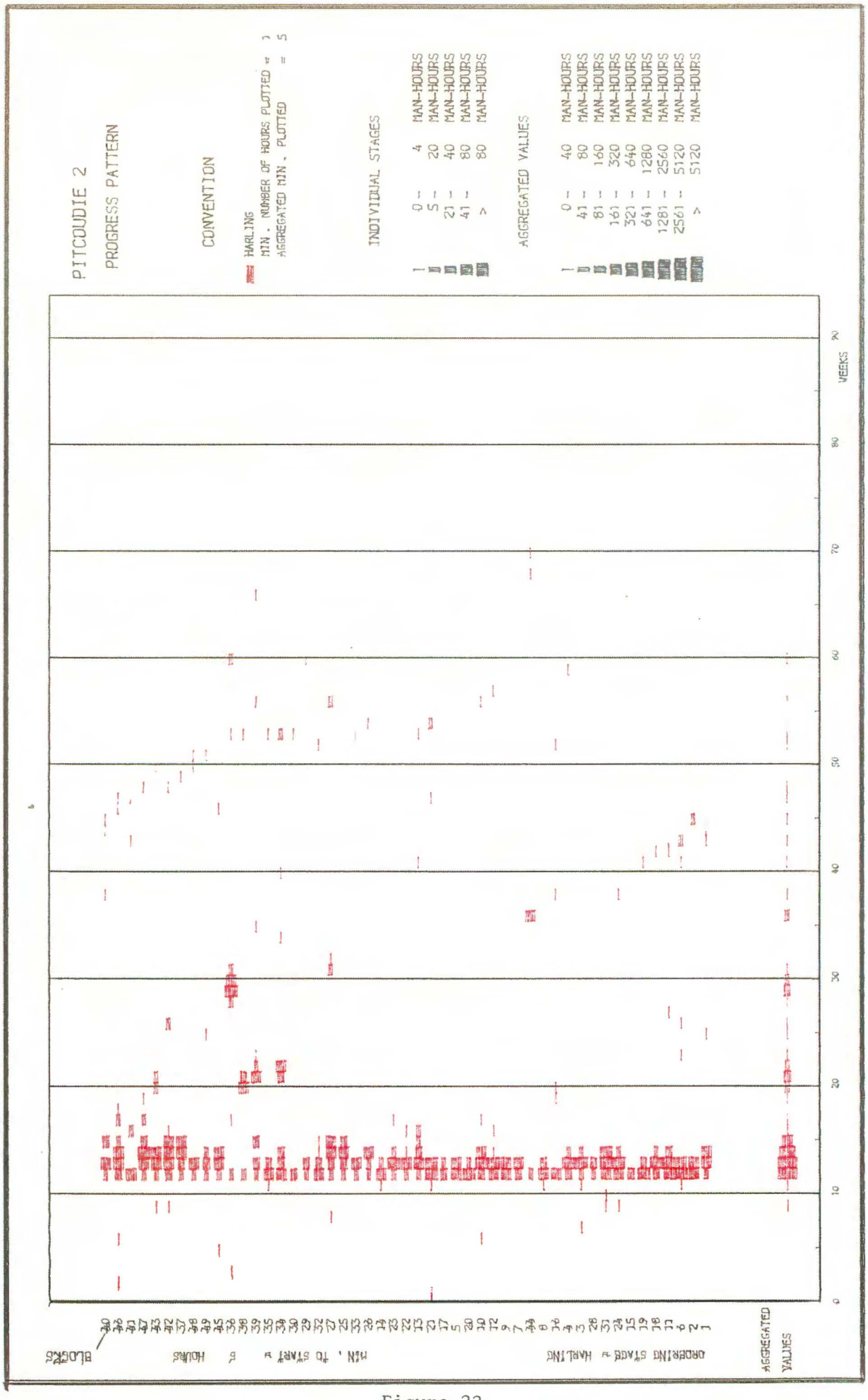

PITCOUDIE 2
PROGRESS PATTERN
CONVENTION
HAAKING
MIN. NUMBER OF HOURS PLOTTED = 1
AGGREGATED MIN. PLOTTED = 5
INDIVIDUAL STAGES
1 0 - 4 MAN-HOURS
2 5 - 20 MAN-HOURS
3 21 - 40 MAN-HOURS
4 41 - 80 MAN-HOURS
5 > 80 MAN-HOURS
AGGREGATED VALUES
1 0 - 40 MAN-HOURS
2 41 - 80 MAN-HOURS
3 81 - 160 MAN-HOURS
4 161 - 320 MAN-HOURS
5 321 - 640 MAN-HOURS
6 641 - 1280 MAN-HOURS
7 1281 - 2560 MAN-HOURS
8 2561 - 5120 MAN-HOURS
9 > 5120 MAN-HOURS
WEEKS
BLOCKS
HOURS
MIN. TO START
ORDERING STAGE - HAAKING
AGGREGATED VALUES

Figure 22

work had apparently a particular starting order. Moreover, even the same stage of work could have had different apparent starting orders, if different starting parameters were used as the criterion to mark the beginning of the work on the stage being considered. Program "Starting Order" was created to investigate starting orders, using a simpler approach than program "Rate of Progress".

Figure 23 studies the joinery stage of work. It can be seen that the lines of starts for the given starting parameters lay inside a band of 15 weeks. Figure 24 refers to first-storey superstructure : a much more stable set of lines of starts is presented; choosing different starting parameters would neither determine very different dates for the start of work in each block nor a completely different arrangement of the y axis. This is caused by the fact that the major effort for this stage was expended as soon as the work began in each block (see figure 09).

Figures 25 and 26 are used to plot the line of starts of 6 major stages of work on site, namely first-storey superstructure, roof covering, dry-linings, joinery, electrical installation, and decoration. It seems that each stage had its own starting order and neither the selection of a particular stage as the leading stage (i.e., the one that provides the starting order in the y axis), nor the selection of a specific set of starting parameters is capable of producing a better agreement between the starting lines of the various stages. Nevertheless, the general trend of the pace of starts was similar for all stages, whichever leading stage and set of starting parameters was chosen. Figure 27 shows that even for operationally similar stages of work, like roof carcassing and roof covering, the starting order was not the same.

Several papers dealing with line of balance programming techniques (see Forbes-1971:2, Lumsden, Price and Horn) emphasized the use of graphical methods to control the progress of work on sites of a repetitive nature. Figure 28 presents the starting lines of the 21 stages of work comprising the majority of the internal work in Pitcoudie 2. The graph is

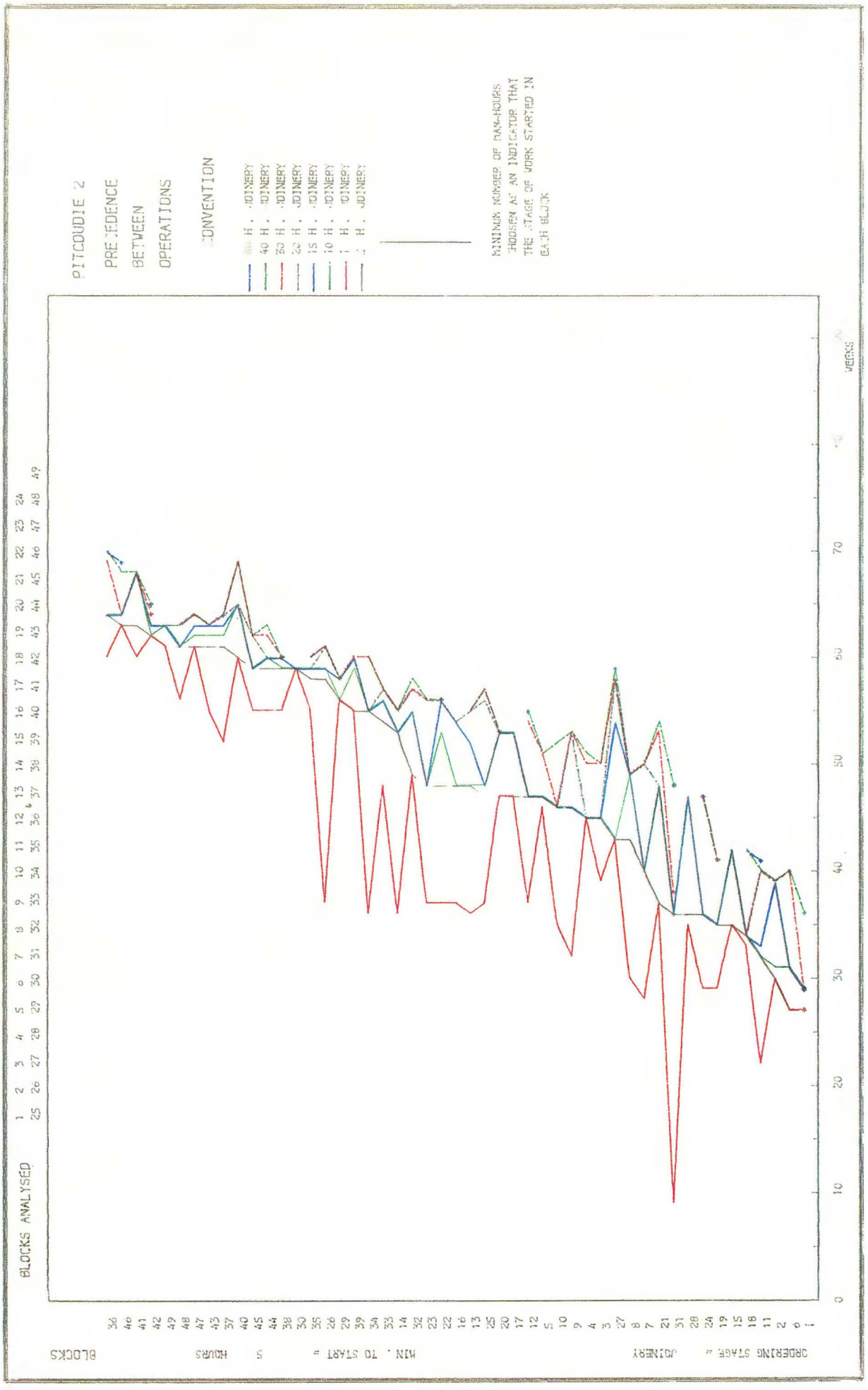

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
60 H . JOINERY
40 H . JOINERY
30 H . JOINERY
20 H . JOINERY
15 H . JOINERY
10 H . JOINERY
5 H . JOINERY
3 H . JOINERY
MINIMUM NUMBER OF MAN-HOURS
CHOSEN AS AN INDICATOR THAT
THE STAGE OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
WEEKS
ORDERING STAGE = JOINERY
MIN. TO START = 5 HOURS
BLOCKS

Figure 23

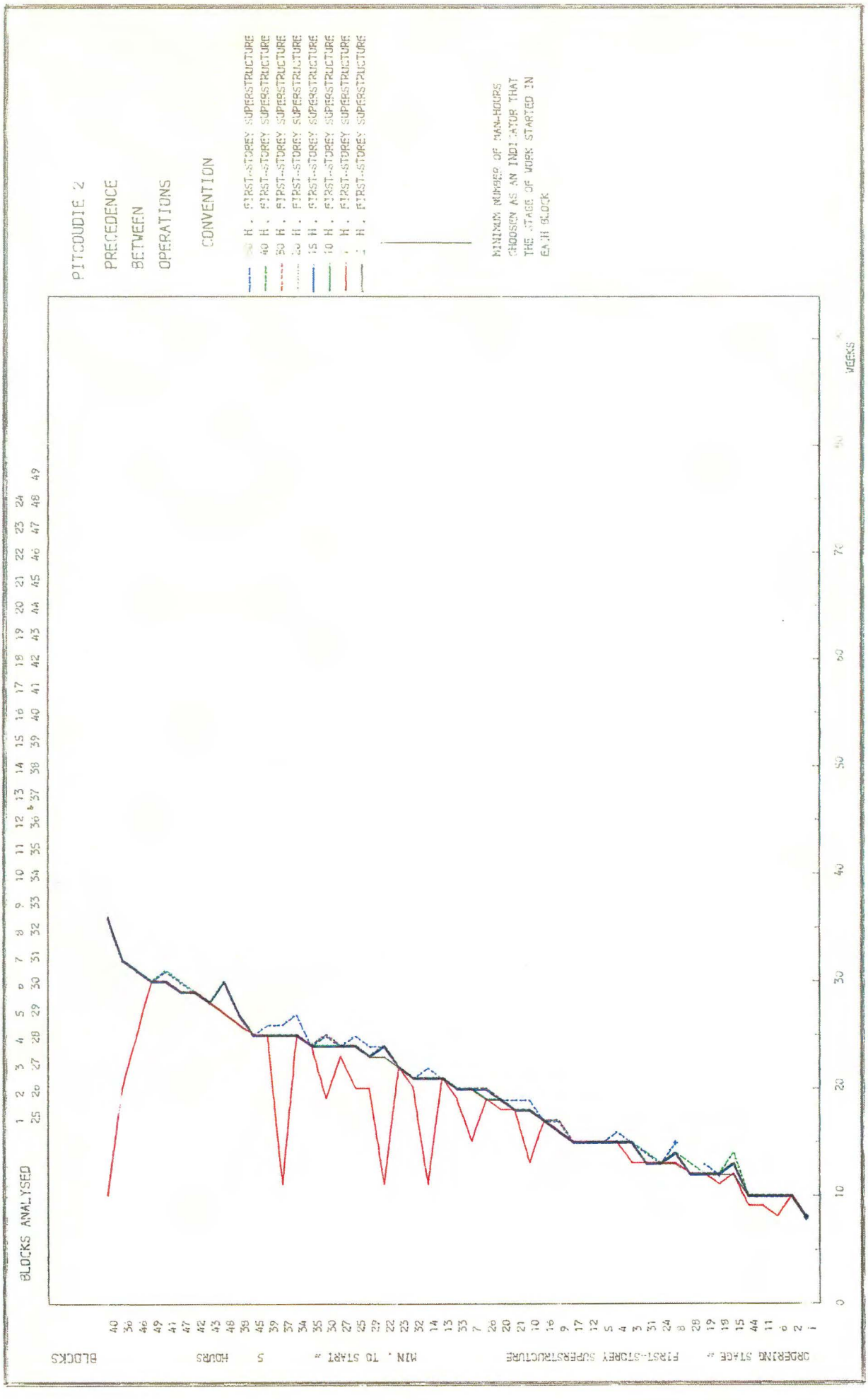

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
H . FIRST-STOREY SUPERSTRUCTURE
MINIMUM NUMBER OF MAN-HOURS
CHOOSEN AS AN INDICATOR THAT
THE STAGE OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
WEEKS
BLOCKS
HOURS
MIN. TO START #
FIRST-STOREY SUPERSTRUCTURE
ORDERING STAGE #

Figure 24

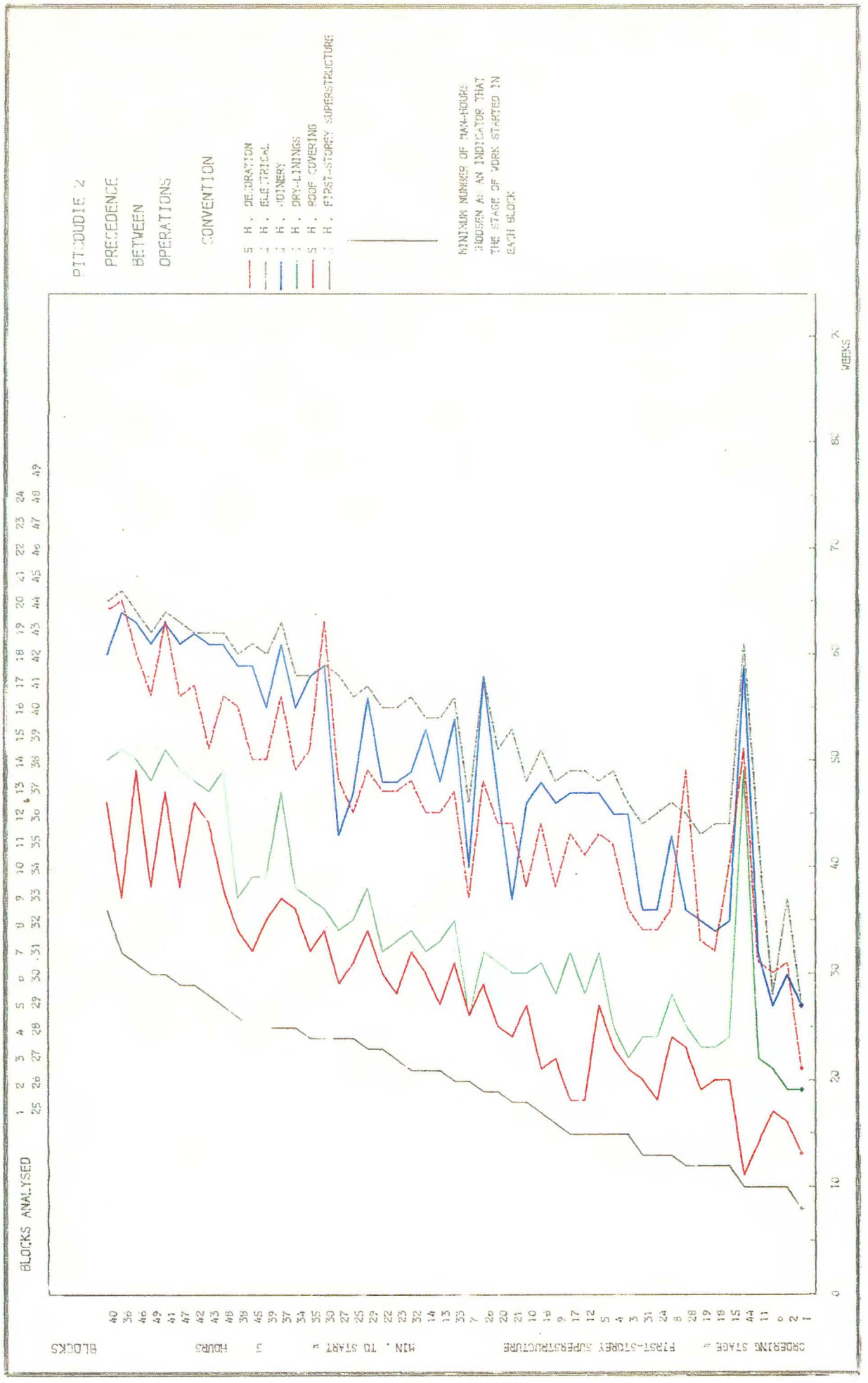

PITTOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
S H . DECORATION
H . ELECTRICAL
H . JOINERY
H . DRY-LININGS
S H . ROOF COVERING
H . FIRST-STOREY SUPERSTRUCTURE
MINIMUM NUMBER OF MAN-HOURS
CHOOSEN AS AN INDICATOR THAT
THE STAGE OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
WEEKS
ORDERING STAGE #
FIRST-STOREY SUPERSTRUCTURE
MIN. TO START #
HOURS
BLOCKS

Figure 25

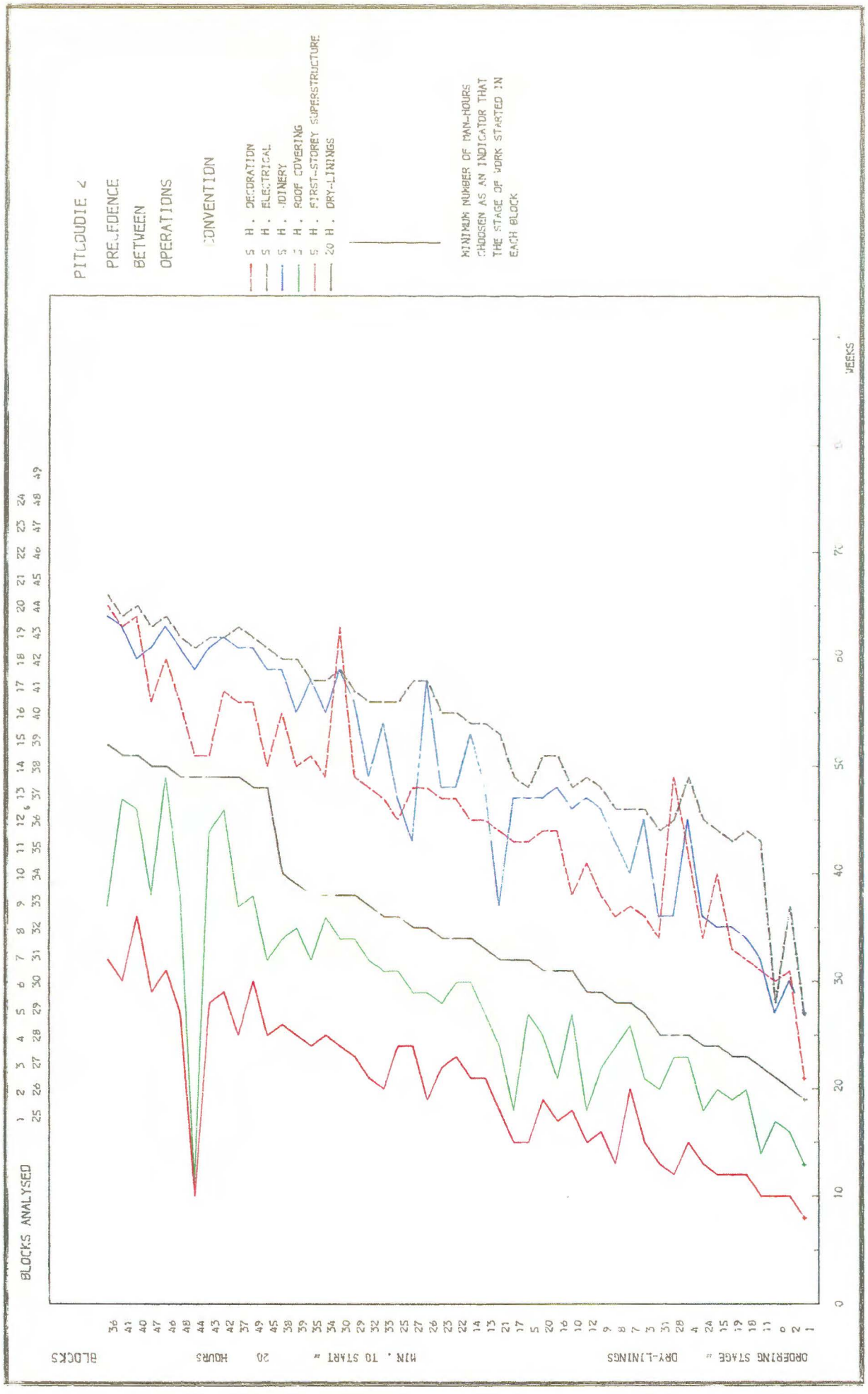

PITLOUDIE
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
5 H. DECORATION
5 H. ELECTRICAL
5 H. JOINERY
5 H. ROOF COVERING
5 H. FIRST-STOREY SUPERSTRUCTURE
20 H. DRY-LININGS
MINIMUM NUMBER OF MAN-HOURS CHOOSEN AS AN INDICATOR THAT THE STAGE OF WORK STARTED IN EACH BLOCK
BLOCKS ANALYSED
WEEKS
ORDERING STAGE = DRY-LININGS
MIN. TO START = 20 HOURS
BLOCKS

Figure 26

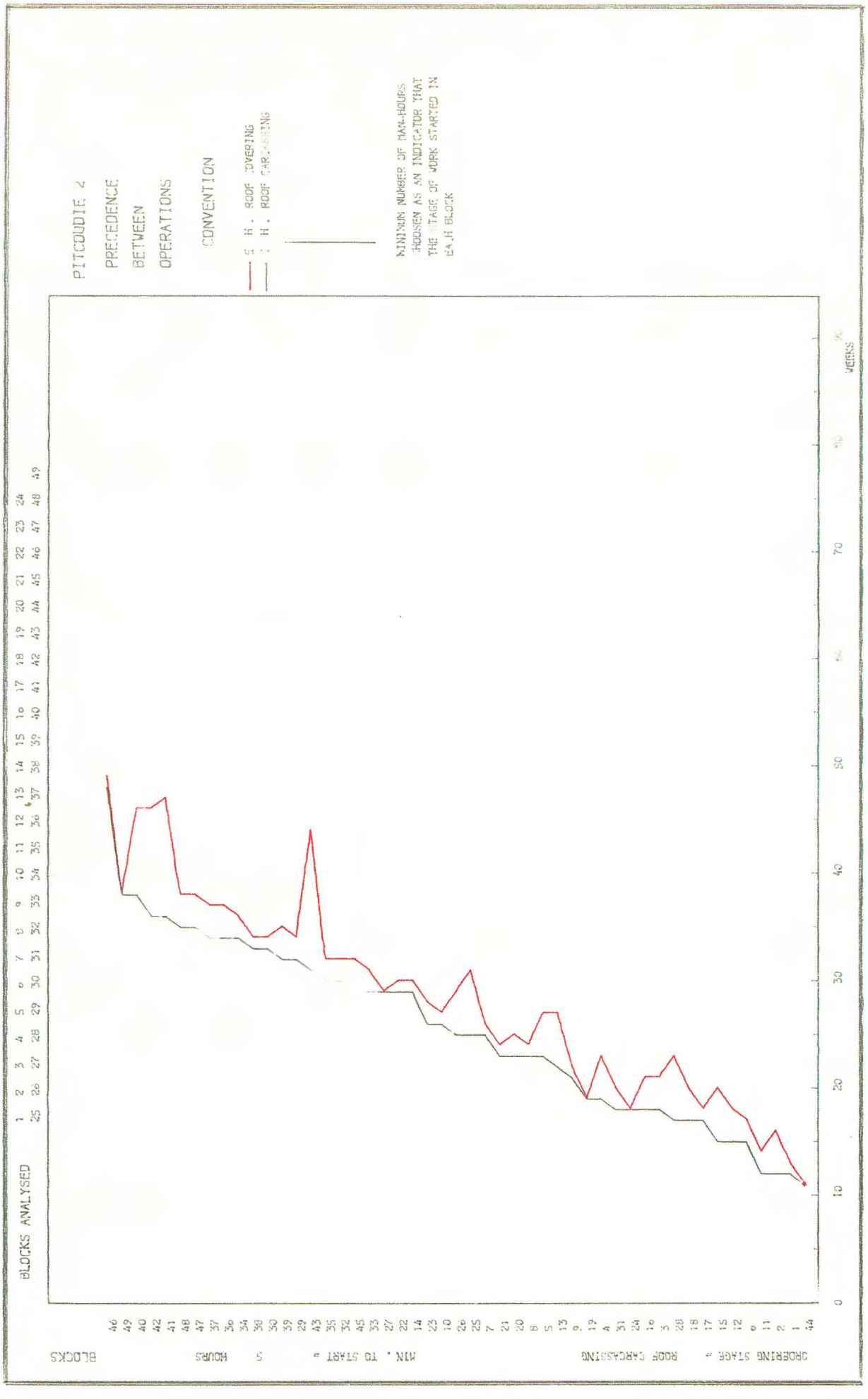

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
S H . ROOF COVERING
H . ROOF CARCASSING
MINIMUM NUMBER OF MAN-HOURS
CHOOSEN AS AN INDICATOR THAT
THE STAGE OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
WEEKS
HOURS
MIN . TO START
ROOF CARCASSING
BLOCKS

Figure 27

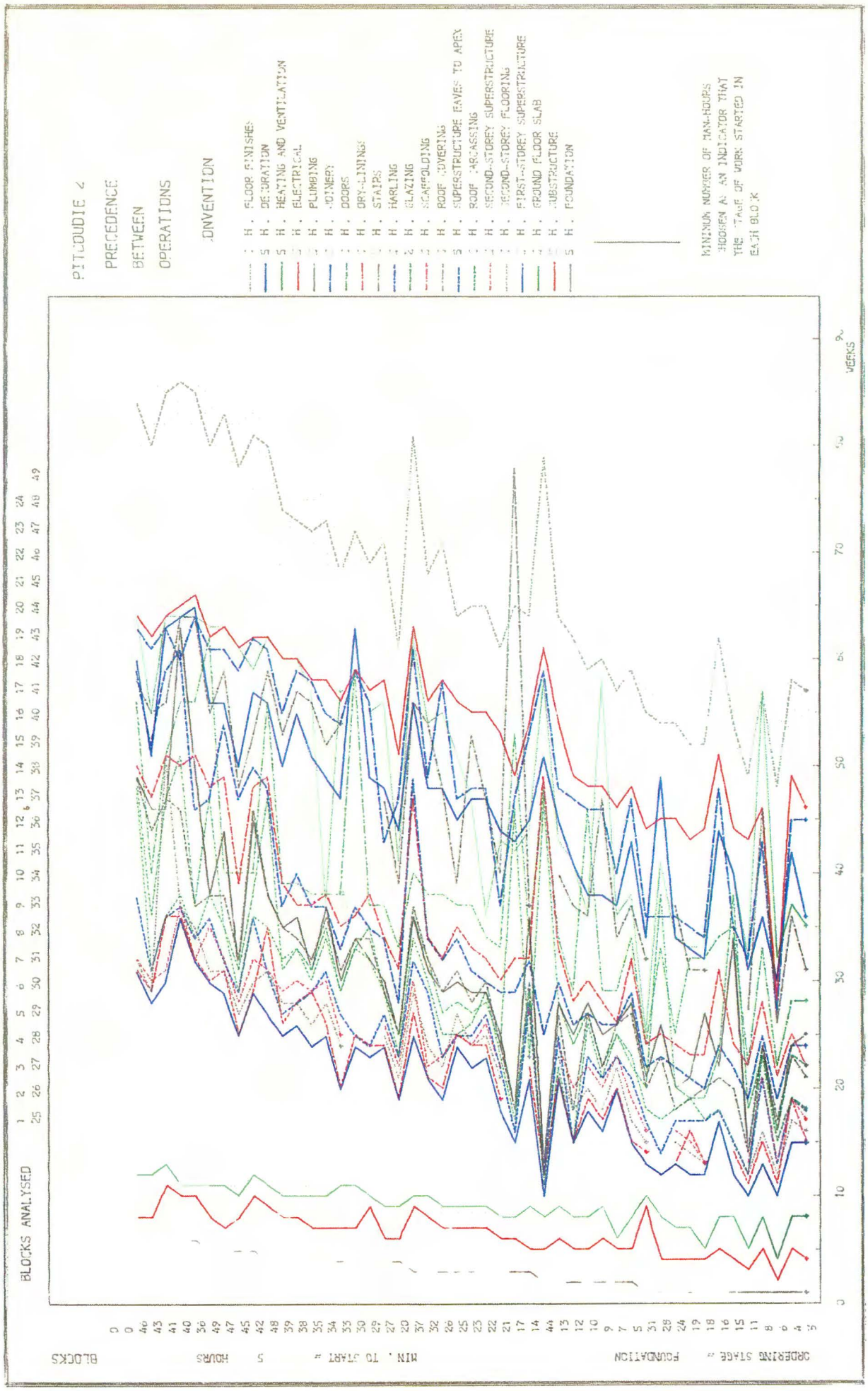

PITLOUDIE 4
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
H. FLOOR FINISHES
H. DECORATION
H. HEATING AND VENTILATION
H. ELECTRICAL
H. PLUMBING
H. JOINERY
H. DOORS
H. DRY-LININGS
H. STAIRS
H. HARLING
H. GLAZING
H. SCAFFOLDING
H. ROOF COVERING
H. SUPERSTRUCTURE EAVES TO APEX
H. ROOF BARGASSING
H. SECOND-STOREY SUPERSTRUCTURE
H. SECOND-STOREY FLOORING
H. FIRST-STOREY SUPERSTRUCTURE
H. GROUND FLOOR SLAB
H. SUBSTRUCTURE
H. FOUNDATION
MINIMUM NUMBER OF MAN-HOURS
HOOKEN AS AN INDICATOR THAT
THE TASK OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
WEEKS
BLOCKS
HOURS
MIN. TO START =
ORDERING STAGE = FOUNDATION

Figure 28

very confusing due to the lack of a rigid sequence of starts, and because several stages of work started almost simultaneously.

4.2.8 Program "Rate of Starts"

Difficulties with monitoring site progress resulting from the apparent unique starting order of each stage of work led to the creation of this program. Each stage of work is plotted according to its own starting order; no y axis annotation is given, because each stage of work would determine a particular one.

Figure 29 shows various lines of starts for the dry-linings stage of work obtained with different starting parameters. A decreasing number of blocks is plotted with increasing starting parameters, because the maximum weekly allocation of man-hours in some blocks was not as high as the minimum allocation of man-hours signaling the start of work.

This form of progress presentation has 2 major advantages over the preceding program output;

- graphical control of progress on site is easier due to the improved clarity;
- information is provided concerning the pool of work available ahead of each trade. It is possible to know the number of blocks started by the preceding trades; it would be necessary to ascertain that the number of blocks started is a good indicator of the work being made available by the preceding crews.

The major shortcoming of this form of presentation is that precedence bottlenecks in the work flow of individual blocks are not detected. Ideally, the line of balance technique gives information not only about precedence bottlenecks, but also about pools of work available ahead of each trade. Due to the uniqueness of the starting order for each

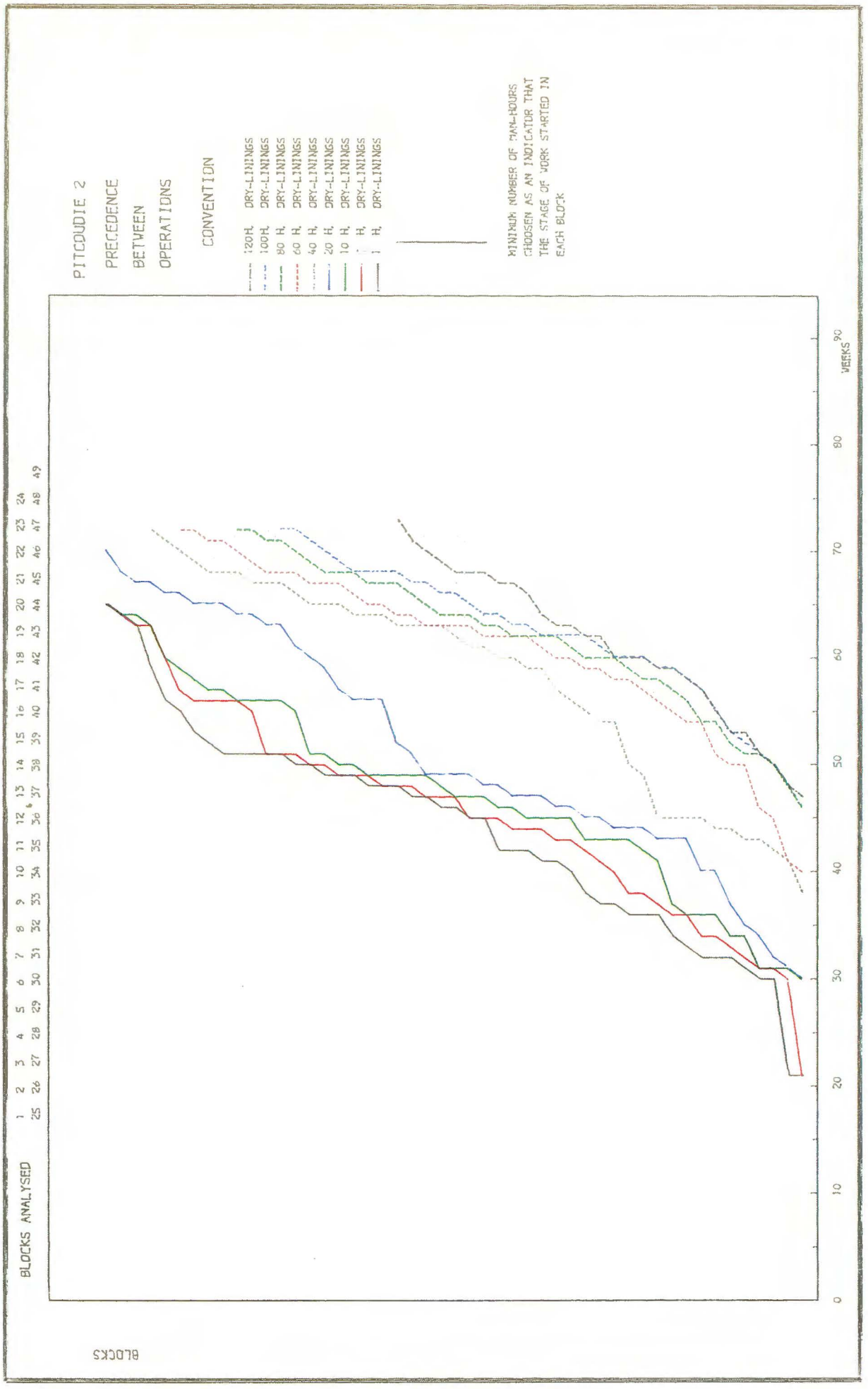

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
120H. DRY-LININGS
100H. DRY-LININGS
80 H. DRY-LININGS
60 H. DRY-LININGS
40 H. DRY-LININGS
20 H. DRY-LININGS
10 H. DRY-LININGS
H. DRY-LININGS
1 H. DRY-LININGS
MINIMUM NUMBER OF MAN-HOURS CHOOSEN AS AN INDICATOR THAT THE STAGE OF WORK STARTED IN EACH BLOCK
BLOCKS ANALYSED
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49
0 10 20 30 40 50 60 70 80 90
WEEKS
BLOCKS

Figure 29

stage of work, these important features of the line of balance progress chart control methods are lost and can only be partially restored by programs "Starting Order" and "Rate of Starts".

The pace of starts of the 21 most important internal stages of work is given in figure 30. The reader is requested to compare it with figure 28 in terms of clarity and usefulness for site progress control.

4.3 Discussion

4.3.1 The Graphical Software as an Analytical Tool

The graphical software was developed because the author felt that the output provided by the Site Activity Analysis Package was not sufficiently quick, flexible, and economical to analyse the wealth of information stored in the Building Research Establishment activity sampling data banks. The extraction of information from the computer files was made easy by the simple set of instructions contained in the package manual: however, the computer printouts were bulky, needing a lot of manual handling and rearrangement of the individual pages (including cutting and glueing) to allow a better appreciation of the information conveyed.

The graphical computer software is a step forward in terms of clarity and conciseness: the use of colour density instead of the number of hours allocated weekly to each stage is more meaningful when a general appreciation of how man-hours were spent on site is required. With small modifications to the programs it would be possible to provide numbers instead of colour densities, exactly as with the computer printout tables, though using a smaller area of paper due to the flexibility in plotting characters of different sizes.

The graphs add to the usefulness of the Site Activity Analysis Package output, because they can handle a greater number of variables per page. The graphs are not a substitute

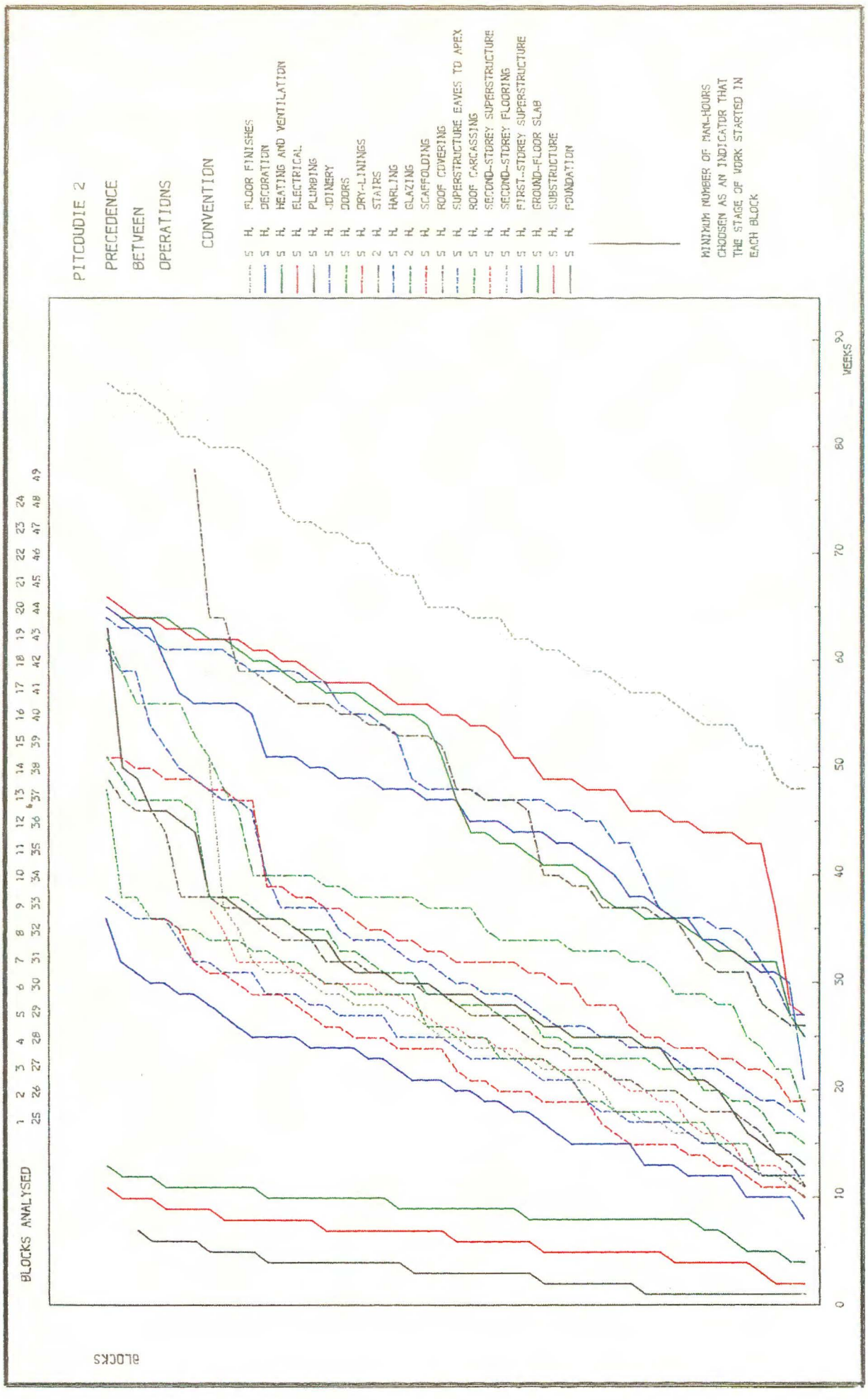

PITCOUDIE 2
PRECEDENCE
BETWEEN
OPERATIONS
CONVENTION
S H. FLOOR FINISHES
S H. DECORATION
S H. HEATING AND VENTILATION
S H. ELECTRICAL
S H. PLUMBING
S H. JOINERY
S H. DOORS
S H. DRY-LININGS
2 H. STAIRS
S H. HARLING
2 H. GLAZING
S H. SCAFFOLDING
S H. ROOF COVERING
S H. SUPERSTRUCTURE EAVES TO APEX
S H. ROOF CARCASSING
S H. SECOND-STOREY SUPERSTRUCTURE
S H. SECOND-STOREY FLOORING
S H. FIRST-STOREY SUPERSTRUCTURE
S H. GROUND-FLOOR SLAB
S H. SUBSTRUCTURE
S H. FOUNDATION
MINIMUM NUMBER OF MAN-HOURS
CHOOSEN AS AN INDICATOR THAT
THE STAGE OF WORK STARTED IN
EACH BLOCK
BLOCKS ANALYSED
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49
BLOCKS
0 10 20 30 40 50 60 70 80 90
WEEKS

Figure 30

for the tables, but should be used in conjunction with them. Numerical and graphical analyses are equally important in studying the progress of work on building sites.

Some of the disadvantages associated with the use of graphs are:

- dependence on scales and conventions to transmit the information: scales and conventions were set on a subjective basis in this research work;
- use of plotting devices rather than line printers; experience gained using the computing facilities at the research center indicates that plotter devices are slower, more expensive to run, and more prone to breakdowns than line printers.

Latterly, the author has been using a Ramtek colour video display unit; this piece of hardware will undoubtedly decrease the inconvenience and cost of using hard copy plotter devices. The provision of colour monitors for the great majority of micro-computers available on the market will also help to overcome the difficulties mentioned earlier on, mainly in practical applications at the level of the construction company. It is interesting to note that the great number of colours available in these monitors add a new dimension to the quantity of information each graph is capable of conveying.

4.3.2 Findings of the Graph Analyses

The more important qualitative conclusions drawn from the set of graphs produced for the 3 sites are given below. The reader is requested to bear the review of the literature in mind: several authors, after investigating the duration, precedence, and progress patterns of operations, have come to conclusions substantially supported by the analyses carried out during the course of this research work.

4.3.2.1 The Duration of Activities

The total duration of activities per block was generally large compared to the total time taken to build the blocks or total project duration. For the Pitcoudie 2 site, the average total duration of activities was in general half the time taken to build individual blocks (60' weeks), and a third of the time needed to complete the whole site (94 weeks). Similar results were produced for the other sites. The minimum average stage duration was 2 weeks, and the maximum average duration was almost equal to the total time taken by individual blocks. The 6 major stages (12 major operations for the Ladygate Lane site) were under construction in each block during 40% of the time taken to complete the sites, and 70% of the time needed to complete individual units. For the Ladygate Lane site, the finishing stages were under construction for an average of 28 weeks in each block, that is, almost half the project duration (65 weeks), and 75% of the time between the start of carcassing and practical completion of individual units (37 weeks).

The large durations were associated with intensities of work (man-hours/week) smaller than the ones that would have been achieved by deploying just one operative full-time to the task.

The average total duration of activities per construction unit far exceeded the time-lags between milestones marking important events in the house building process: for the Pitcoudie 2 site, the group of operations "carcassing", comprising first-storey superstructure, second-storey flooring, second-storey superstructure, roof carcassing, roof covering, and superstructure eaves to apex, was mainly performed between the "start of superstructure" and the "roofed-in" milestones; the time-lag between these milestones was on average 13 weeks, but the individual stages listed above took on average 26 weeks to be completed. The majority of the effort allocated to the activities was, however, deployed during the 13 weeks time-lag period (carcassing period).

The information presented in the preceding paragraphs was obtained purely on a qualitative basis; the development of more rigorous techniques to evaluate durations will be presented in Chapter Five.

The stages of work were interrupted several times; the long durations can be partially explained by the existence of a number of weeks when no work was recorded.

The allocation of resources was not constant throughout the duration of the activities. It became apparent that some particular weeks were responsible for the major use of resources. The "major effort" in each activity took only a small number of weeks of the total duration.

In the light of these findings, it is suggested that the concept of the duration of an activity should be reviewed: instead of talking in terms of an absolute duration, from the start to the finish of an activity, it would be better to talk in terms of the time taken to reach a predetermined level of effort, time taken at a sustained level of effort, or, finally, in terms of a set of durations more accurately reflecting the various phases of the allocation of resources.

4.3.2.2 The Precedence of Work within and between Blocks

Due to the fact that stages of work took a long time to be completed, it might have been expected that the precedence relationship between stages would not be of a head and tail type, but of an overlapping one. Proportions of the work of one stage were preceded or succeeded by proportions of the work of the other stages. This is not a new concept: reported research work by Carr (1971) suggests, and even commercially available network planning software allows, the introduction of lead/lag factors (overlapping factors) between activities or stages of work. The crux of the matter is the availability of quantitative measures of suitable lead/lag factors drawn from practical experience. The work described

in this chapter was not able to provide this information, because a rigorous analyses of durations is needed before any calculation of overlapping factors is possible. However, it makes it clear that precedence should not be defined as rigid chains of tasks, but as proportions of work accomplished on preceding activities such as to allow succeeding activities to be started or continued.

This concept could be applied not only to different activities in the same construction unit, but also to similar activities on sequential units. This research work showed that as far as the "minimum parameter" is a good criterion for the start of the stages work in a particular block, no 2 stages followed the same order of starts from construction unit to construction unit. It seems that wherever work was made available, operatives moved in, with little regard for the required sequence of work (flow of work) from block to block.

The fact that it was difficult to define the sequence of work through the use of a minimum allocation of man-hours signaling the effective start of work in each construction unit reflects 2 characteristics of the building sites under examination. First, that the blocks were not tackled on an individual sequence basis, but on a "rolling group of blocks" basis. Under these circumstances it would be preferable to specify a general flow of work through the site rather than a sequence of block numbers. The ordering of blocks in a Line of Balance control chart would be meaningless, and would cause confusion in terms of graphical presentation. Control charts of this kind would be useful only if blocks are treated on a non-specific basis, that is, it should not be a requirement to associate the progress of work on site with specific building units.

Secondly, the apparent lack of a stable sequence of work using different minimum starting parameters hints at the variability in the allocation of man-hours to stages during the initial weeks of their duration. In conclusion, the apparent lack of a stable sequence of work is what could

have been expected, if work was tackled on a rolling group of blocks basis, and highly variable allocations of man-hours were made during the initial weeks.

4.3.2.3 Time taken to build the Blocks

The average time taken to build the blocks on the 3 sites was of the same magnitude of the total project duration (blocks took on average 80% of the project duration for the Ladygate Lane and Pitcoudie 1 sites, and 70% for the Pitcoudie 2 site). The implications of these large durations are more important for the Pitcoudie 2 site than for the other 2 sites: Pitcoudie 2 was a much bigger site (4.5 times bigger than Ladygate Lane, and 2.5 times bigger than Pitcoudie 1). It is interesting to note that the total time taken for each block was fairly constant, despite the physical differences in their size: the duration of blocks produced coefficients of variation smaller than 10% within each individual site.

4.3.2.4 Inter-milestone Time-lags

The observation of figures like No. 05, No. 06 and No. 07 allowed the identification of the kind of milestones used in recent developments of programming techniques (D. Morris-1982, Crandall and Woollery). It was possible to identify 7 milestones and 5 groups of operations, according to the following breakdown:

milestone	group of operations
start of substructure	
	substructure
end of substructure	
start of superstructure	
	carcassing
"roofed-in"	
	dry-linings
end of dry-linings	
	finishings
practical completion	
	scatter finishings
final handover	

A brief analysis of milestones and groups of operations led to the following conclusions:

- time-lags between milestones within a site were fairly constant, despite the differences in block size; in general, they produced coefficients of variation of around 15%;
- the timber-framed superstructure for the Ladygate Lane site led to a decreased time-lag for the carcassing and plastering work (10.8 weeks against 21.8 and 24.0 weeks respectively for the Pitcoudie 1 and 2 sites); it was not possible to subdivide the work in carcassing and dry-linings as for these 2 latter sites. The finishing stages, though, took longer on the Ladygate Lane site (35.8 weeks against 18.9 and 27.0 weeks for Pitcoudie 1 and 2);
- the finishing trades paid several random visits to each block after practical completion; this low intensity and discontinuous work increased the total duration per block by an average of 9.3 weeks for the Ladygate Lane site, and 5.3 and 7.0 weeks, respectively, for the Pitcoudie 1 and 2 sites;
- substructure proceeded at a much faster pace than the other groups of operations creating a lock-up of capital at Pitcoudie 2 (substructure standing ready for further work during an average of 7 weeks), and the interruption of substructure work at Ladygate Lane for 13 weeks to let the other stages catch up;

- blocks passed through milestone events at a reasonably constant rate for each group of operations; the lines of progress showed very little curvature. The practical completion rate was constant, but the rate of final handovers was erratic;
- the rates at which blocks passed through the various milestone events declined from start of substructure to practical completion. Practical completion events were reached at a rate 35% slower than superstructure starts for the Pitcoudie 2 site; the same rate was 48% slower for the Pitcoudie 1 site. No decline was observed for the Ladygate Lane site, probably due to the small number of repetitions (10 blocks);
- the rates at which milestones were reached varied from 7.0 blocks/week for start of substructure on the Pitcoudie 2 site to 0.4 blocks/week for all the milestone events on the Ladygate Lane site. Practical completion rates were 1.7 blocks/week and 1.4 blocks/week on the Pitcoudie 1 and 2 sites respectively.

The use of the graphical software to obtain production information indicated the need for more quantitative studies with a view to supporting the qualitative evidence that has been gathered. The next chapter describes the numerical and statistical techniques used to study the duration of activities as a function of the resources deployed on them.

CHAPTER FIVE

NUMERICAL AND STATISTICAL ANALYSES OF THE DURATION OF ACTIVITIES

This chapter deals with the analyses and estimation of the duration of activities. A new methodology for the measurement of durations based on activity sampling data is given, together with a description of the major difficulties faced during its development.

5.1 The Definition of the Duration of Activities

5.1.1 Introduction

The original data bank for the Ladygate Lane, Pitcoudie 1, and Pitcoudie 2 sites comprised the totality of snap observations, respectively some 104,000, 110,000 and 290,000 pieces of time-related information. The production of the Site Activity Analysis Package tables is aimed at reducing this enormous amount of data to manageable proportions. For several reasons already dealt with in Chapter Three, the author decided to produce tables at higher levels of aggregation. Chapter Three and Chapter Four discussed some of the advantages and disadvantages associated with that decision. The forthcoming section will illustrate a particular problem in the measurement of durations caused by the decision to work with data aggregated at the level of weeks rather than days. The identification of significant weeks in terms of resource allocation was the first step in the development of work for this chapter.

5.1.2 The Identification of Weekly Significant Occurrences of Work

The total number of hours allocated per stage per week was the information available for the calculation of durations.

A straightforward measurement of the duration of activities would be just to count the number of weeks in which work had occurred. However, this oversimplification of the problem was not encouraging as will be seen in the following paragraphs.

Due to the workings of the Site Activity Analysis Package, the amount of labour resources allocated weekly , represents an accumulation of man-hours deployed to the activity from Monday to Monday, with no indication on the exact timely occurrence of work during the week, or on its continuity. For example, a weekly allocation of 10 man-hours could have been obtained through the observation of one man working continuously during 10 hours, or visiting the work place 10 times during the week, or, finally, by the observation of a gang of 10 operatives instantaneously engaged in the activity. The duration of the activity would be taken as one week, while according to the latter example it could have been instantaneous.

Even if it is apparently obvious that the activity was performed continuously during a number of weeks, some uncertainty still remains on the exact number of days represented by the first and last weeks. In the hypothetical example given below, the specially high allocations (as it will be demonstrated later) in the intermediate weeks are an indication that work was performed continuously during weeks No. 11 and 12; however, the actual duration can be anything between 2 and 4 weeks, depending on how far work spread to weeks No. 10 and 13.

weekly allocation (man-hours)			25	60	75	35			
Week No.	08	09	10	11	12	13	14	15	16

It should be borne in mind that the availability of information aggregated on a daily basis would solve the problem only partially; again, due to the nature of the package aggregation process, no information would be available on exactly when during the day the activity started or finished. The same reasoning can be extended to all other levels of data aggregation, that is, morning or afternoon periods, hours,

minutes, etc. The use of activity sampling data to calculate durations will always imply an inaccuracy of the same magnitude of the average intervals between observation rounds. Furthermore, high values for the average intervals (say days) will make it increasingly difficult to attest on the continuity of work on site.

This first difficulty could be considered irrelevant, because activity sampling data could have been obtained at any duration-related accuracy, as a function only of the frequency of observation rounds. Observations were made in general at hourly intervals for the 3 sites under investigation: therefore it would be possible to produce durations accurate at the level of hours. However, the next paragraph will show that the frequency of observation rounds is not the only factor influencing the identification of the duration of activities.

Scattergrams of the weekly allocation of man-hours to the activities showed a wide dispersion of the amount of resources deployed in consecutive weeks. Figure 31 depicts 3 typical examples of scattergrams obtained for the Ladygate Lane site. Just a few of the operations produced graphs as in figure 31.a, that is, work occurring during only 1 or 2 weeks. Figure 31.b and 31.c are representative of the majority of scattergrams produced. No clear pattern of allocation is discernible; there was a great number of interruptions of work and allocations of different magnitude; the number of weeks without the occurrence of work was of the same order as the number of weeks in which work had taken place. If anything, the cumulative plot of resources allocated vs. time elapsed might produce an "s" shaped curve, but certainly the interruptions of work would blur the picture, and make it more difficult to fit a representative curve. Weeks without work could be removed, but it would still be necessary to justify the inclusion of weeks with low allocations of man-hours.

The observation of the 90 scattergrams similar to those ones, respectively dealing with 51 operations in Ladygate Lane, 18 stages of work in Pitcoudie 1, and 21 stages of work

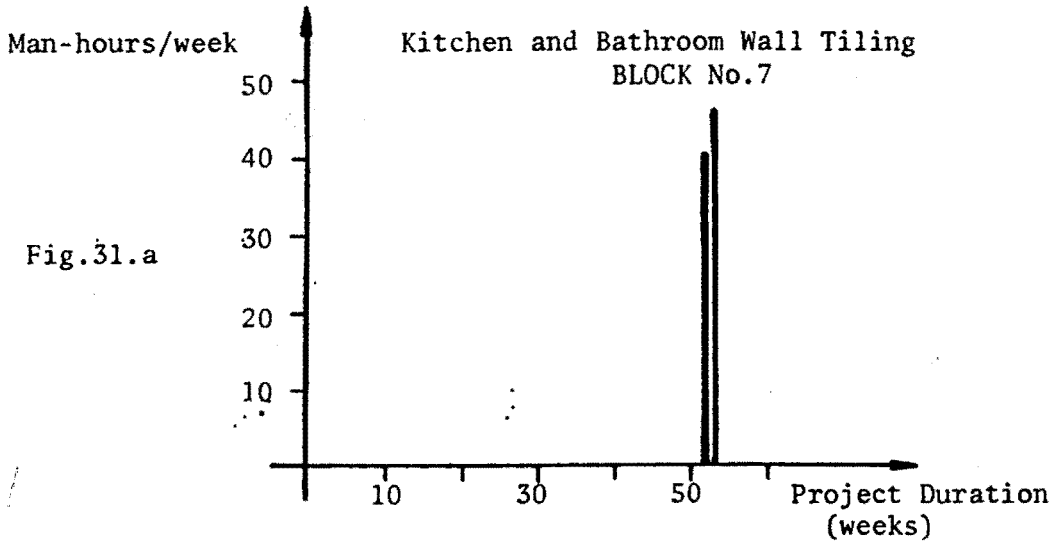


Fig.31.a

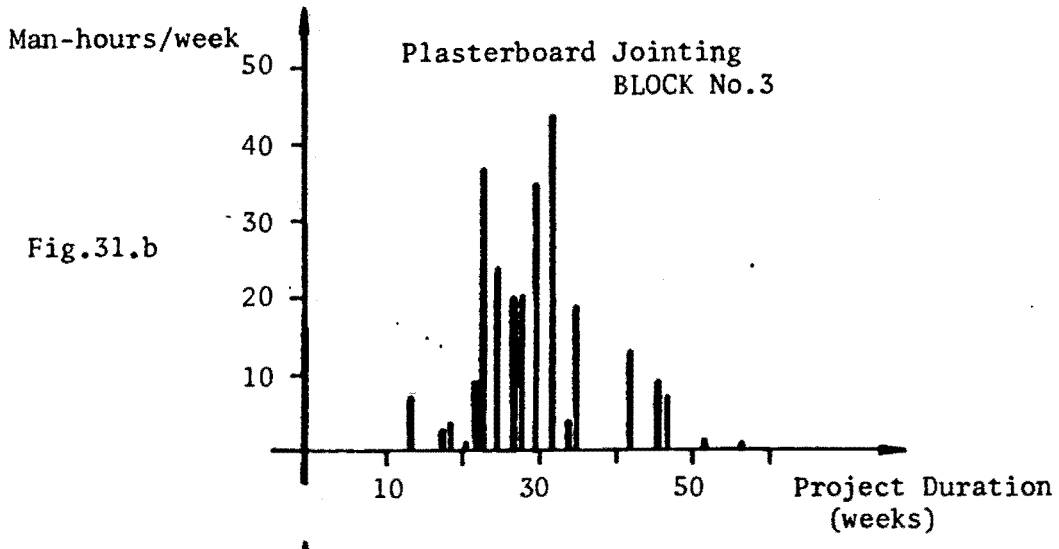


Fig.31.b

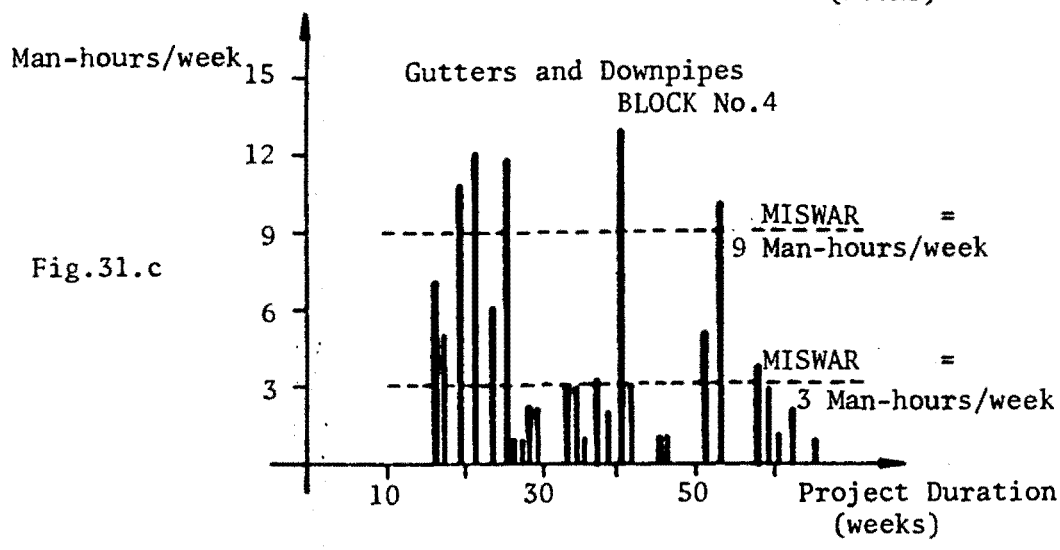


Fig.31.c

Figure 31

Weekly Allocation of Man-hours to 3 Operations

on the Ladygate Lane Site

in Pitcoudie 2, suggested that it is not possible to obtain the duration of activities just by counting the weeks in which work had taken place. Common sense dictates that the allocation of just 1, 2, or 3 man-hours per week to an activity is not an indication that work was undertaken seriously during that time period. This is more so if it is remembered that the data bank used in this research work contained all observations made on site, including productive, ancillary, and non-productive time. If the operative was just passing by the work place, or if he decided to take his unofficial tea break there, the observation will still count as one man-hour of work, and after the aggregating procedure, as one week duration of work. Therefore, it is necessary to decide first on a minimum weekly allocation that would be a good indication that substantial effort was devoted to the activity during the time period.

A reasonable approach is to count towards the total elapsed time only the weeks in which the allocation exceeded a given amount. Graphically this approach corresponds to drawing horizontal lines at specific y values in figure 31.c, and counting the number of weeks with allocations that are at or above this line. These y values will be called minimum significant weekly allocation of resources (MISWAR for short) throughout the rest of the thesis.

The observation of the scattergrams allowed 3 main types of occurrence of work to be identified. They are illustrated in the following hypothetical diagrams:

- isolated:

weekly allocation			12		01		43			
week No.	03	04	05	06	07	08	09	10	11	12

- semi-isolated

weekly allocation			14	01		18	31			
week No.	03	04	05	06	07	08	09	10	11	12

- continuous

weekly allocation		02	18	23		20	11	35	01	
week No.	03	04	05	06	07	08	09	10	11	12

The continuous case can be further subdivided into starting/finishing weeks and truly continuous weeks. In the diagram for the continuous case, weeks No. 4, 6, 8, and 11 would be considered starting/finishing weeks, while weeks No. 5, 9, and 10 would be truly continuous weeks.

A different approach would be to count towards the, duration of the activity only the number of truly continuous weeks, adding or not adjusted amounts corresponding to the isolated, semi-isolated and starting/finishing continuous occurrences of work. However, the proportion of the duration spent on truly continuous weeks is rather small: it accounted for less than 45% of the total number of occurrences of work for the 6 major stages, and less than 15% for the 6 least important stages in terms of total consumption of man-hours on the 3 sites. This fact, plus the lack of any objective procedure for adjusting the durations for the isolated, semi-isolated, and starting/finishing weeks prevented the use of this approach.

Therefore, the problem of identifying the duration of activities for each construction unit (10 blocks, 29 blocks, and 49 blocks for the Ladygate Lane, Pitcoudie 1, and Pitcoudie 2 sites respectively) requires not only the identification of significant weekly efforts but also the acceptance of high uncertainty for the values of the measured durations: actual durations will probably exceed the number of truly continuous weeks, provided that a high minimum significant weekly allocation of resources is set as the criterion to include or exclude weeks in their measurement; however, the actual duration for the stages of work on each site could be anything between the number of truly continuous weeks and the total number of weeks; the range of values established by these numbers was almost 1:2 for the major stages of work on the 3 sites.

The ultimate goal of this research work is to provide means of predicting the duration of activities. This can be achieved, for example, by relating the duration of the activities to the respective labour consumptions per block. A regression model would be able to define such relationship. However, the

inaccuracy in the measurement of both variables, durations and resources, is large. The example of figure 32 should be sufficient to illustrate the wide range of relationships that it is possible to obtain. Data for figure 32 was prepared under the assumption that the isolated, semi-isolated, and start/finishing continuous weeks for a MISWAR of 8 man-hours were subject to a uniform distribution. The assumption of a uniform distribution means that work had an identical probability of starting and finishing in any day of the week. The variance (square of the standard deviation) for a uniform distribution is given by the range of possible values (0 to 1 week) divided by 12. The work on different weeks was considered statistically independent, thus standard deviations were combined according to the square root formula. The following hypothetical example should make it easier to understand how durations were calculated.

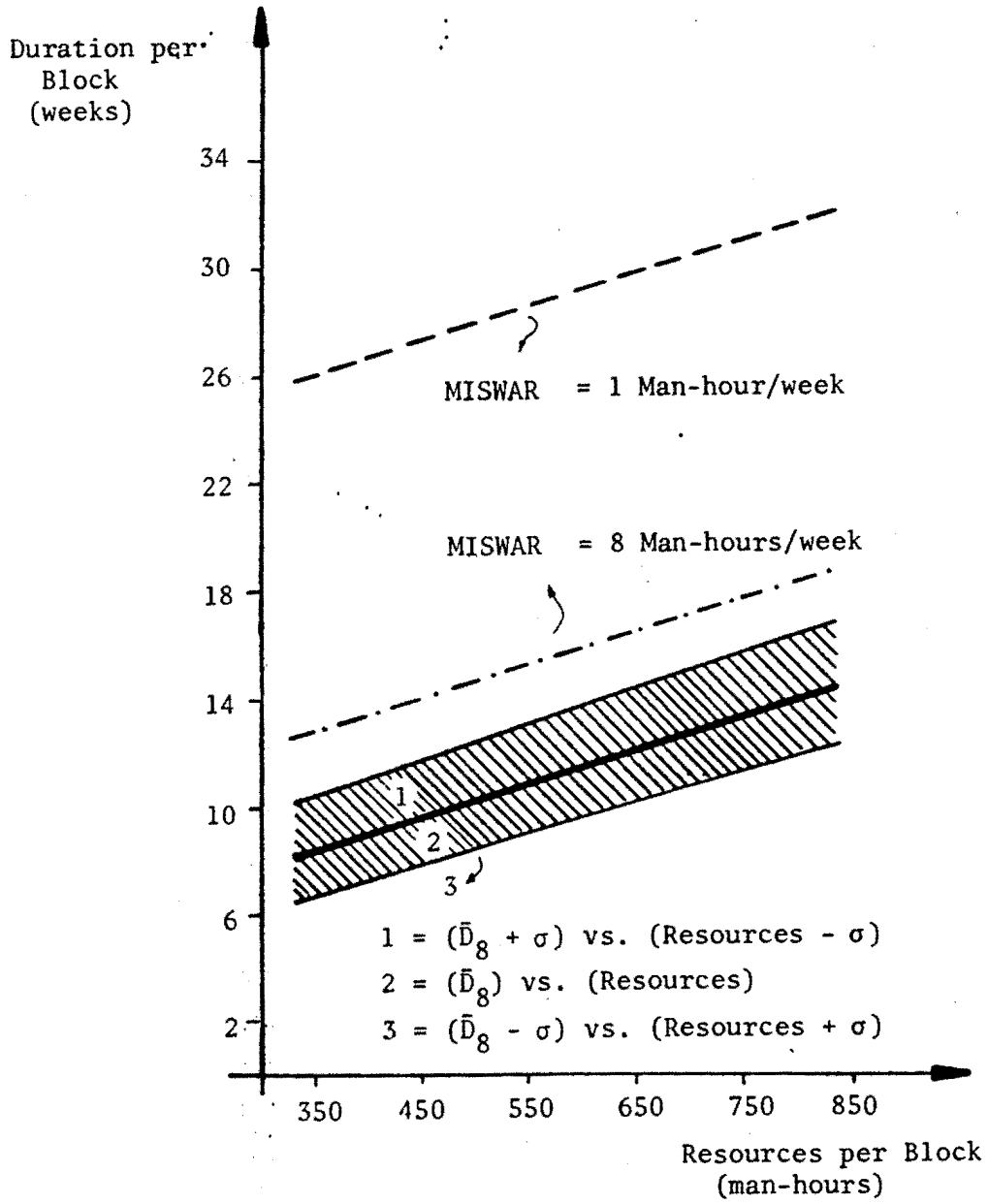


Figure 32

Regression of Durations on Resources for the Operation "Window Linings, Doors, Skirtings", Ladygate Lane Site

weekly allocation		18		01		04	13	23		02	09	18	34	
Week No.	03	04	05	06	07	08	09	10	11	12	13	14	15	16

Calculations for an Hypothetical Example standard deviation= std.	Contribution to the Duration		
	Duration -1 std.	Average Duration	Duration +1 std.
- weeks without work:			
No. 3, 5, 7, 11, 16	0.00	0.00	0.00
- weeks not taken into account (allocation <8):			
No. 6, 8, 12	0.00	0.00	0.00
- isolated weeks:			
No. 4			
average duration= 1*0.50=0.50	0.50	0.50	0.50
standard deviation (1*1/12)**0.50=0.29	-0.29	-	+0.29
- semi-isolated weeks:			
No. 9, 10			
average duration= 2*0.50=1.00	1.00	1.00	1.00
standard deviation= (2*1/12)**0.50=0.41	-0.41	-	+0.41
- continuous weeks:			
starting/finishing weeks:			
No. 13, 51			
average duration= 2*0.50=1.00	1.00	1.00	1.00
standard deviation= (2*1/12)**0.50=0.41	-0.41	-	+0.41
truly continuous weeks:			
No. 14			
average duration= 1*0.50=0.50	0.50	0.50	0.50
standard deviation= nill	-	-	-
Total Duration (weeks)	2.39	3.50	4.61

Three pairs of duration and total labour consumption per activity per block were calculated. The first one corresponds to the average duration and the number of hours allocated to the activity, as obtained from the Site Activity Analysis Package tables. The second one corresponds to the average duration less 1 standard deviation, and the upper 1 standard deviation confidence limit for the number of hours observed.

Finally, the third pair corresponds to the average duration plus 1 standard deviation, and the lower 1 standard deviation confidence limit for the number of hours observed. Figure 32 shows the regression lines for these 3 types of pairs of values. In addition, it depicts the regression model obtained for durations calculated with a 1 man-hour MISWAR and a 8 man-hour MISWAR, that is, counting towards the duration of the activity weeks in which the allocation of resources exceeded 1 and 8 man-hours respectively. Lines 1, 2, and 3 in figure 32 set the boundaries for all possible regression models obtained with durations and resource allocations varying within ± one standard deviation of the measured values. It should be emphasized that the band of values has nothing to do with the usual confidence limits of regression models, originated by the fact that data represents only a sample from a wider population: the band of regression lines is solely related to the inaccuracy in measuring durations and resource usage. The inaccuracy in measuring resources is relatively small when compared with the inaccuracy in measuring durations: activity sampling data used to obtain figure 32 indicated that errors for the measurement of resources had a coefficient of variation of 3.7%, against 27% for the measurement of durations. Therefore, the band width of regression models is mainly due to the inaccuracy in the measurement of durations.

The band of regression lines derived for the particular set of confidence limits imposed on the measurement of duration and resource allocation is such that predicted durations will fall in a range 1:1.7 for every amount of total estimated resource consumption. The example put forward in figure 32 indicated that the level of activity sampling data aggregation was still small for the building of useful and accurate models.

Thus, data was aggregated at another still higher level of aggregation. Stage labour consumption was totalled for all blocks; likewise, durations were taken as the sum of durations in each individual block. For the 3 sites under investigation, the total duration of an activity calculated by this method was different from the total time taken by the activity (the time that the trade concerned stayed on site).

This was caused by the overlapping of work in consecutive blocks. It is worth mentioning that Line of Balance concepts for just one crew per activity would equal these 2 durations, because no overlapping of work is considered. Figure 33 illustrates how this new aggregate duration was defined, and how it differs from the total time the respective trade stayed on site. The improvement in accuracy is illustrated in table 07; data for the "window linings, doors, skirtings" operation for the Ladygate Lane site was used in the calculations; a MISWAR of 8 man-hours was considered; isolated, semi-isolated, and starting/finishing continuous weeks were assumed to follow a uniform distribution. Table 07 shows that there is a 66% chance that durations and resources were in a band ± 8.89% and 3.71% respectively around the values measured for individual blocks; if durations and resources are aggregated according to the proposed method, the band of values is narrowed down to ± 2.74% and ± 1.10% respectively.

The remainder of this chapter deals with the analyses of durations and resources aggregated at this new higher level. The 2 main disadvantages of this proposed method are discussed in the following paragraphs.

Information at the level of individual construction units is lost. However, the developments in Chapter Four showed that overlapping of work was considerable; blocks were undertaken on a rolling group of units basis. This fact allows the author to suggest that the production information for each individual block is not as important for the crews concerned as the total amount of work available on site, the permissible spreading of work to the various blocks, and the approximate flow of work. General information at tactical level should be sought before the detailed information at operational level. Moreover, the small architectural differences from housing type to housing type, and the different dwelling mix of blocks make it more difficult and less statistically significant to compare resources and durations for individual units.

No advantage is taken of the repetitive nature of house building sites to provide statistical information;

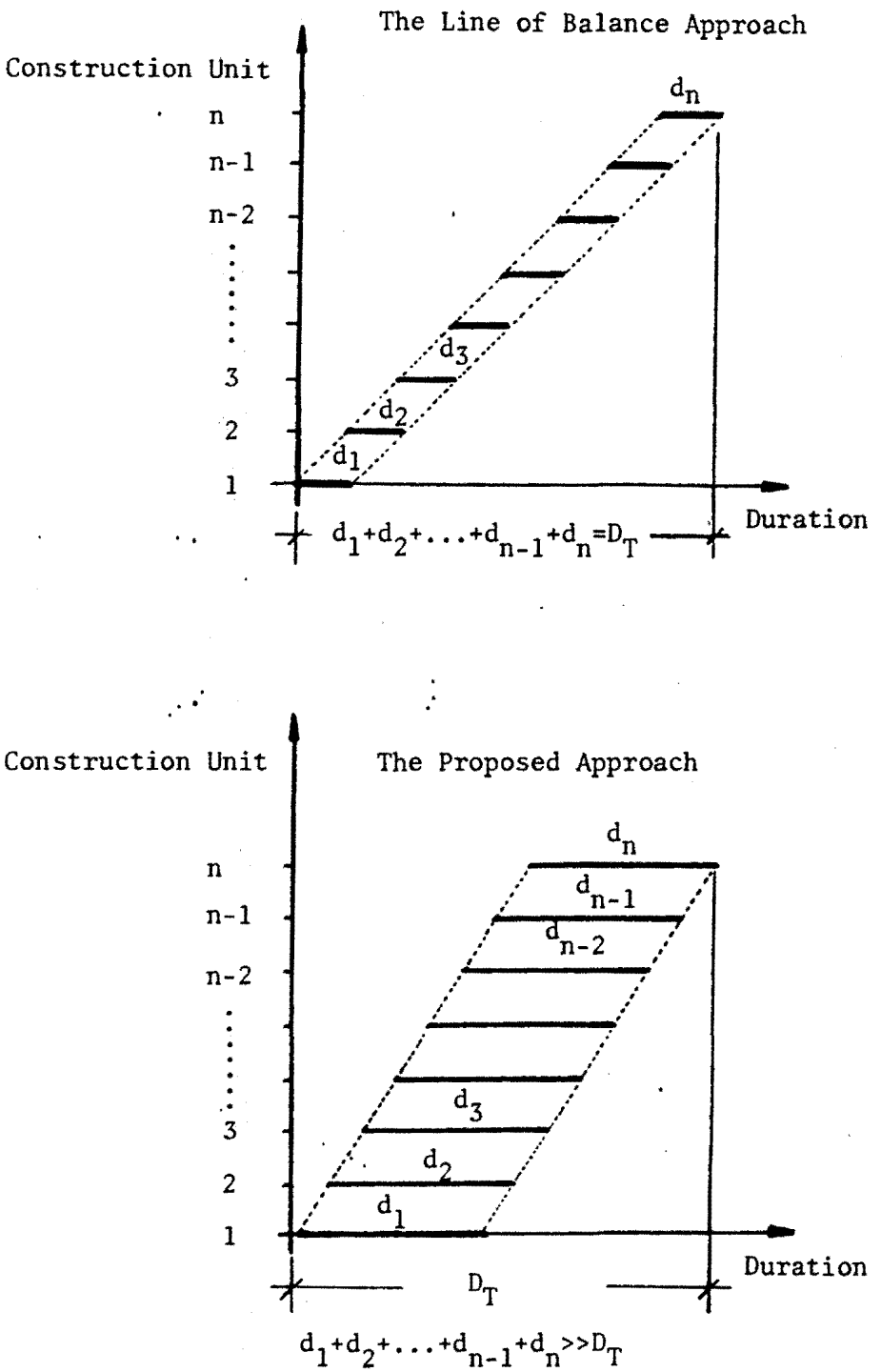


Figure 33

The Line of Balance and the Proposed Approach

for Unit Duration and Total Duration

TABLE 07

Improvement in the Accuracy of Durations and Resources for Aggregate Data, Ladygate Lane Site, "Window Linings, Doors, Skirtings" Operation

Blocks	Durations			Resources	
	Average D_8	s.t.d.	c.v. %	Man-hours	Accuracy ± %
1	10.5	0.958	9.12	354	4.33
2	10.5	0.866	8.25	479	3.72
3	11.0	0.817	7.43	599	3.32
4	6.0	0.817	13.62	488	3.68
5	7.5	1.118	14.91	411	4.02
6	12.0	0.913	7.61	751	2.96
7	15.5	0.958	6.18	835	2.81
8	12.0	0.577	4.81	478	3.72
9	8.5	0.866	10.19	395	4.10
10	9.5	0.646	6.80	329	4.49
Average	10.3		8.89%	512	±3.71%
TOTAL	103		2.741	5119	±1.10%

NOTES

1) s.t.d. = standard deviation
2) c.v. = coefficient of variation
3) Accuracy was calculated for a 66% confidence level

construction industry projects are generally of a "one-off" kind; construction companies have very few opportunities to observe the repetition of experiments, that is, to build the same building again or to undertake the same set of activities on different sites, under controlled conditions. House building sites provide the unique opportunity for replicated experiments; for example, the largest of the 3 sites, Pitcoudie 2, would make it possible to make statistical inference based on 49 repetitions (there are 49 housing blocks on this site); the proposed aggregating method reduces the 49 repetitions to just one pair of variates (resource usage and duration). Fortunately, as it will be seen in this Chapter, the activities showed very similar production characteristics, which made it possible to explore in a unique study the variates produced by the 51 operations in Ladygate Lane, the 18 stages of work in Pitcoudie 1, and the 21 stages of work in Pitcoudie 2 (total of 90 activities).

Some other definitions were needed before it was possible to derive the duration vs. resource models for this research work. Firstly, instead of defining a specific value for the minimum significant weekly allocation of resources, all possible durations for the whole range of MISWAR were calculated, in the hope that the different durations thus obtained could be somehow related. Secondly, the duration was taken as the number of weeks in which an allocation greater or equal to the MISWAR occurred. Isolated, semi-isolated, and starting/finishing continuous weeks were not assumed to follow a uniform distribution as in the preceding examples. This clearly introduced a bias in the calculation of durations. Durations obtained with a small MISWAR (say 1 to 10 man-hours) were overestimated, because the work performed in weeks with total man-hour allocations in this range probably did not take the whole week. Durations obtained with a large MISWAR (say greater than 40 man-hours) were probably unbiased due to 2 reasons:

- high MISWARs tended to eliminate the majority of isolated, semi-isolated, and start/finishing continuous weeks, thus counting only the truly continuous weeks;

- the review of literature in Chapter Two pointed out that weekly allocation of resources to activities or even houses was small on the sites observed by different authors (in general less than 40 man-hours); therefore, it is likely that the activity was worked all the time available during the week, if allocations greater than 40 man-hours were to be achieved.

The aggregating procedure just made the biases more stable than they would be if durations and resources were to be calculated at the level of individual blocks. A calibration exercise is still needed, using work study or other continuous method of observation, in order to throw light on the quantitative aspects of the bias introduced by each MISWAR.

5.1.3 The Relationship between Different MISWARs and some Duration-related Production Characteristics

5.1.3.1 Total Duration of Activities and the Number of Interruptions

This section is aimed at supporting the conclusions, put forward in Chapter Four, that activities took a long time period to be completed, with a great number of interruptions.

The total duration for each activity was obtained by adding the total duration for the activity in each block. For each block, the activity was considered started once the MISWAR was exceeded and finished once all the succeeding allocations were smaller than the MISWAR. The total duration was taken as the time lapsed between the starting and finishing week. Total durations measured in this way were called "DOn", where "n" is the MISWAR value. For example, "DO1" is the total duration, including interruptions of work, for a 1 man-hour MISWAR. D1 and D8 were obtained by counting towards the duration of the activity only the weeks with allocations greater or equal to 1 and 8 man-hours respectively.

The following example will illustrate the procedure to arrive at the number of interruptions and total duration

for different MISWARs: a hypothetical stage and block are examined; a MISWAR of 16 man-hours was chosen for this example.

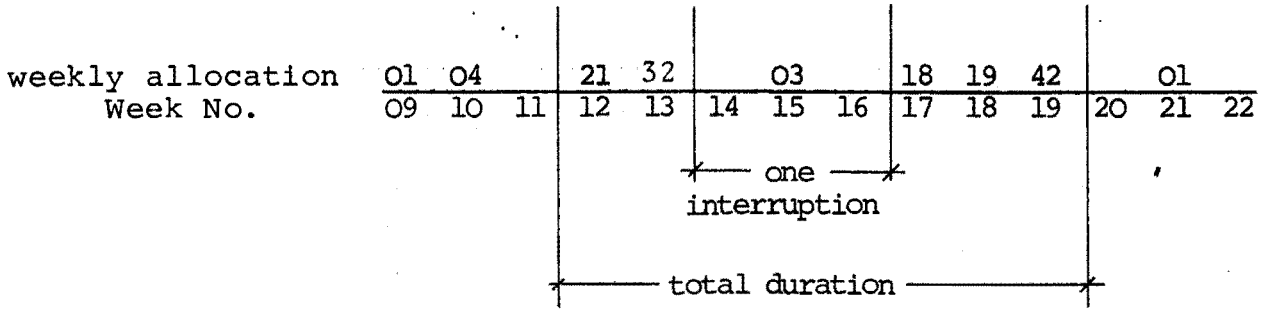


Table 08 shows the total duration and number of interruptions for the 6 stages of work that consumed more labour resources on each site. A 1 man-hour and a 8 man-hour MISWARs were used to produce the table. Durations and interruptions are given as averages per block. Interesting points that arise from the table are: total duration (D01) was around 30 weeks; on average 4 work interruptions were made per stage, that is, it was necessary to visit the work place 5 times to complete the stage; the number of weeks without work (D01-D1 or D08-D8) was slightly higher than the number of weeks with work; design rationalization for the finishing stages in the Pitcoudie Project was successful in producing a smaller total duration and number of interruptions; the electrical stage of work (the object of several remarks throughout this thesis) was actually performed without interruptions, if an 8 man-hour MISWAR is the criterion for the measurement of durations; the average duration of interruptions of work was around 4 weeks.

5.1.3.2 Percentage Duration vs. Percentage Resource Usage

Durations were calculated for every MISWAR, now taking into account only the number of weeks with the occurrence of labour allocation greater, or equal to, the chosen parameter; interruptions of work were disregarded. The maximum duration for each activity was given by setting MISWAR to 1 man-hour; this duration was called D1 or DT. The durations

TABLE 08

Average Total Duration and Number of

Interruptions per Stage per Block

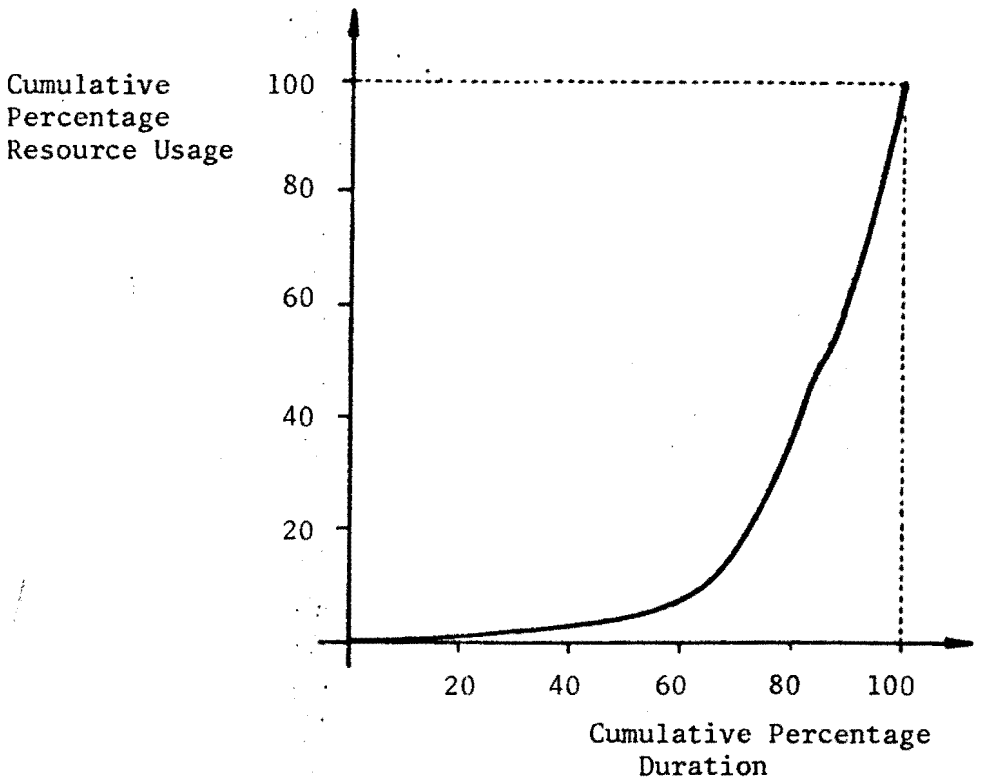
SITE AND ACTIVITY	DURATION AND NUMBER OF INTERRUPTIONS					
	MISWAR = 1 MAN-HOUR			MISWAR = 8 MAN-HOURS		
Ladygate Lane	weeks D01	weeks D1	No. N1	weeks D08	weeks D8	No. N8
Window linings, doors,skirtings	44	28	6.6	36	15	5.3
Gloss paint to woodwork	32	12	3.7	16	7	1.7
Heating	30	17	4.4	24	10	3.3
Brickwork outer leaf	46	11	5.0	24	6	1.9
Plasterboard to walls	21	10	2.8	8	6	0.7
Water pipes, tanks, cisterns	34	18	4.8	17	7	3.2
Average	35	16	4.6	21	9	2.7
Average duration of interruptions		4.1			4.4	
Pitcoudie 1						
Decoration	19	13	2.7	11	6	1.4
Dry-lining	19	8	3.2	10	4	1.1
Superstructure to first-floor	37	15	6.3	13	5	1.9
Doors	24	15	3.9	14	5	2.1
Superstructure to second-floor	27	10	3.8	5	3	0.6
Electrical work	12	6	1.9	2	2	-
Average	23	11	3.6	9	4	1.2
Average duration of interruptions		3.3			4.2	
Pitcoudie 2						
Decoration	29	16	4.3	22	10	2.6
Dry-lining	35	14	5.3	17	7	2.1
First-storey superstructure	31	9	3.5	10	5	1.5
Second-storey superstructure	20	7	2.1	9	4	1.0
Joinery	29	14	5.0	12	6	1.9
Electrical work	19	7	2.6	4	3	0.4
Average	27	11	3.8	12	6	1.6
Average duration of interruptions		4.2			3.8	

NOTES: Activities listed were the six more important ones in order of consumption of man-hours.

obtained by setting MISWAR to 2, 3, 4, ..., n (D2, D3, D4,..., Dn) can be expressed as a percentage of the above maximum duration. The same procedure was used to quantify the allocation of resources associated with each MISWAR and its respective percentage in relation to the total resource consumption for the activity. Various relationships between durations and resources are examined in the following sections.

5.1.3.2.1 The Cumulative Percentage Resource Usage vs. Cumulative Percentage Duration Relationship

Both percentage resource usage and percentage duration were ordered and accumulated along the y and x axis respectively; the ordering was given by increasing value of MISWAR. Figure 34 and the accompanying table are an example of this procedure and the curve that results for the relationship between cumulative percentage resource usage and cumulative percentage duration. Figure 35 was obtained by plotting on the same graph similar curves for the 90 activities available on the 3 sites. This figure shows that all activities had a similar pattern of relationship between cumulative percentage resource usage and cumulative percentage duration, despite the fact that they were performed on 3 different sites, had different labour contents, were defined at different hierarchy levels (operations in Ladygate Lane and stages of work in Pitcoudie 1 and 2), and referred to the work of different size of blocks. In essence, the graph demonstrates that a large proportion of the total duration of activities (Dt) consists of weeks in which small allocations of man-hours were made. Figure 35 establishes that for 50% of the total duration, resource utilization, as percentage of the total resources used in the activity, was only 10%; conversely, only a small proportion of the total duration was used in connection with significant allocations of man-hours. Provided that it is possible to associate the progress of work with the deployment of resources, it can be said that the bulk of advance towards completion of the activities was made during a small proportion of their total duration.



M I S W A R	DURATION	RESOURCES	DURATION i + j - 1	RESOURCES i + j - 1	CUMULATIVE DURATION	CUMULATIVE RESOURCES	CUMULATIVE PERCENTAGE DURATION	CUMULATIVE PERCENTAGE RESOURCES
1	48	732	18	18	18	18	38	2
2	30	714	5	10	23	28	48	4
3	25	704	3	9	26	37	54	5
5	22	695	1	5	27	42	56	6
6	21	690	2	12	29	54	60	7
7	19	678	1	7	30	61	63	8
12	18	671	1	12	31	73	65	10
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
39	8	413	1	39	41	358	85	49
40	7	374	1	40	42	398	88	54
44	6	334	1	44	43	442	90	60
46	5	290	1	46	44	488	92	67
51	4	244	1	51	45	539	94	74
61	3	193	1	61	46	600	96	82
60	2	132	2	132	48	732	100	100

Figure 34

Cumulative Percentage Resource Usage vs. Cumulative Percentage Duration, "Ground-Floor Panels" Operation, Ladygate Lane Site

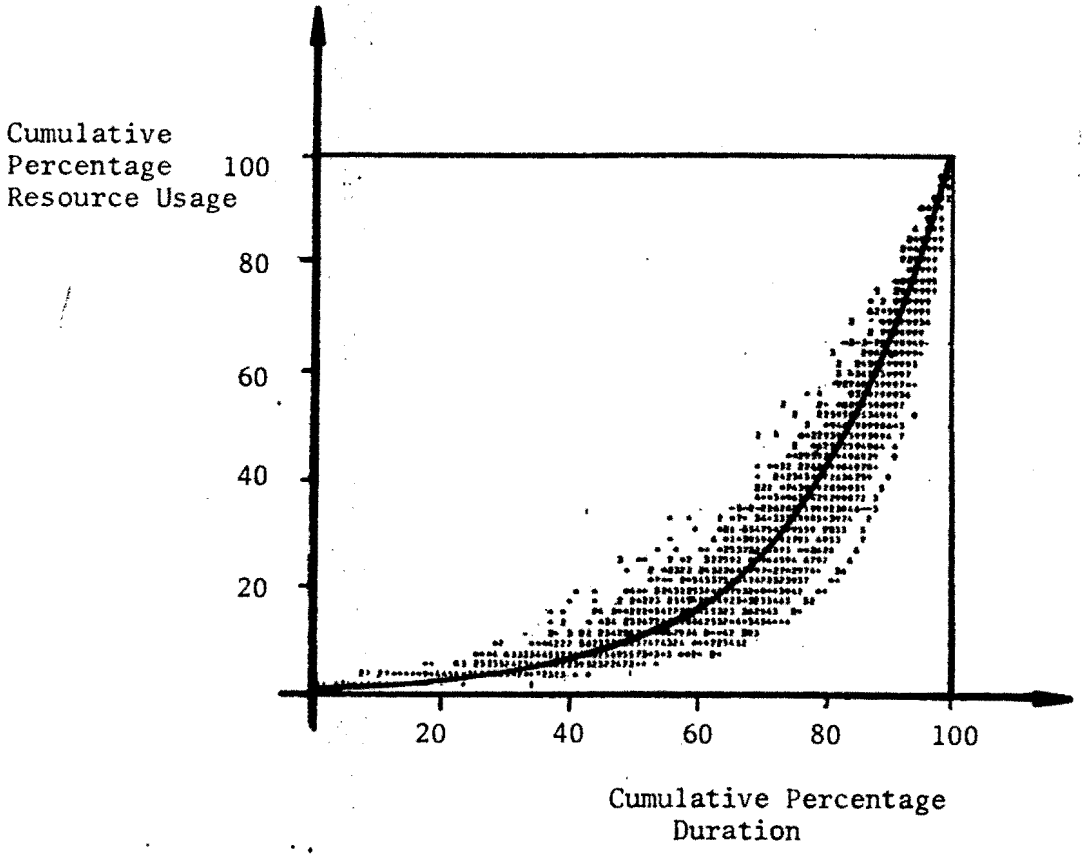


Figure 35

Cumulative Percentage Resource Usage vs. Cumulative Percentage Duration for 90 Activities on the 3 Sites

A curve fitting exercise was conducted to produce a model for the relationship between cumulative percentage resource usage and cumulative percentage resource duration. Various polynomial models were successful in representing the relationship, but the following approximate model was selected for its simplicity:

$$f(x) = 100^{x} \qquad (5)$$

where:

$f(x)$ = cumulative percentage use of resources; $0 < f(x) < 100$;

x = cumulative percentage duration/100; $0 < x < 1$;

If the weekly occurrence of work were ordered according to decreasing MISWARs, the following equation would be derived directly from f(x):

$$g(x) = 100 - (100^{1-x}) \qquad (6)$$

where

$g(x)$ = cumulative percentage use of resources; $0 < g(x) < 100$;

x = cumulative percentage duration/100; $0 < x < 1$;

It is important to distinguish between the above relationships and the "s" progress curves usually used in building programming. The latter considers the cumulative resource usage and cumulative resource duration associated with the exact sequence of allocation of resources over time; the former first regroups the occurrences of work according to the weekly allocation of resources, and then reorders their sequence from the smaller allocations to the larger ones (or vice-versa). Progress "s" curves and f(x) type curves will probably never coincide, since it is unlikely that the allocation of resources to an activity will increase or decrease continuously, time period after time period, to the completion of the activity. The "s" shaped curve suggests that small allocations are made at the start of the activity, they increase up to a peak, and then decrease towards its

completion. Nevertheless, the f(x) curve and its counterpart, the g(x) curve, provide respectively a lower and upper bound for the "s" shaped resource allocation curve; neither are the allocations during the first weeks likely to be smaller than the allocations given by f(x), nor are they likely to be larger than the allocations given by g(x). Figure 36 depicts the relationship between the "s", the f(x), and the g(x) curves for the Joinery stage of work, Pitcoudie 2 site. Durations were calculated at the level of individual blocks rather than at the level of aggregated durations for the 49 blocks on this site: f(x) and g(x) curves could be expected to apply also at this level of breakdown. Figure 11 in Chapter Four demonstrated that one of the interesting features of the progress of work for the Joinery stage on the Pitcoudie 2 site was the fact that the occurrence of significant weekly allocations of work tended to move from the ends of the durations to their starts, as new blocks were tackled. This is illustrated in figure 36 by the movement of the "s" curve away from the f(x) curve towards the g(x) one; block No. 2 was one of the first blocks tackled on site, while block No. 40 was one of the last ones.

5.1.3.2.2 The Weekly Allocation of Resources vs. Cumulative Percentage Duration Relationship

The f(x) function represents a cumulative resource usage curve: its first derivative is thus related to the weekly allocation of resources. The following mathematical relationships will allow the derivation of the necessary equations:

Dt = total duration of the activity, aggregated for all blocks (Dt = Dl);
Rt = total activity resource consumption, aggregated for all blocks;
D = cumulative duration;

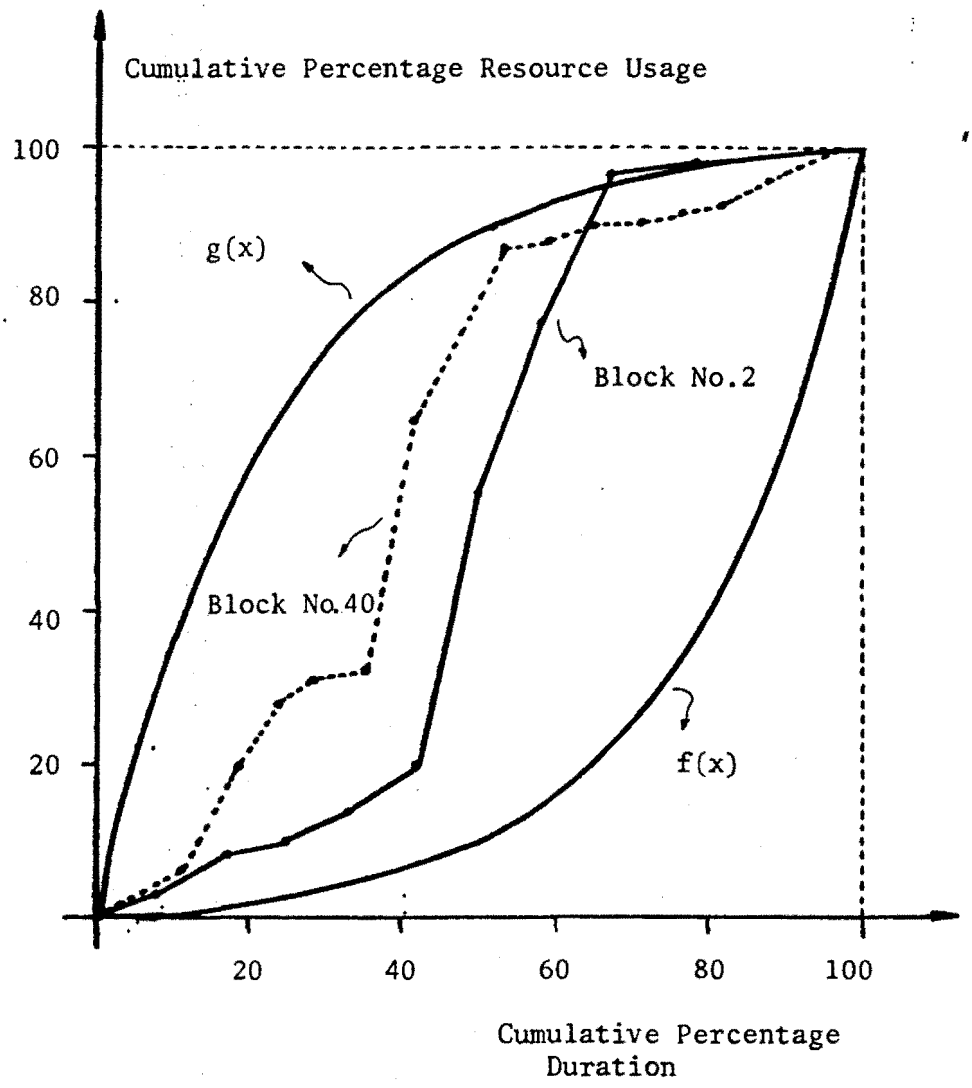


Figure 36

f(x), g(x) and "S" Curves for the Joinery Stage of Work, Blocks No.2 and No.40, Pitcoudie 2 Site.

R = cumulative resource consumption up to the "nth" time period, after reorganizing the weekly allocations according to increasing MISWARs;

$$x = D/D_T;\ f(x) = (R/R_T) \times 100;$$

$$f(x) = 100^x;\ (R/R_T) \times 100 = 100^{D/D_T};\ R = \frac{R_T \times 100^{D/D_T}}{100};$$

$$R = \left(\frac{R_T}{100}\right) \times (100^{1/D_T})^D;\ \frac{dR}{dD} = \text{weekly allocation};$$

$$\frac{dR}{dD} = \left(\frac{R_T}{100}\right) \times (100^{1/D_T})^D \times \ell n(100^{1/D_T});$$

$$\frac{dR}{dD} = \frac{4.605 \times R_T}{100 \times D_T} \times 100^{D/D_T};\ \frac{dR}{dD} = \frac{4.605 \times R_T \times 100^x}{100 \times D_T};$$

$$\frac{dR}{dD} = \frac{R_T}{100 \times D_T} \times 4.605 \times f(x);\ \frac{dR}{dD} = \frac{R_T}{100 \times D_T} \times \frac{df}{dx};$$

$$\frac{df}{dx} = 100 \times \frac{dR}{dD} \times \frac{D_T}{R_T}; \qquad (7)$$

The first derivative of f(x) is equal to the weekly allocation of resources (dR/dD) multiplied by the total duration (Dt) and divided by the total allocation of resources (Rt). Going still further, the above expression becomes:

$$f(x) = 100^x;\ \frac{df}{dx} = 100^x \times \ell n\ 100;$$

$$\frac{df}{dx} = 4.605 \times 100^x; \qquad (8)$$

$$4.605 \times 100^x = \frac{100 \times (\text{weekly allocation}) \times D_T}{R_T} \qquad (9)$$

These equations will be used in the following sections to express cumulative percentage duration and cumulative percentage resource usage as functions of the minimum significant weekly allocation of resources (MISWAR).

Figure 37 shows the correspondence between the actual allocation of resources and the allocation predicted by the df/dx model (equation 7) for some activities on the 3 sites. The area under each curve is equal to the total amount of resources deployed to the activity (Rt). Figure 37.c illustrates one case where the actual allocation did not follow the predicted one. As the areas under the predicted and actual allocation curves are the same, greater than predicted intermediate allocations were obtained at the expense of smaller than predicted final allocations.

It already has been mentioned that the weekly allocation of resources varied wildly from week to week, with no apparent rule governing this variability. While it is still not possible to explain and predict the allocation of resources week after week, the df/dx equation is at least able to model the magnitude of the various allocations that took place and their associated durations; the model is able to indicate the various allocations that took place on site, but does not give any information regarding the timing of these allocations. Further studies are necessary to determine the distribution of these allocations over time.

The df/dx allocation model behaved well for the majority of activities on the 3 sites. However, it should be noted that the model is extremely sensitive to the correct estimation of the total duration of the activity (Dt): the string of allocations predicted by the model for an activity not yet performed can be completely different from the actual string of allocations, depending on the estimating accuracy for the total duration. For example, if the total actual duration is only 10% larger than the predicted one, say 110 weeks rather than 100 weeks, for a constant labour content of 1100 man-hours, the string of allocations between the 90th and 100th week will drop by some 40%. The use of the information provided by the f(x) and df/dx models will be further investigated in the section devoted to applications (section 5.3).

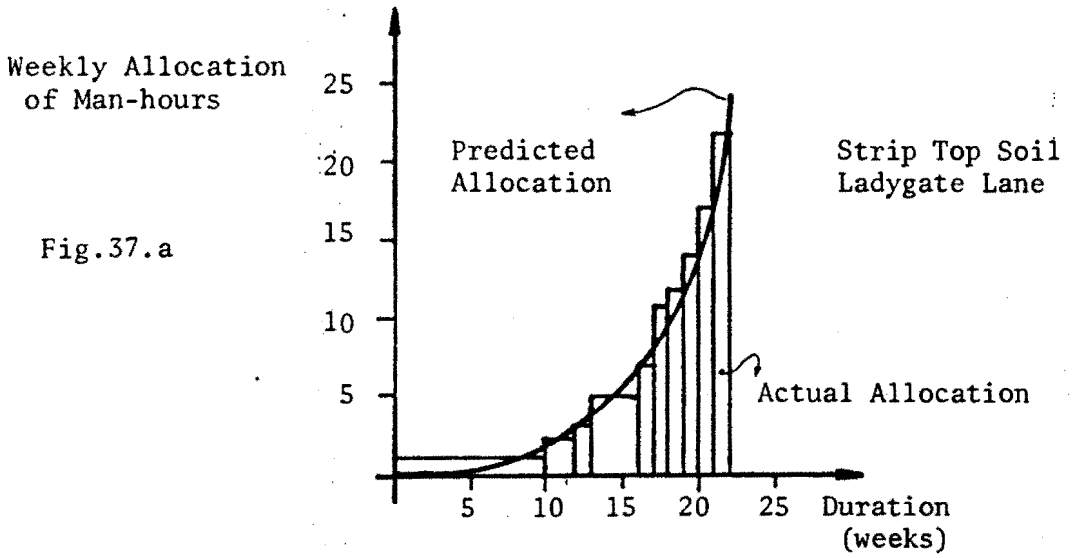


Fig.37.a

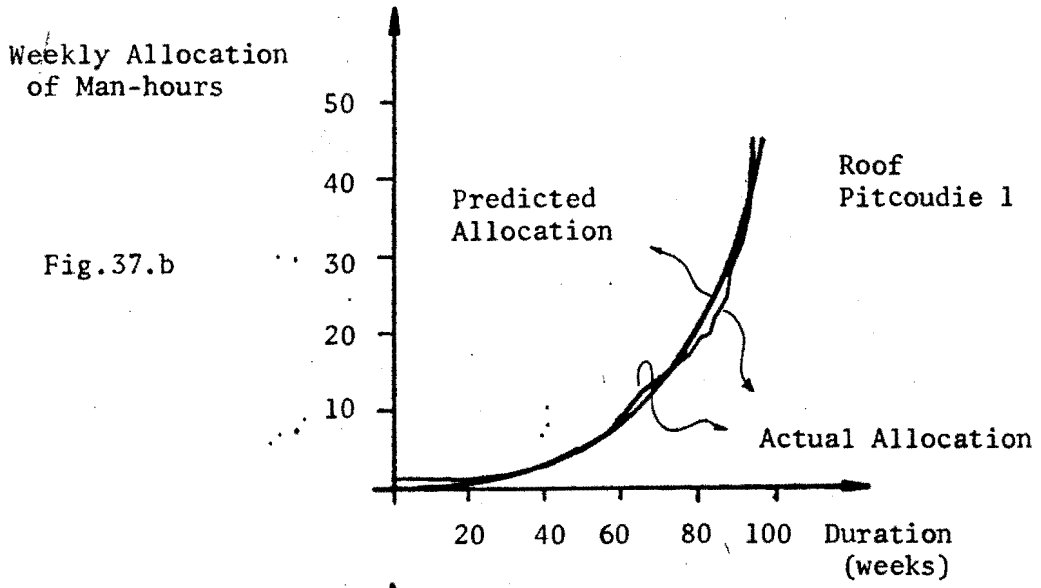


Fig.37.b

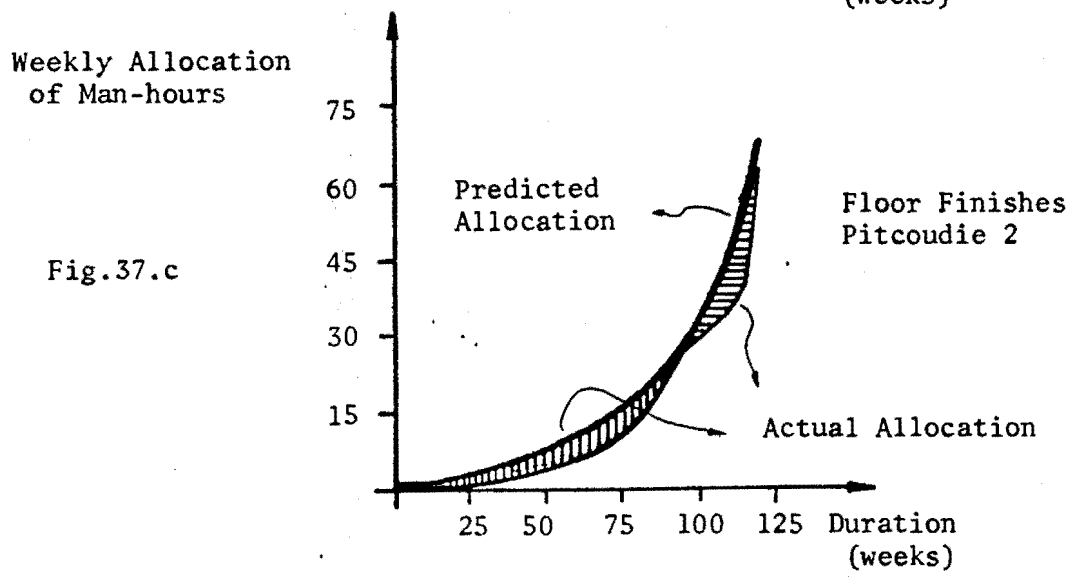


Fig.37.c

Figure 37

Predicted and Actual Weekly Allocation of Man-hours

5.1.3.2.3 The Percentage Resource Usage vs. Weekly Allocation of Resources Relationship

One criterion for objectively defining the duration of activities would be to relate them to cumulative percentage usages of resources. For example, choosing a 90% cumulative use of resources as the criterion yields at least 3 different approaches to the calculation of durations:

- to take into account weeks in which work has occurred from the first week until 90% of resources were deployed; this approach would lead to the elimination of much random work that occurred after the practical completion of the activity;
- to take into account weeks in which work has occurred after the initial 10% of resources were deployed; this approach would disregard the work done during the initial uncertain weeks, while operatives were still gathering momentum;
- to ignore both the initial and final 5% occurrences of work, taking into account only the 90% intermediate allocation of resources.

The high variability in the weekly allocation of resources prevents the meaningful use of the above methods: they do not preclude including in the calculation of durations the small allocations (1, 2, 5 man-hours) that were often intermingled with the significant allocations.

A different approach would be to relate the cumulative percentage resource usage to different MISWARs; given a certain cumulative percentage of resources, the duration would be obtained through the use of the f(x) model (equation 5). For example, if a 90% cumulative percentage resource usage is chosen as the criterion, the duration of the activities would be only 50% of the total duration (Dl = Dt) because:

$$f(x) = 100^{x};\ (100\% - 90\%) = 100^{x};$$

$$\log 10 = x \times \log 100;$$

$$x = 0.5;$$

Typically, activities with large labour contents consumed 15,000 man-hours in total, and activities with small labour contents had some 100 man-hours devoted to them. For a 90% cumulative resource usage criterion, weeks with allocations smaller than 11 man-hours would not be counted towards the durations of the large labour content activities, while weeks with allocations as small as 3 man-hours would be included in the computation of durations for the small labour content activities. Therefore, this percentage approach to the calculation of the duration of activities is not entirely satisfactory: it is difficult to justify why allocations which were significant enough in one case to warrant their inclusion in the calculation of the duration of one activity, were not significant enough in the other case.

Instead of trying to define the duration through a unique percentage resource usage, it was decided to formulate the mathematical relationship between the minimum significant weekly allocation of resources and the cumulative percentage resource usage. Given any MISWAR it would be possible to know the cumulative percentage resource usage; once the latter is known, it would be possible to calculate the cumulative percentage duration; finally, the duration (in weeks) associated with each MISWAR would be known once the total duration for the activity (Dl=Dt) is estimated.

Suppose that the duration of an activity was only recorded on a site for the weeks with an allocation greater or equal to 40 man-hours. This could be motivated by practical reasons: if the production card method of recording information is being used it would only be practical to record the significant allocations of resources to the activities. Given the duration obtained with this MISWAR of 40 man-hours, and the total amount of resources deployed on a greater than 40 man-hours per week basis (that is, the sort of information that the production card method could have provided), it would be possible to calculate not only the total duration Dl,

but also the total amount of resources used by the activity as if smaller than 40 man-hours per week allocations were also recorded.

The percentage resource usage and the MISWAR relationship can be derived as follows:

$$\frac{df}{dx} = 100 \times \frac{dR}{dD} \times \frac{D_T}{R_T};$$

$$MISWAR = \frac{dR}{dD}; \tag{10}$$

$$4.605 \times 100^X = \frac{100 \times MISWAR \times D_T}{R_T}; \tag{11}$$

$$MISWAR = \frac{4.605 \times 100^X \times R_T}{D_T}; \tag{12}$$

$$MISWAR = \frac{4.605 \times f(x) \times R_T}{D_T}; \tag{13}$$

This formula indicates that MISWAR is a function not only of the percentage resource usage f(x), but also of Rt and Dt. The MISWAR would be a function solely of f(x) only if Dt is found to be a constant proportion of Rt. Towards the end of this chapter it will be demonstrated that this is not so; it is a more complex function of Rt. Therefore, MISWAR is a function of the cumulative percentage resource usage f(x) and the total amount of resources used by the activity (Rt). Conversely, the cumulative percentage resource usage is a function of MISWAR and the total consumption of resources by the activity. Three variables are involved: however, MISWAR, Rt, and Dt can be combined into just one variable, df/dx, using equations 8 and 9. Thus, it is possible to express the relationship between cumulative percentage usage of resources and the weekly allocation of resources using only 2 variables, f(x) and df/dx. From equation 5 and equation 8 it follows that:

$$f(x) = \frac{df/dx}{4.605} \tag{14}$$

Figure 38 depicts the relationship between f(x) and df/dx for the 90 activities on the 3 sites. The coefficient of correlation for this scattergram is 0.90, a relatively high value in statistical terms. For small cumulative percentage usage of resources, the band of scatter points is quite narrow, showing a very good correspondence between the model and actual data; for higher cumulative percentage of resource consumption, an increasing dispersion of points is observed. This is caused by the fact that activities followed with varying degrees of accuracy the allocation pattern described in figure 37. Both the f(x) and df/dx models are very accurate in describing the percentage of resources taken by small allocations; however, they lose some accuracy for large allocations.

Figure 39 presents 3 examples of the predicted and actual relationship between f(x) and its first derivative, df/dx, for individual activities on the 3 sites.

The previous section dealing with the cumulative percentage resource usage vs. cumulative percentage duration relationship concluded that it is possible to know the percentage of work completed for each component percentage duration, despite the fact that the order in which these percentages of work occurred is not known. This section has seen the development of a corollary to that finding; it is possible to know the percentage of resources used by weekly allocations greater or smaller than the MISWAR parameter; however, the order in which these percentages of work occurred is still not known.

Both models, f(x) and df/dx, can be used as predictive tools for the programming of work on new sites. However, they require the estimation of the total resource consumption (Rt) and total duration (Dt) for the activities.

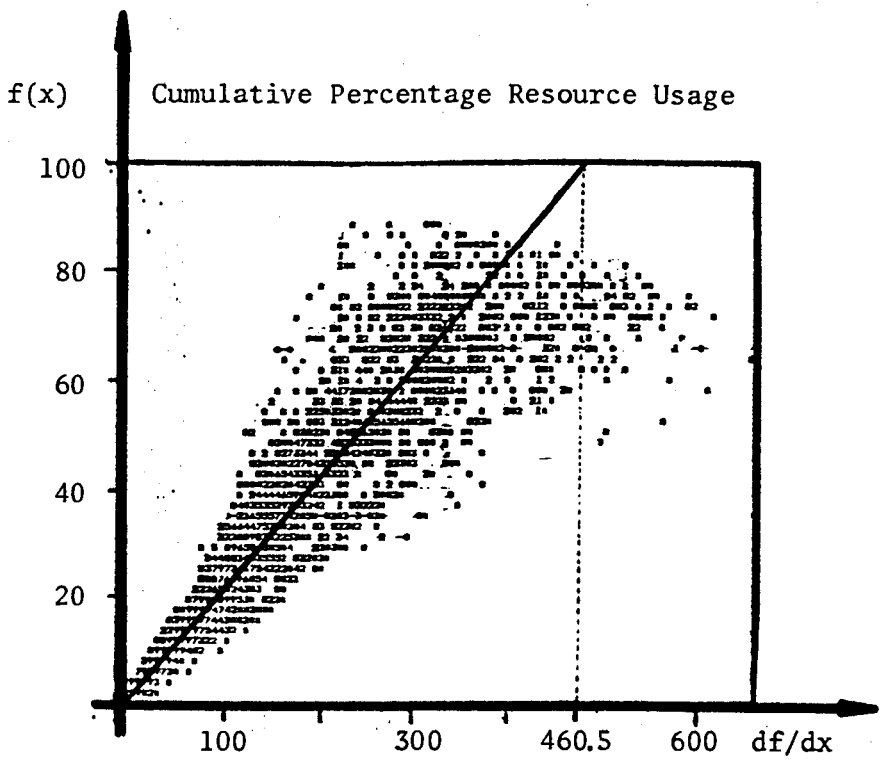


Figure 38

f(x) vs. df/dx for 90 Activities on the 3 Sites

Fig.39.a

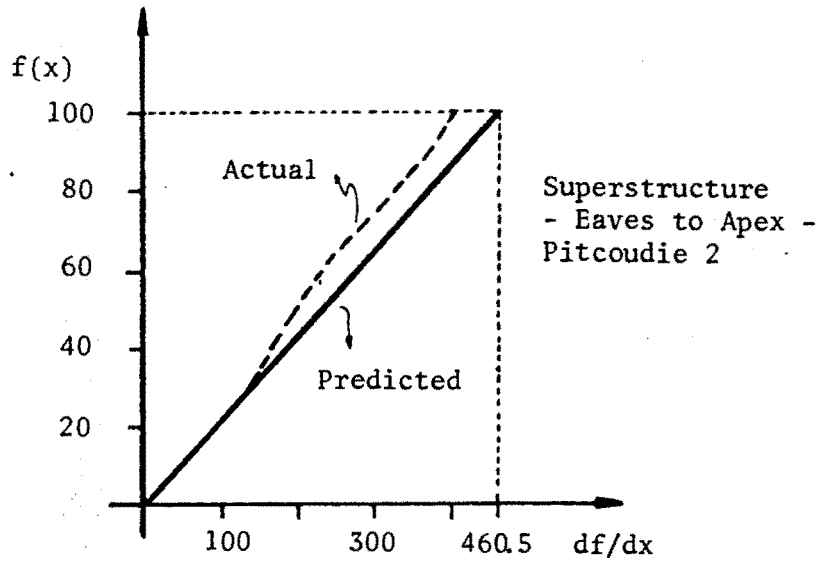


Fig.39.b

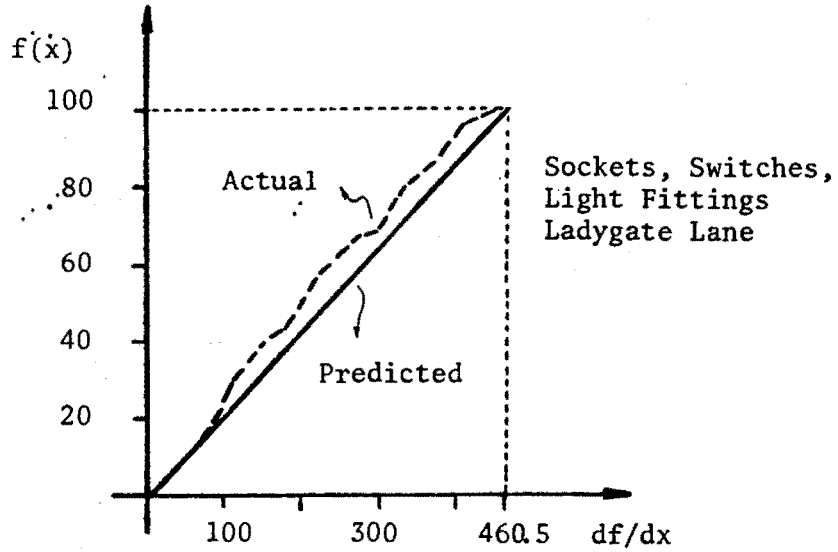


Fig.39.c

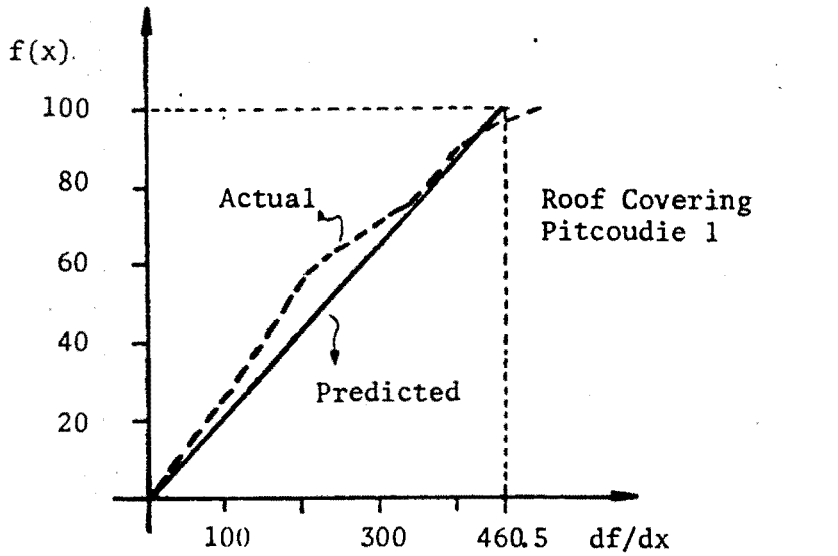


Figure 39

f(x) vs. df/dx for 3 Activities

5.1.3.2.4 The Percentage Duration vs. Weekly Allocation of Resources Relationship

Given the f(x) and df/dx models of the previous sections, the relationship between the cumulative percentage duration and the minimum significant weekly allocation of resources is straightforward. It can be derived as follows:

$$\frac{df}{dx} = 4.605 \times 100^{x};$$

$$\log(df/dx) = \log 4.605 + x \times \log 100;$$

$$x = \frac{\log (df/dx) - 0.663}{2};$$

$$\frac{df}{dx} = 100 \times \frac{dR}{dD} \times \frac{D_T}{R_T};$$

$$x = \frac{\log(100 \times MISWAR \times \frac{D_T}{R_T}) - 0.663}{2}; \qquad (15)$$

As before, equation 15 involves 3 independent variables, MISWAR, Dt, and Rt; Again, the df/dx function can be used to represent them. Figure 40 shows the relationship between the actual cumulative percentage duration (x) and df/dx for the 90 activities on the 3 sites. Figure 41 presents 3 examples of the actual and predicted relationship between the cumulative percentage duration and df/dx.

Given Rt and Dt is is possible to predict the cumulative percentage duration associated with any MISWAR. Furthermore, if the duration of the activity is known for a particular MISWAR, it is possible to derive the expected duration corresponding to any other MISWAR. This capability of the model in equation 15 removes the need for defining objectively the most suitable MISWAR for the calculation of durations; any MISWAR can be used as the criterion; the resulting duration can then be adjusted to correspond to any other MISWAR.

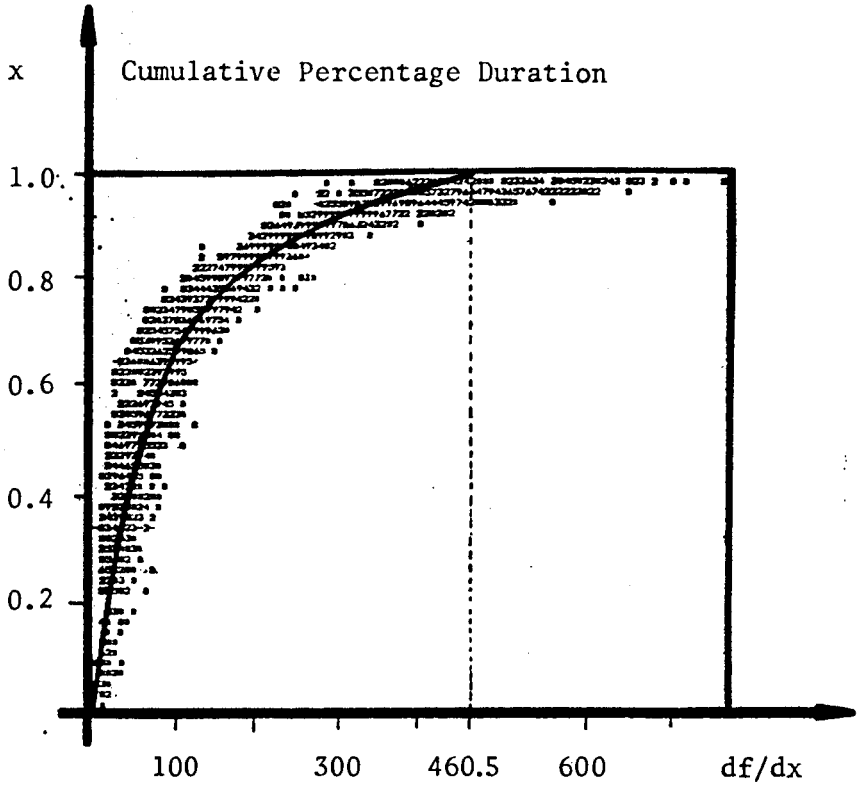


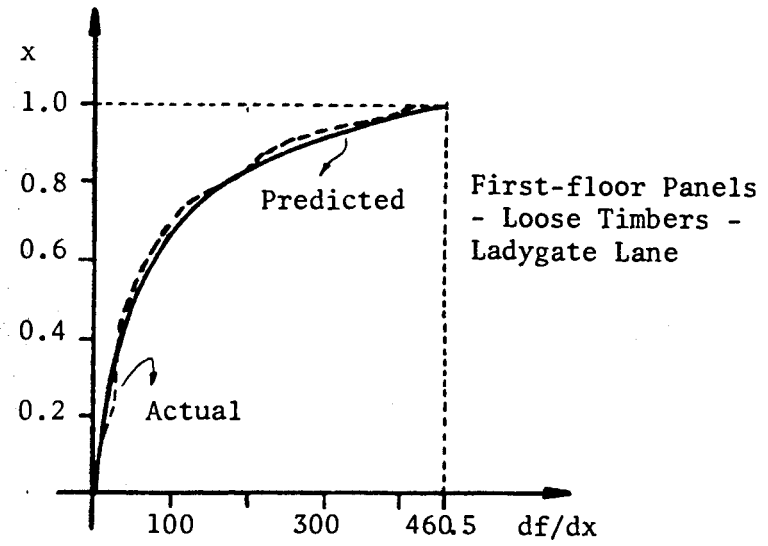
Figure 40

Cumulative Percentage Duration ("x") vs. df/dx

for 90 Activities on the 3 Sites

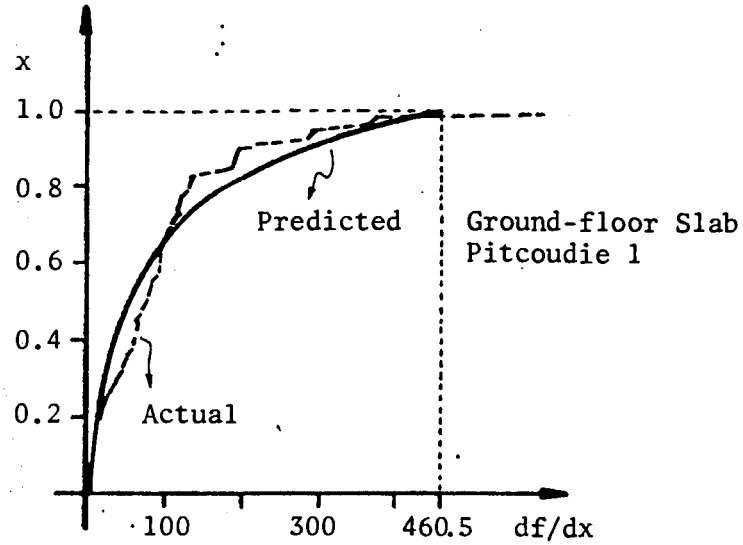
Cumulative Percentage Duration

Fig.41.a



Cumulative Percentage Duration

Fig.41.b



Cumulative Percentage Duration

Fig.41.c

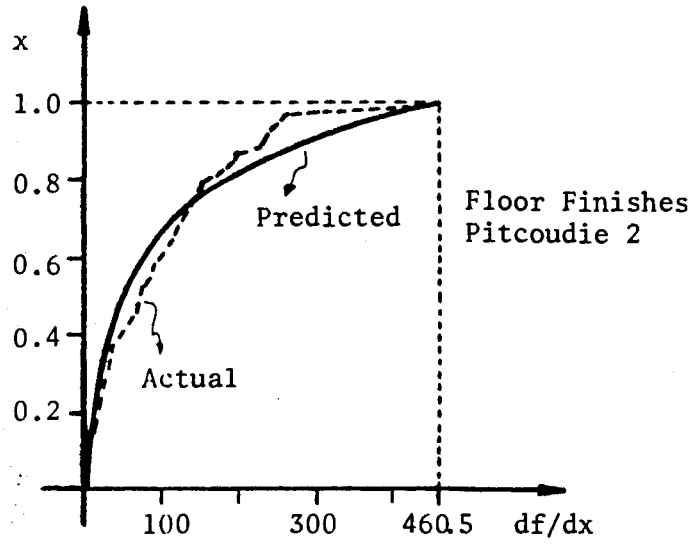


Figure 41

Cumulative Percentage Duration ("x") vs. df/dx for 3 Activities

The availability of a model depicting the relationship between MISWAR and their associated durations gives the construction manager the opportunity to know more about the resource allocation process than he otherwise would be capable of knowing by subjectively fixing a minimum significant weekly allocation of resources criterion, and ignoring the smaller allocations; these smaller allocations, despite their insignificant direct cost, most probably interfere negatively with the production process. The management feedback system should take note of their presence.

The next section deals with the estimation of total duration using resource consumption as the independent variable; the estimation of total duration is the first step in the use of the f(x) and df/dx models as predictive tools.

5.2 The Estimation of the Duration of Activities as a Function of the Total Consumption of Labour Resources

5.2.1 Introduction

The ultimate goal of this research work is to develop a procedure for estimating the duration of the activities. Durations can be measured and estimated on their own, without the need to relate them to any other parameter, as was discussed in Chapter Two. However, practical considerations dictate the need to relate them to some variables, the alternative being to measure and estimate durations individually for every possible occurrence of work: if no relations are established with independent variables, historical data would only be useful in calculating durations for situations identical to those that have already occurred.

Basically, the duration of activities can be related to 2 different sets of variables: the physical quantity of the work done, and the quantity of resources consumed by the activity (expressed by costs, labour and equipment usage, etc.). At first sight, the use of physical quantities as the indepen-

dent variable seems more suitable. Measurement of physical quantities of work is already a fairly standardised procedure, and could provide unbiased and accurate figures to serve as the independent variable for the estimation of durations. Furthermore, it avoids the consideration of the cause/effect relationship between durations and resources: common sense dictates that activities that are carried out during a long period of time are likely to consume more resources and vice-versa. However, the review of the literature indicated that the consumption of labour resources on building sites is only partially related to physical quantities of work; it can be expected that durations would likewise be only partly related to physical measures of work; administrative aspects, found to be important in explaining the consumption of labour on sites, can likewise be expected to influence the duration of activities.

Moreover, the use of activity sampling has called for the aggregation of observations related to different physical measures in order to improve the accuracy of both resource usages and durations. Thus, durations can only be related to a set of physical measures. Two approaches can be used to deal with the set of physical measures: they can be combined into overall measures, such as area of floor, ceiling, wall, lineage of foundation, etc., or they can be treated as separate variables in multi-regression models. The first method determines that jobs of different complexities, but with similar areas, lineage, volume, etc. would be treated similarly. The second method suffers from a lack of independence between the variables contained in the set of physical measures. For example, the operation "gloss paint to woodwork" on the Ladygate Lane Site included observations for the painting on flat surfaces (shelves and cupboards), linear surfaces (skirtings), doors, and windows; large blocks had not only large areas of doors and windows but also large areas of flat and linear surfaces. This multi-collinearity between variables makes it theoretically improper to use multi-regression analysis; in practice it can be used, but the confidence limits for the model parameters tend to be

very large (see Beamish for a complete exercise in the application of multi-regression analyses to the modelling of resource consumption by the plastering operation on 300 sites).

Due to the practical difficulties in using physical measures for the prediction of durations, this research work concentrated on the examination of labour resource consumption as a suitable independent variable for their estimation. Labour resources will be readily available as independent variables, because present estimating techniques already take them into account, implicitly or explicitly. It should be pointed out that, according to present estimating techniques, labour resources are a function of physical measures; hence, ultimately, durations will be a function of physical measures of work.

Other advantages of the use of labour resources as the independent variable are:

- labour resources provide a common measure to relate the duration of activities performed under different circumstances. In this sense, labour resources have the same characteristics of costs as far as the use of a single measurement yardstick is concerned, without the disadvantages of rapid nominal change as occur with the latter. The review of literature showed that costs were successfully used to model the total duration of projects (Bromilow-1969, Lemessany and Clapp-1975, Soeterik);
- labour resources already contain allowances for some factors affecting productivity (and hence probably affecting durations as well). For example, no adjustment will be needed to cater for the learning phenomenon; smaller labour usage will be automatically associated with smaller durations. Durations should be adjusted, however, according to the likely influence of weather; man-hours lost due to bad weather on the 3 sites under investigation were not directly allocated to the activities, but to the site as a whole.

The estimation of durations as a function of resource consumption requires not only previous estimation of the total labour content of activities, but also requires decisions on the likely composition of gangs and number of crews assigned to the job. The determination of the size and number of crews is critical for the resource-related methods of estimating durations reviewed in Chapter Two. The Site Activity Analyses Package allows the identification of the operatives engaged in each activity on a weekly basis (or any other time period basis). Due to the massive size of the printed tables providing this information, the author did not obtain data on the size and number of gangs associated with each activity. However, observation of site attendance tables suggested great variability in the number of tradesmen available on site from week to week, and a changing pattern of crew composition. This indicates that the number of men assigned to the activities was also subject to variability. Forbes (1980:2), reporting on the work of bricklayers on the Pitcoudie 1 site, confirmed that the bricklayer operation in each block was performed week after week by a multitude of different operatives, grouped in crews of varying sizes and skilled/unskilled ratios.

It is reasonable to assume that if multiple crews were used, they were allocated to different working places. Common sense dictates that it is not a good strategy to place different crews of the same trade, with different paces of work, side by side on the same block. Based on this assumption, the durations calculated in this research work are those associated with single crews. Consequently, the relationship between duration and total labour content will be valid on the assumption that a single crew was assigned to the job. The exact size of the crew is ignored: it is assumed to be a standard crew, that is, the crew that would normally be assigned to a job, according to construction industry practice.

5.2.2 The Duration vs. Labour Content Regression

The independent variable for the forthcoming models is always the total amount of labour resources expended on the

activity: the total amount of labour resources is the information that can be made available by the estimating department.

The maximum weekly allocation of resources for the largest of the 90 activities on the 3 sites was around 300 man-hours. This means that in theory some 300 models could be built; the first model would relate the total duration of activities (including interruptions) to the total consumption of resources for the 90 activities on the 3 sites; the second model would consider durations obtained with a MISWAR equal to 1 man-hour, again for the 90 activities on the 3 sites; the last model would take into account durations calculated with a MISWAR as near as possible to the 300 man-hours mark; just 2 or 3 activities amongst the 90 available on the 3 sites had any allocation as high as that.

The large number of regression exercises conducted is summarized here by a set of models obtained with a geometric series of MISWARs (D1 = 1, D2 = 2, D4 = 4, D8 = 8, D16 = 16, D32 = 32, and D64 = 64 man-hours). Of the 90 activities, only 45 had any allocation greater than 64 man-hours. Due to this fact, and the decreasing coefficient of correlation found for the relationship between duration and labour content for high MISWARs, only models of up to a 64 man-hours minimum significant weekly allocation of resources are proposed.

Individual regression models were developed for each of the sites under investigation. However, despite the differences in block sizes, dwelling types, size of projects, and site hierarchies, the regression models for the 3 individual sites showed similar characteristics. Therefore, it was decided to produce just one regression model per MISWAR. The analysis that follows refers to these unified models.

The scattergrams for durations and labour usages did not firmly suggest the suitability of linear regression models; for this reason, a logarithmic transformation of durations and resources was also tried. Both types of models presented similar correlation coefficients; for some MISWARs, the linear

assumption on the relationship between duration and total resource usage produced slightly better correlation coefficients; for some other cases, the transformed logarithmic relationship yielded better results. The deciding factor on the choice of a linear or logarithmic model was the analyses of the residuals of regression. The logarithmic models, in general, performed better in terms of the usual tests for the appropriateness of regression analyses (see Norusis).

It will be appreciated, after the presentation of the various regression equations, that the logarithmic models associated with 8 and 16 man-hour MISWARs are in fact almost linear, despite their power form. The correlation coefficients and analyses of residuals for both linear and logarithmic models were very similar for this range of MISWARs.

Table 09 presents, for the selected group of geometric MISWARs, the square of the coefficient of correlation (coefficient of determination), the standard error of estimate, the average coefficient of variation for the dependent variable after regression, and the model equation. The coefficient of determination shows how much of the variability of the dependent variable (duration) can be explained by the independent variable (labour content). The standard error of estimate can be interpreted as the standard deviation of the residuals (actual durations less the predicted ones). The average coefficient of variation is obtained by dividing the standard error of estimate by the average value of the dependent variable.

D01 is the total duration of the activity taking into account the interruptions of work. The coefficient of determination at 0.67 is the lowest for all models. The coefficient of determination, the associated standard error of estimate, and the average coefficient of variation all improve with increasing MISWARs; they reach a maximum around D8 and then start to decline.

One interesting feature of table 09 is the high coefficient of determination for durations associated with

TABLE 09

Regression Models

MODEL	A	B	C	Equation
D_{01}	0.67	0.29	12%	$1.97697 \quad R^{0.70261}$
D_1	0.85	0.18	9%	$0.57794 \times R^{0.73610}$
D_2	0.86	0.18	10%	$0.28121 \times R^{0.80414}$
D_4	0.92	0.14	8%	$0.19143 \times R^{0.81101}$
D_8	0.96	0.12	8%	$0.06483 \times R^{0.90622}$
D_{16}	0.90	0.19	14%	$0.02094 \times R^{0.98073}$
D_{32}	0.88	0.21	20%	$0.00291 \times R^{1.12395}$
D_{64}	0.71	0.33	42%	$0.00053 \times R^{1.18675}$
D_{80}	0.67	0.36	48%	$0.00015 \times R^{1.29347}$

NOTES:

A = coefficient of determination = r^2 ;

B = standard error of estimate;

C = average coefficient of variation = $B/\bar{D}_n$

where $\bar{D}_n$ is the average duration D_n;

MISWARs between 1 and 32 man-hours. It should be stressed again that there is very little in common between the sites and the level of detail at which the information was obtained, especially between the Ladygate Lane and the other 2 sites. The dwelling mix, the size and shape of blocks, the method of construction, the structure, the external finishing, the size of project, and the geographical area where they were built (near London and in Scotland) are all different.

The fact that the 90 activities were able to follow so closely the same regression models indicates that there was a common rule governing the deployment of resources to the activities, the average intensity of work, and hence the durations. This similarity in production characteristics for the 3 sites was also detected in the previous sections dealing with the cumulative percentage resource usage vs. cumulative percentage duration relationship and its corollaries. However, much should not be read into the low figures for the standard errors of estimate and average coefficients of variation; the use of logarithmic scales for durations and resource usage explains these low figures.

Figure 42 shows the logarithmic graphs for the regression models corresponding to D1, D8, and D16. The expected durations for constant allocations of 20, 40, and 80 man-hours/week are also depicted, for the sake of comparison. The narrow band determined by ± one standard error of estimate in figure 42.a is misleading as far as model fitting accuracy is concerned; the fact that nearly 68% of the durations-resource consumption points lie within that band is not very significant if it is remembered that, for the same amount of resources, durations in the range of 1:2.3 can also lie within those limits.

Figure 43 shows the logarithmic models for D1, D4, D8, D16, and D32 now using linear scales for both axes. The various models have the general power form given below:

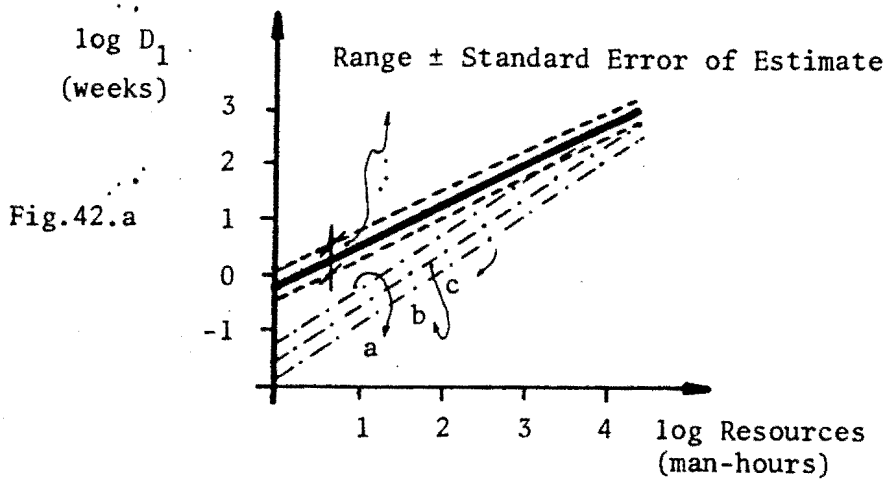


Fig.42.a

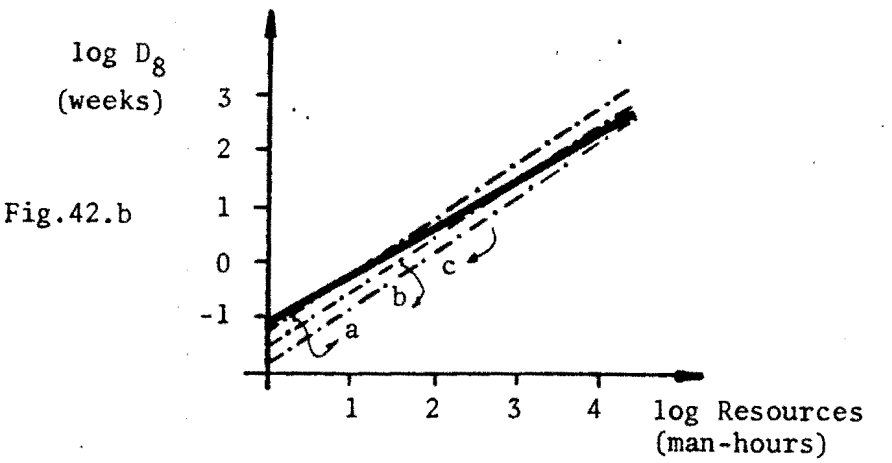


Fig.42.b

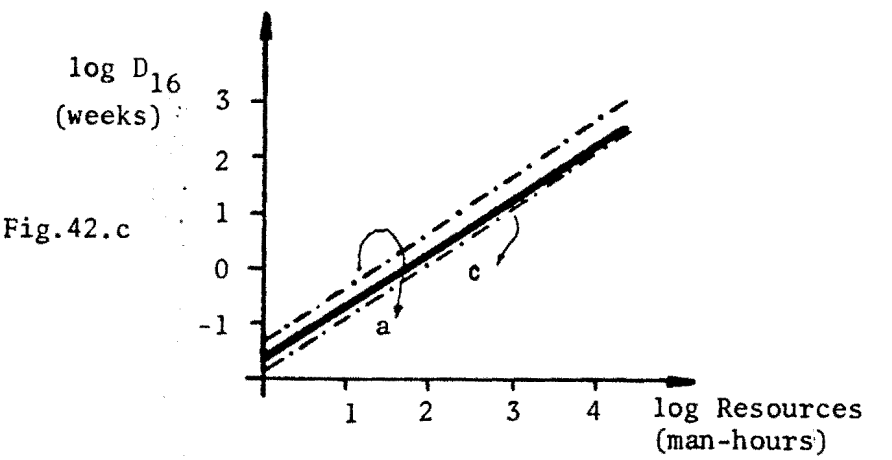


Fig.42.c

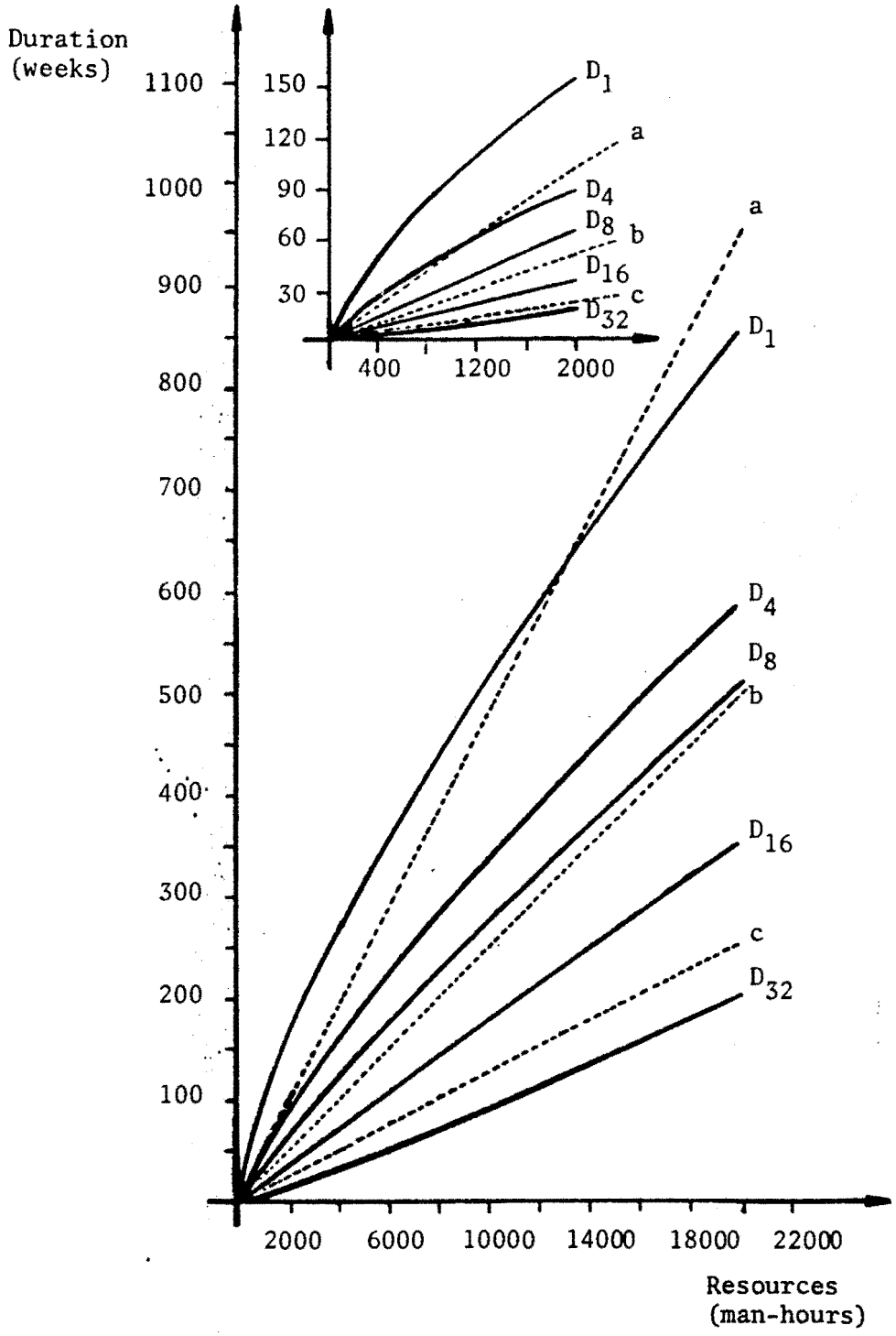
a: Duration = Total Man-hours/20 Man-hours/week

b: Duration = Total Man-hours/40 Man-hours/week

c: Duration = Total Man-hours/80 Man-hours/week

Figure 42

Regression Models for D_1, D_8 and D_{16},
Logarithmic Scales



a: Duration = Total Man-hours/20 Man-hours/week

b: Duration = Total Man-hours/40 Man-hours/week

c: Duration = Total Man-hours/80 Man-hours/week

Figure 43

Regression Models for D_1, D_4, D_8, D_{16} and D_{32}, Linear Scales

$$\text{Duration} = a \times \text{Resource}^{b} \qquad (16)$$

where:

a, b = constants;

Resource = total amount of man-hours consumed by the activity in all blocks.

If "b" is smaller than 1, as happens for D1 and D4, the model has a concave curvature; if "b" is near to 1, as for D8 and D16, the curvature is very small and the power model approximates a linear one; if "b" is greater than 1, as for D32, the curvature is convex.

The concave curvature for small MISWARs means that activities with large labour content were performed in proportionally less time than small labour content activities. This is explained by the fact that for any percentage duration the allocation of resources is more than proportional to the ratio of labour contents of the activities: taking the duration associated with a 1 man-hour MISWAR as the total duration (that is, D1=Dt) and recalling the relationship between the weekly allocation of resources and cumulative percentage duration derived in section 5.1.3.2.2 it follows that:

$$\frac{df}{dx} = 4.605 \times 100^{x};$$

$$\frac{(\text{weekly allocation}) \times D_T}{R_T} = 4.605 \times 100^{x};$$

$$0 \leq x_i < 1; \quad 4.605 \times 100^{x}i = k_1;$$

$$D_T = D_1 = 0.58 \times R^{0.73610};$$

$$(\text{weekly allocation}) = \frac{k_1 \times R_T}{0.58 \times R_T^{0.73610}};$$

$$(\text{weekly allocation}) = k_2 \times R_T^{0.26390};$$

$$\text{If } R_{T_2} = k_3 \times R_{T_1} \text{ and } k_3 > 1;$$

$$(\text{weekly allocation})_2 = k_2 \times k_3^{0.26390} \times R_{T_1}^{0.26390};$$

$$\text{For } k_3 > 1 \; ; \quad k_3^{0.26390} > 1 \; ;$$

$$(\text{weekly allocation})_2 > (\text{weekly allocation})_1;$$

This development shows that over the whole range of cumulative percentage duration, from 0 to 1 (0 to 100%), the weekly allocation of resources is higher for the second activity, percentile by percentile; hence the second duration is smaller than the first one multiplied by "k3".

For large MISWARs the explanation for the convex curvature is different; the greater the labour content of the activity, the more it relied on large weekly allocations to be performed; activities with large labour contents had proportionately more weeks with large allocations than activities requiring less labour; for example, some small activities, with labour contents in the region of 100 man-hours, did not even have an allocation as high as 32 man-hours.

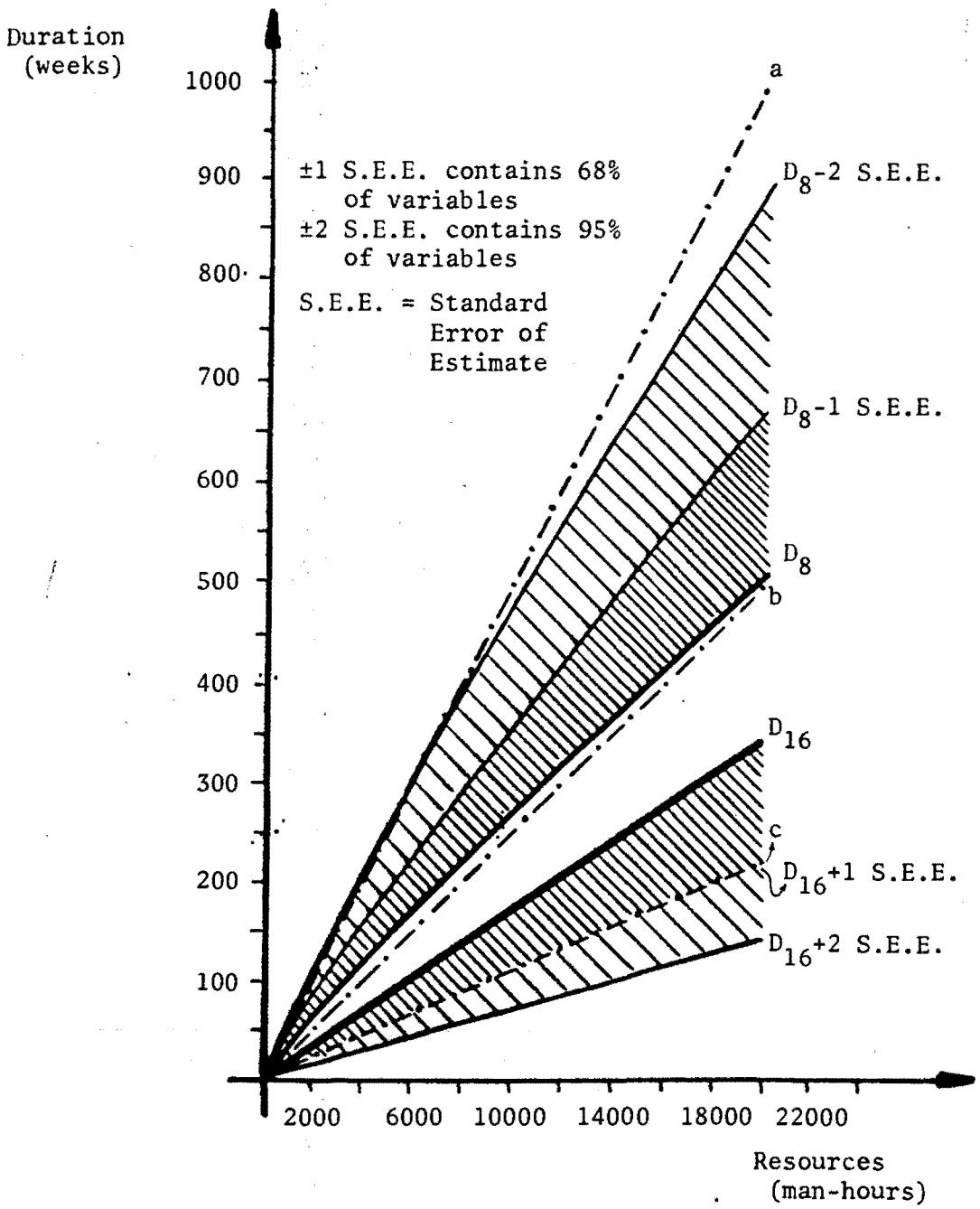
Figure 43 also depicts the hypothetical durations that would be obtained with constant allocations of 20 man-hours, 40 man-hours, or 80 man-hours per week (approximately equal to half man-week, one man-week and 2 man-weeks work). The 80 man-hour curve represents the duration that would be expected for any job, assuming that the minimum crew for building operations is 2 men, one skilled and one unskilled. The observation of durations on these 3 sites revealed that they were far greater than which would be expected according to the above assumption; the durations would be similar to those predicted by the minimum crew assumption only if weeks in which the allocation was higher than 32 man-hours were taken into account. This duration, D32, represents only 9% of the total duration D1 for a job with 1,000 man-hours, and 27% for a job with the maximum labour content found on the 3 sites (20,000 man-hours). Only qualitative evidence was put forward in Chapter Four regarding the low intensity of work; that is now supported by the quantitative analyses of this chapter.

Figure 44 shows the lines of regression for D8 and D16, together with the band of values inside which 68% and 95% of the cases fell. For the sake of clarity only the upper and lower half bands of the D8 and D16 models, respectively, are shown. If these bands are compared with the 20, 40, and 80 man-hour curves it is possible to conclude that not only was the average allocation of resources for all 90 activities smaller than expected, but also that individual activities had smaller allocations than expected for the majority of the 90 cases under examination. For example, only 16.0% of the activities had average allocations greater than 80 man-hours/week, for a 16 man-hour MISWAR. The selection of a 16 man-hour MISWAR determines that 75% and 60% of the weeks in which some work occurred for activities with 1,000 and 20,000 man-hours respectively would have not been taken into account.

The developments of this chapter attest to the fact that the notion of a nominal constant rate of deployment of resources should be abandoned in favour of models based on varying patterns of allocation of resources. The next section shows how the estimation of durations and the concept of varying patterns of allocation of resources can be put together.

5.2.3 The Integration of the Duration vs. Labour Content Regression Models and the Percentage Resource Usage vs. Percentage Duration Models

The cumulative percentage duration can be calculated either through the use of the f(x) and df/dx models or through the set of duration vs. labour content regression models developed in the preceding section. Table 10 illustrates the relationship between the various durations derived from the regression models, together with the percentage duration for selected values of the total labour content of activities. As demonstrated in section 5.1.3.2.3, the cumulative percentage duration for each MISWAR is a function of the total amount of resources (Rt) devoted to the activity.



a: Duration = Total Man-hours/20 Man-hours/week

b: Duration = Total Man-hours/40 Man-hours/week

c: Duration = Total Man-hours/80 Man-hours/week

Figure 44

Regression Models for D_8 and D_{16}

and Ranges Containing 68% and 95% of Variables

TABLE 10

Percentage Durations Calculated

Using the Regression Models

Percentage Duration Equations	D_m/D_n for Selected Amount of Resources			
	100 man-hours	1000 man-hours	10000 man-hours	20000 man-hours
$X_{01,1}=D_{01}/D_1=3.39655 \times R^{-0.03349}$	2.91	2.70	2.50	2.44
$X_{2,1}=D_2/D_1=0.48657 \times R^{0.06804}$	0.67	0.78	0.91	0.95
$X_{4,1}=D_4/D_1=0.33123 \times R^{0.07491}$	0.47	0.56	0.66	0.70
$X_{8,1}=D_8/D_1=0.11217 \times R^{0.17012}$	0.25	0.36	0.54	0.60
$X_{16,1}=D_{16}/D_1=0.03623 \times R^{0.24463}$	0.11	0.20	0.34	0.41
$X_{32,1}=D_{32}/D_1=0.00504 \times R^{0.38785}$	-	0.07	0.18	0.23
$X_{64,1}=D_{64}/D_1=0.00092 \times R^{0.45065}$	-	-	0.06	0.08

Using the equations given in table 10 and equation 7, it is possible to calculate for every MISWAR and every labour content a pair of points corresponding to df/dx (equation 7) and the cumulative percentage duration (equations in table 10). If these pairs of points are plotted on a graph as in figure 45 it is possible to reproduce the theoretical df/dx vs. cumulative percentage duration curve. The difference between the cumulative percentage durations predicted by the 2 different approaches is always less than 10%. Therefore, the pattern of resource allocation described by the theoretical df/dx vs. "x" cumulative percentage model is confirmed by the set of regression equations.

The independence of these analyses must be considered. It is not possible to obtain the durations associated with every labour content even when the pattern of resource allocation is known. Similarly, it is not possible to derive the models for the allocations of resources (f(x) and df/dx) when the relationship between the various durations (D1, D2,..., Dn) is known. The f(x) and df/dx models require the calculation of both Rt and Dt. They do not imply any relationship between Rt and Dt. The f(x) and df/dx curves for an activity can be obtained with any pair of Rt and Dt. Inverting the Dt vs. Rt relationship and taking its first derivative provides a pattern of allocation of resources that can be compared with the pattern given by f(x) and df/dx:

$$D_T = 0.58 \times R_T^{0.73610}$$

$$R_T = \left(\frac{D_T}{0.58}\right)^{1/0.73610}$$

$$R_T = 2.096 \times D_T^{1.35851} \qquad (17)$$

$$\frac{dR_T}{dD_T} = 2.096 \times 1.35851 \times D_T^{0.35851}$$

$$\frac{dR_T}{dD_T} = 2.848 \times D_T^{0.35851} \qquad (18)$$

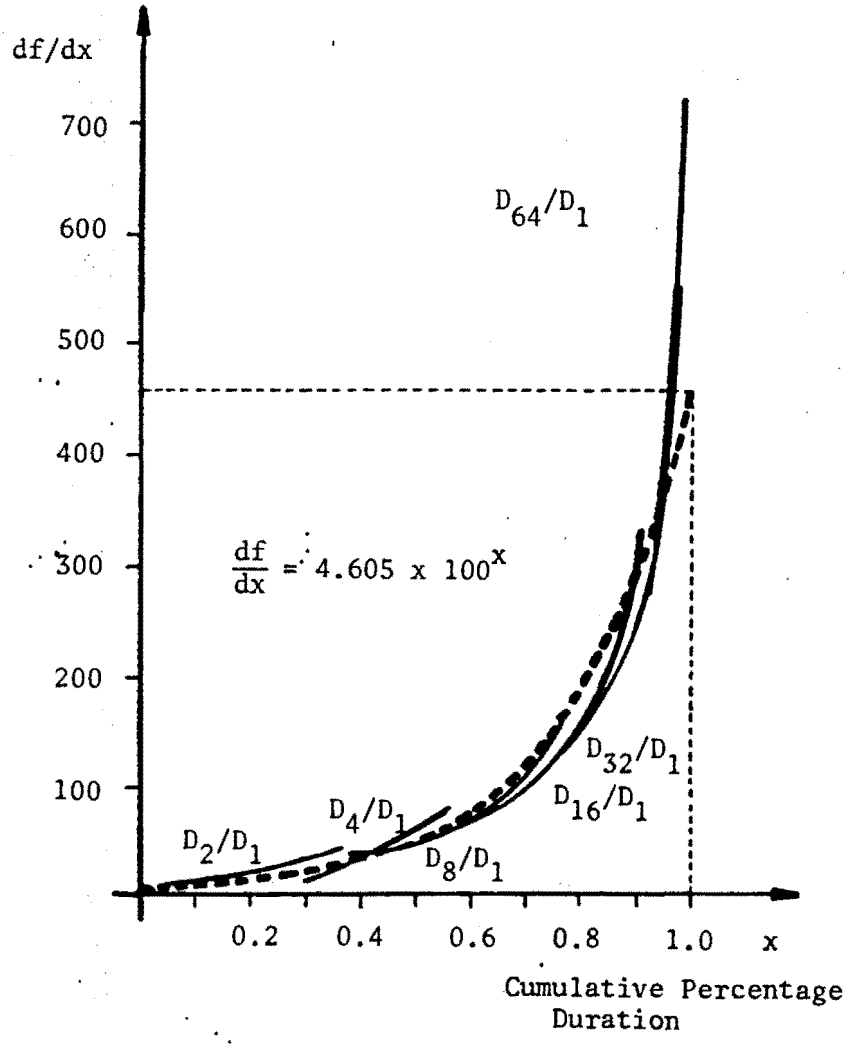


Figure 45

Comparison between the df/dx Model and df/dx obtained through the Regression Equations D_1, D_2, D_4, D_8, D_{16}, D_{32} and D_{64}

The cumulative total resource curves corresponding to f(x) and to the model developed in equation 17 are compared in figure 46.a; the allocation models given by df/dx and the above equation 18 are compared in figure 46.b. Both the f(x) and df/dx models differ markedly from the comparable models given by equations 17 and 18. Figure 46.b demonstrates that activities with an increased labour content did not have a resource allocation pattern characterized by some extra high allocations, with the rest of the string of allocations identical to the ones achieved by activities with smaller labour content; for every increase in labour content there is a complete change in the amount of work allocated to each component of the string of durations. Figure 46.b depicts the differences in the allocation pattern for an increase in the labour content of activities of from 1000 to 1300 man-hours. In conclusion, the set of equations relating durations to total labour content and the set of models dealing with weekly allocation models (f(x) and df/dx) are independent and cannot be derived one from the other.

5.3 Practical Uses of the Models

The duration vs. labour content regression models allow the prediction of durations associated with every MISWAR, once the total labour content for the activities is estimated. The cumulative percentage resource usage and the cumulative percentage duration models provide information on the probable pattern of labour resource allocation. Furthermore, both sets of models produce similar results in terms of predicting the percentage duration associated with every MISWAR, as it can be seen in Table 11.

The practical use of this type of information is better illustrated by an example taken from the Pitcoudie 2 site. Suppose that the program of work for a site similar to Pitcoudie 2 is being established. The programmer is particularly interested in the production characteristics of the

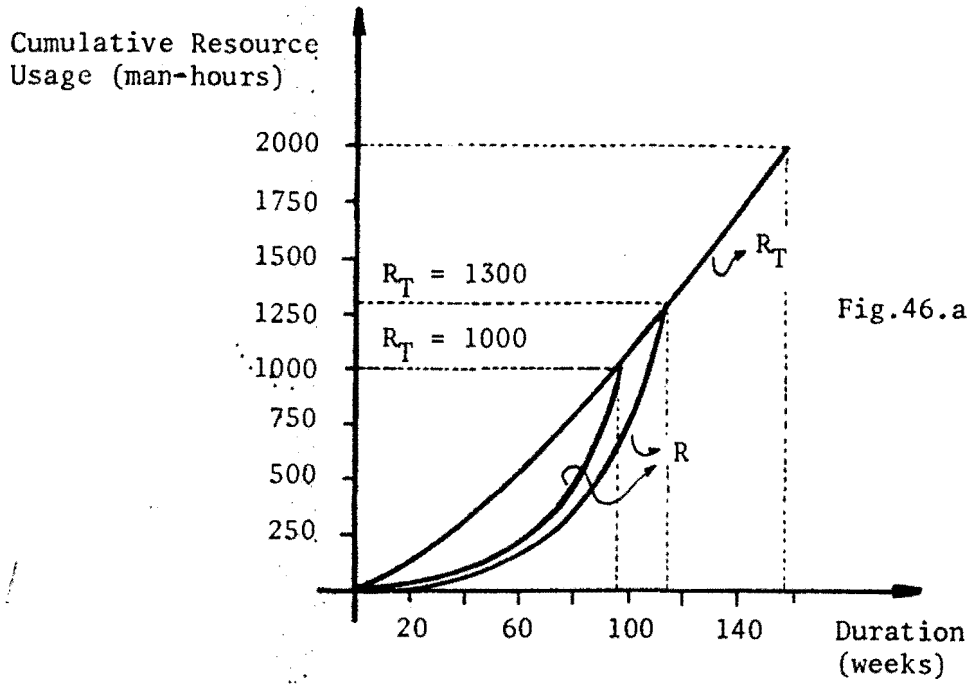


Fig.46.a

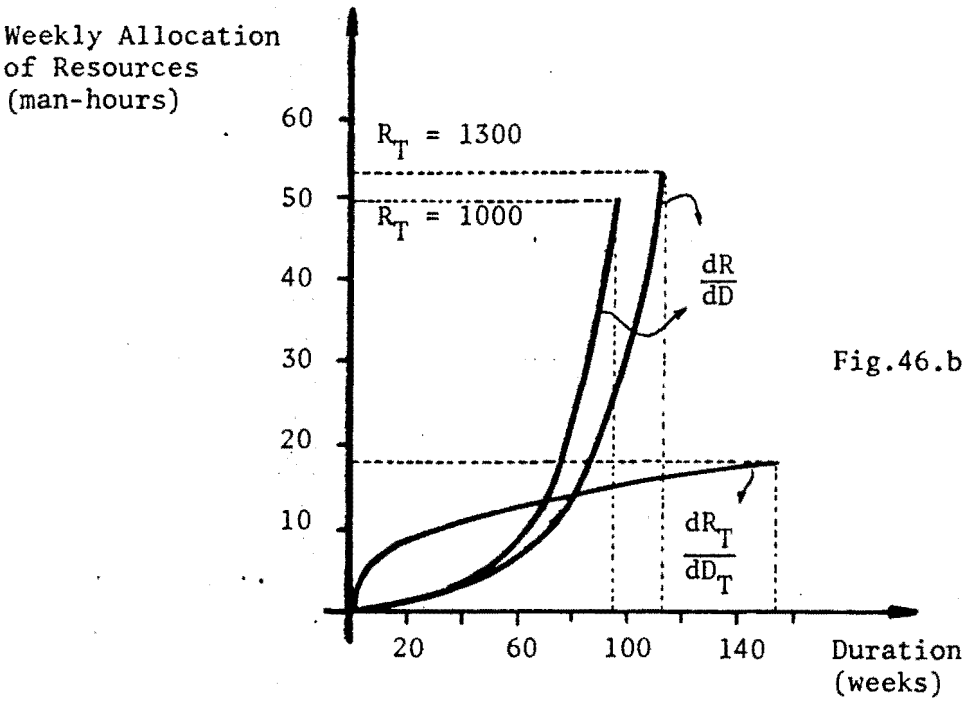


Fig.46.b

Figure 46

Differences between the Model for the Pattern of Allocation of Resources and the Inverse of the Equation to Estimate D_T

TABLE 11

Comparison between Actual and Predicted

Percentage Durations

	TOTAL LABOUR CONTENT man-hours	DURATIONS				PERCENTAGE DURATION		
		ACTUAL D_1 weeks	ESTIMATED D_1 weeks	ACTUAL D_8 weeks	ESTIMATED D_8 weeks	ACTUAL D_8/D_1	A ESTIMATED D_8/D_1	B ESTIMATED D_8/D_1
Ladygate Lane Site								
Strip top soil	115	22	19	5	5	0.23	0.26	0.27
First-floor panels, loose timbers	578	71	63	25	21	0.35	0.33	0.36
Plasterboard to ceilings	812	73	81	32	28	0.44	0.35	0.38
Sockets, switches, and light fittings	1614	121	133	63	52	0.52	0.39	0.42
Pitcoudie 1 Site								
Roof structure	958	96	91	39	33	0.41	0.36	0.39
Roof covering	2760	191	198	101	85	0.53	0.43	0.45
Stairs	738	75	75	32	23	0.43	0.31	0.38
Decoration	7655	368	419	173	215	0.47	0.51	0.51
Pitcoudie 2 Site								
Ground-floor slab	4900	327	302	153	144	0.47	0.48	0.49
Superstructure								
Eaves to Apex	2672	181	193	92	83	0.51	0.43	0.45
Dry-linings	17780	690	779	353	462	0.51	0.59	0.56
Decoration	20285	801	859	483	520	0.60	0.61	0.57

NOTES:

A = percentage duration calculated using regression models;

B = percentage duration calculated using f(x) and df/dx models, equation 15;

Joinery stage of work. This stage consumed 8,900 man-hours in Pitcoudie 2; this figure is taken as the estimated labour content for this stage on the new site. The rate of progress is obtained from past experience or from contractual documents. Figure 47.a shows that the rate of progress was on average 1.20 blocks/week. It is worthy of mention that the actual rate of progress for this stage ranged from 1.40 to 1.00 blocks/week, depending on the criterion used for its calculation (rate of starts, rate of practical finishings, and rate of actual finishings).

The total duration, including interruptions, is given by the DO1 regression model; it is estimated to be 1172 weeks. The number of blocks on the new site is the same as on Pitcoudie 2, 49 blocks, thus yielding an average total duration per block of approximately 24 weeks. Figure 47.a compares the predicted and actual band of man-hour allocations for the Joinery stage on the Pitcoudie 2 site. The total time the trade will be needed on site is directly derived from the band of allocation parameters (see Gates and Scarpa-1976) and equals 65 weeks. The number of blocks to be visited weekly and the total weekly allocation of resources can also be derived from the band of progress parameters. However, care should be exercised, because DO1 takes into account weeks in which work will not occur; the estimated total number of weeks in which work will take place is D1=466 weeks, that is, 40% of DO1. Henceforth, the average number of blocks visited per week will be "diluted" in the larger band of durations given by DO1; this "dilution" should be taken into account in working out the number of construction units to be visited in any week.

Figure 47.b compares the actual and estimated number of blocks visited weekly. As the actual number of weeks with allocations greater or equal to 1 man-hour exceeds the estimated D1 (672 vs. 466 weeks), the predicted profile of the number of blocks to be visited falls short of the actual average profile. Figure 48.a shows the actual number of working places available each week, that is, the number of blocks where work had been

Fig.47.a

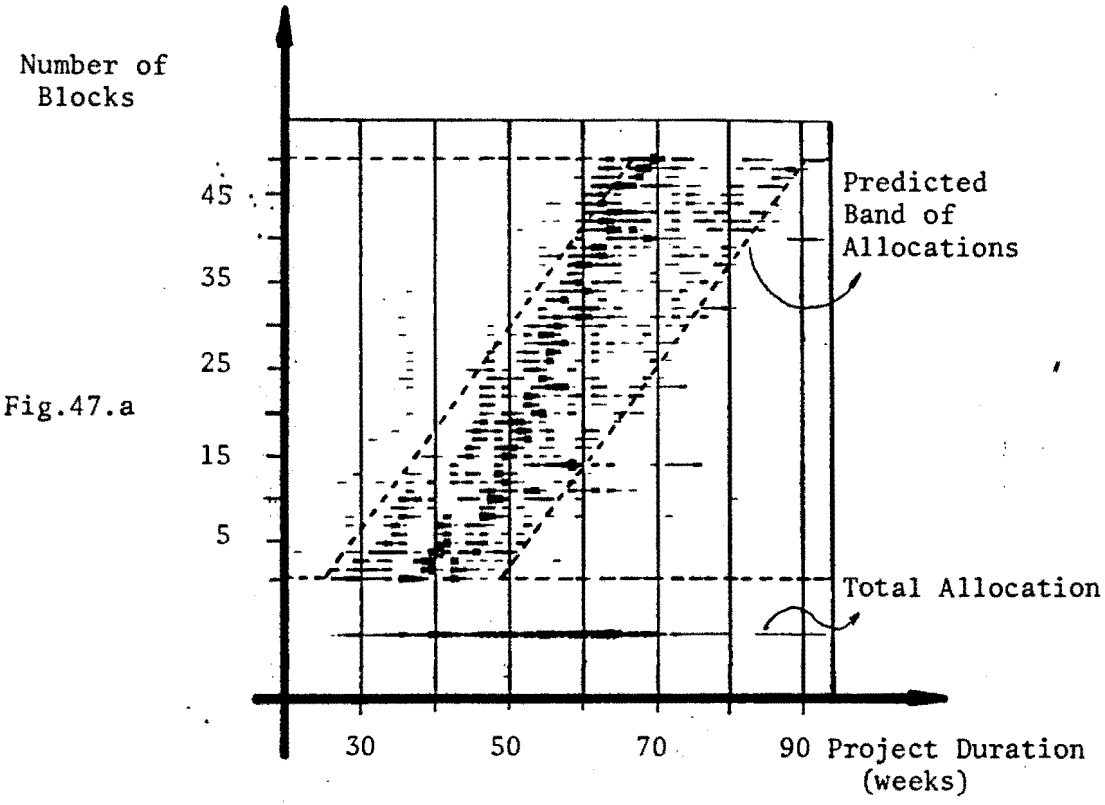


Fig.47.b

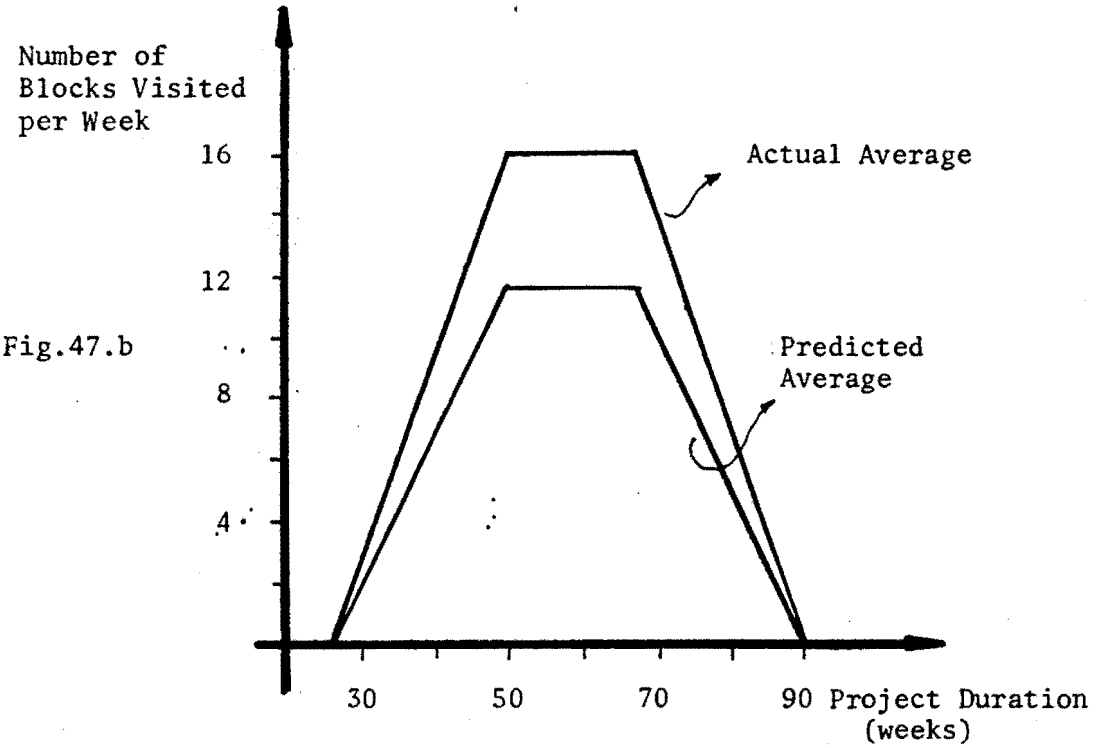


Figure 47

Comparison between Predicted and Actual Number of Blocks Visited per Week, Joinery Stage of Work, Pitcoudie 2 Site

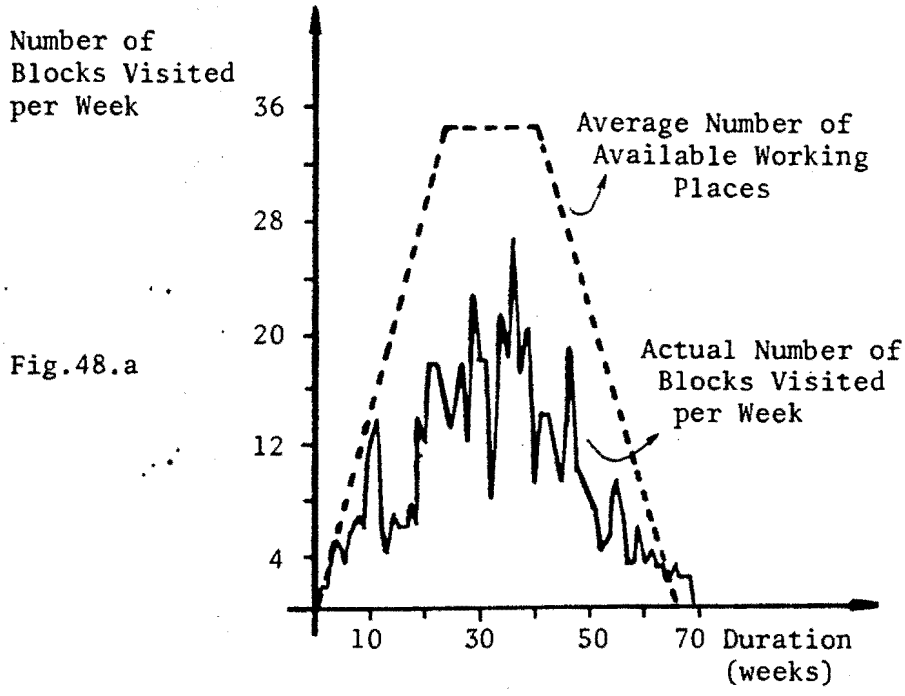


Fig.48.a

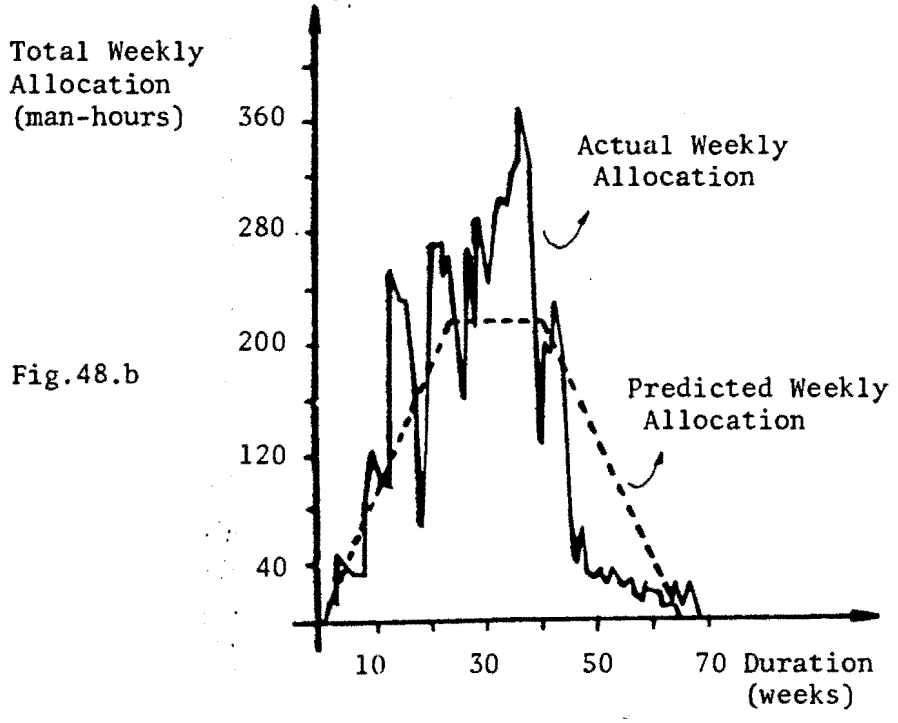


Fig.48.b

Figure 48

Number of Blocks Visited per Week and Weekly Allocation of Man-hours for the Joinery Stage of Work, Pitcoudie 2 Site

started but not finished; the various peaks in the actual number of blocks visited weekly reached some 60% to 70% of the actual number of available work places.

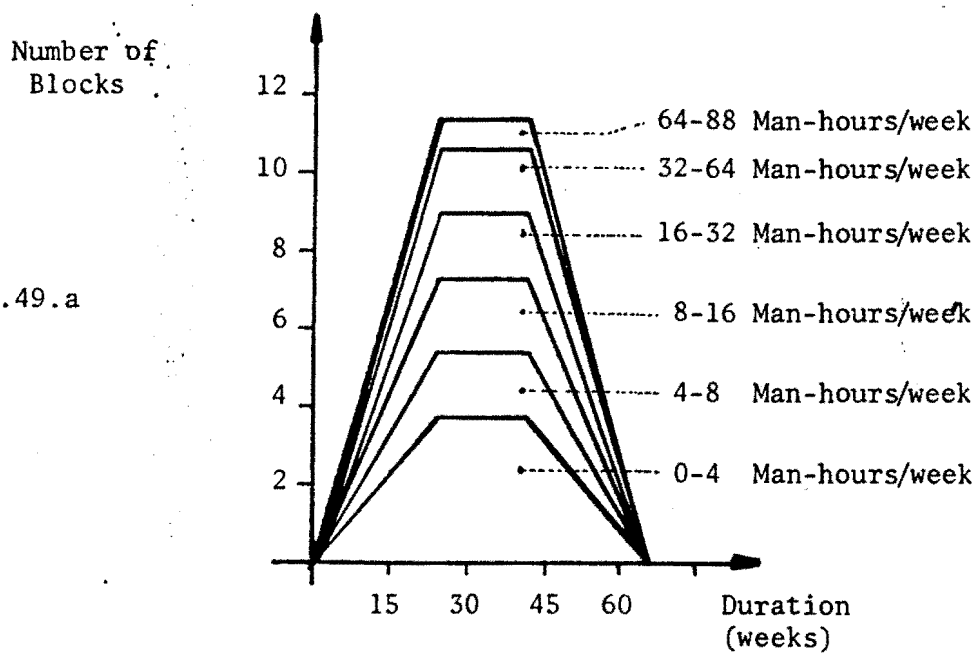
Figure 48.b compares the actual and predicted weekly allocation of resources. The left-skewed pattern of actual allocations is due to the movement of the "major effort" part of the work from the end of the duration of the stage in each block towards its start, as can be seen in figure 47.a. The variability in the actual number of blocks visited weekly and in the total weekly allocation of resources is just an illustration of the kind of problem faced by site managers in scheduling the work on site on a short time basis.

Figures 49.a and b depict the break down of the work to be performed on site according to the various magnitudes of resource allocation. Table 12.a, obtained through the use of the f(x) and df/dx models, provides the data for the profile curves. While the greatest number of visits will be performed in connection with allocations of low magnitude (in the range of 0-4 man-hours), they will take the smallest amount of resources. The smallest number of visits will be associated with the larger allocations (greater than 64 man-hours/week). The amount of resources consumed by allocations of this magnitude will be second to the total allocation for the 32-64 man-hours range, because the maximum predicted allocation (88 man-hours) is too close to 64 man-hours; there will not be a sufficient number of allocations greater than 64 man-hours to make this last subdivision of the work the more resource-consuming one, as might have been expected.

The information provided by Table 12.a and figures 49.a and b can be used to plan the work at a greater level of detail. During the period of maximum deployment of trade resources, some 215 man-hours and 11 visits to different blocks will be needed on site every week. Previous experience will dictate that, perhaps, 2 crews are necessary to carry out work of this magnitude. Table 12.b gives one possible assignment

- Number of Blocks to Visit per Week -

Fig.49.a



- Total Weekly Allocation -

Fig.49.b

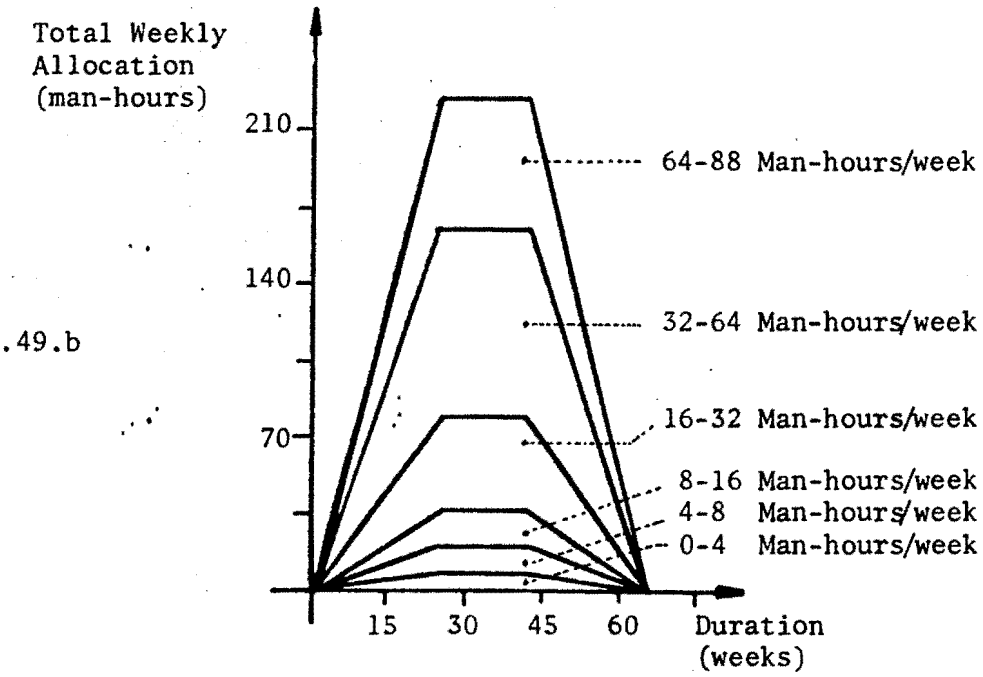


Figure 49

Estimated Number of Blocks to Visit per Week
and Total Weekly Allocation of Resources for the
Joinery Stage of Work on a Site Similar to Pitcoudie 2,
Broken down in 6 Ranges of Man-hours

TABLE 12

Estimated Number of Visits per Week and Weekly Allocation of Resources for the Various Components of the Joinery Work

Pitcoudie 2 Site

TABLE 12.a BREAKDOWN OF WORK

A	B	C	D	E	F	G
Range of wkly. allocations	Total Duration	Total Resources	Average Duration/ Block	Average Resource / Duration	Maximum No. of Visits	Maximum Weekly Allocation
(Man-hours)	(weeks)	(Man-hours)	(MH/Block)	(MH/Week)	(Blocks/wk.)	(Man-hours)
0-4	154	316	3.14	2.05	3.77	7.73
4-8	70	405	1.43	5.79	1.72	9.96
8-16	70	810	1.43	11.57	1.72	19.90
16-32	70	1619	1.43	23.13	1.72	39.78
32-64	70	3242	1.43	46.31	1.72	79.65
64-88	32	2404	0.65	75.13	0.78	58.60
TOTAL			9.51		11.43	215.62

TABLE 12.b ALLOCATION OF WORK TO THE CREWS

	H	I	J	L	K	N	O
Range of wkly. allocations	Approx. Resource/ Duration	Approx. max. no. of visits	Approx. max.wkly. allocation	CREW 1		CREW 2	
				No. of visits	Approx. max.wkly. allocation	No. of visits	Approx. max.wkly. allocation
(man-hours)	(MH/week)	(Blocks/ week)	(MH/week)	(No.of blocks)	(MH/Week)	(No.of blocks)	(MH/Week)
0-4	2	4	8	2	4	2	4
4-8	5	2	10	1	5	1	5
8-16	10	2	20	1	10	1	10
16-32	20	2	40	2	40	-	-
32-64	40	2	80	-	-	2	80
64-88	75	1	75	1	75	-	-
TOTAL		13	233	7	134	6	99

of work to the crews, after some approximations to the number of visits and average resource usage are made. Each crew will undertake a "package" of weekly work assignments. Crew 1, for example, would be responsible every week for one visit taking approximately 2 full man-weeks of work (75 man-hours to be precise), 2 visits taking half a man-week of work (20 man-hours), one visit taking a quarter man-week of work (10 man-hours), one visit taking an eighth man-week of work (5 man-hours), and 2 visits occupying just 2 man-hours. The difference in the total work assignment to each crew (maximum assignments of 134 and 99 man-hours respectively) could reflect differences in the composition or efficiency of crews.

This research work was devoted to studying the string of durations and associated resource allocations from the labour content viewpoint. A complementary study is needed of the pattern of allocation of resources from the crew-output viewpoint: the example given in the preceding paragraph assumed that perhaps 2 crews would be needed to carry out a work package requiring a maximum of 215 man-hours/week and 11 weekly visits to different construction units; no information is available for judging the appropriateness of choosing 2 crews for this job, or for giving guidance on the composition of such crews.

5.4 Discussion

The definition of durations in terms of the aggregate time taken by the activities in each construction unit proved to be a correct decision: the accuracy in measuring durations was greatly improved, while the measurement bias was stabilized. Due to the similar production characteristics of the 90 activities on the 3 sites, it was possible to obtain good correlation coefficients for the models of resource allocation patterns and predictions of total durations. It seems that, despite the differences between activities, common rules governed the allocation of resources to them.

The relationship between durations and resources for every possible minimum significant weekly allocation of resources allows the integration of different feedback information recording methods. The whole string of durations and allocations, including the very small allocations of between 1 and 5 man-hours/week, are recordable only by methods such as activity sampling; other methods, such as production cards, could be used to record the really significant allocations of resources; given that such significant allocations are known, it is possible to predict the rest of the string of allocations and associated durations. The development of models for every MISWAR precluded the need for objectively defining what is a significant allocation of resources; consequently, it is not necessary to define which weeks will be taken into account in measuring the duration of activities; once one duration is known (D1, D8, D16, etc.) the others can be objectively derived.

For the first time the relationship between the duration of activities and resource consumption was established. Despite the fact that various methods for estimating durations rely on the existence of a linear relationship between time and resource consumption, no research work had so far, to the author's knowledge, quantitatively substantiated the above relationship. The fact that the relationship showed a high coefficient of correlation means that durations were highly associated with resource consumption; not only can durations be estimated using the labour content of activities as the independent variable, but the coefficients of variation for resource consumption on similar activities can also be tentatively extended to durations. The coefficients of variation for resource consumption were exhaustively reviewed in Chapter Two. Applying these generally high values of coefficients of variation to the duration of activities supports the view that the programming of building sites should be considered a stochastic exercise, and not a deterministic one as claimed by some authors.

The information provided by the techniques developed in this chapter has generalised the Line of Balance programming concepts. The latter technique is applicable to the particular case where blocks are tackled sequentially, one block at a time, with a constant rate of deployment of resources; the models of this chapter allow the detailed specification of variable patterns of allocation of resources, the amount of overlapping between identical activities on different units, and the spreading of work to various blocks.

The regression models for estimating durations and the models for investigating the pattern of allocation of resources (f(x)) and df/dx) are independent, but produced similar results in terms of the cumulative percentage duration associated with every MISWAR. This gives support to the assertion that there was a common rule governing the allocation of resources to the activities, and hence their durations. One of the most important characteristics of this common rule was the low average intensity of work (resource consumption/ duration), consequently leading to large durations. Due to the fact that a range of durations can be calculated for every activity, one for every MISWAR, it is difficult to give an average figure for these low intensities of work; suffice it to say that the intensity of work can be calculated for every MISWAR, and then compared with the expectations of practitioners in the construction industry.

Activities were found to be interrupted several times; the number of weeks without work exceeded the number of weeks in which work was observed; interruptions further increased the total duration of activities and decreased the average intensities of work.

Models were developed for application on a "site basis" or on a "trade basis", rather than on an "activity-construction unit" basis. This should not prove to be a serious shortcomings of the models, due to the spreading of work to various blocks noted in Chapter Four; it seems that the trades saw the work on site as a whole, and concentrated

on a rolling number of blocks at a time, rather than on individual units. Moreover, the physical differences between construction units called for the use of average values for resource consumptions and durations; these are readily obtainable from the models, simply by dividing the aggregate figures for resources and durations by the number of blocks on site. It is the totality of work to be done on site that governed the production characteristics of individual activities in individual blocks, and not the other way round.

The large duration of activities necessarily implied the overlapping of the work of identical operations in different blocks, that is, the spreading of work to various construction units. This characteristic of the progress of work on the 3 building sites raises the question of programming the spread of work, or simply costing its consequences; the knowledge that work spread to the whole site calls for management and design action to avoid its detrimental implications; certainly it should not be taken as a standard for the programming of house building sites. However, while successful management and design solutions are not implemented, the programs of work should be sufficiently flexible to allow the simultaneous work in different construction units, thus avoiding idle time.

Total duration and total resource allocation were broken down and rearranged into strings of components. While it is possible to know the duration and resources associated with every component of this string accurately, no information is available on their timely sequence of occurrence. It is necessary to study the "s" shape resource allocation curves for the activities further, in order to increase the applicability of the models put forward in this research work.

The resource allocation models ($f(x)$ and df/dx) have an exponential form; they are thus highly sensitive to the correct estimation of durations. Small differences in total duration result in completely different patterns of resource allocation. Both the duration vs. labour content regression models and the resource allocation models require estimates

of the total resource consumption of activities; Chapter Two showed that these estimates are potentially biased and inaccurate.

The logarithmic graphs for the duration vs. labour content regression models produced narrow bands containing the majority of the 90 cases under investigation, implying that durations can be predicted with accuracy; the average coefficients of variation for D8 and D16 were 7.6 and 13.9% respectively for the activities observed on the 3 sites. This is much better than the estimating accuracy for the consumption of resources for individual activities mentioned in Chapter Two. However, these low figures were caused by the use of logarithmic variables. If the logarithmic variables are transformed back to the linear ones, the coefficients of variation increase to some 25%, which is in line with figures put forward for the estimation of labour consumption. The coefficients of variation for the other durations (D01, D1, D2, D4, D32, and D64) are larger, reaching 70% for the estimation of D01.

The models took into account the production characteristics of the 90 activities available, without distinction in terms of site. This strategy allowed generalised conclusions to be drawn, with small sacrifices in the modelling accuracy for individual sites. One such sacrifice is that the duration vs. labour content regression models produced biased estimates for the individual duration of activities within each site. D8 and D16 were predicted with the lowest actual/estimated duration bias (average of +5% for the 3 sites) while D64 had an estimating bias of +50%. This high figure reflects the inadequacy of the latter model as a predictive tool.

Beeston (1978) found that the coefficient of variation could increase by up to 50% when regression models were applied to data that was not used to generate them; McCaffer argued that this increase could be in the range of 25 to 50%. Adding the inaccuracy in estimating total labour content to the inaccuracy of the duration vs. labour content regression models produces an enormous range of possible estimated durations for the activities. Nonetheless, this is the best that can be achieved, even in the presence of fine feedback data, as made available for this research work.

Durations like D1 and D2 were clearly overestimated; the mere allocation of one or more man-hours/week to an activity is not an indication that work took place throughout the week. In the light of the low average intensities of work, it can be argued that durations such as D8, D16, and D32 were correctly estimated; allocations of work greater than 8 man-hours/week can be accepted as indicative that work spread to the whole week.

Durations D8 and D16 may be proposed as the standard durations for the activities. Their advantages over other possible standard durations (D01, D1, D2, D4, D32, and D64) are: higher correlation coefficients, smaller average coefficients of variation, and smaller estimating biases for the duration vs. labour content regression models; almost linear relationships with resource consumption; likely presence in activities with either small or large labour contents; and sufficient magnitude to be recognised on site, whatever the feedback system being used (even the simplest of the feedback systems is likely to note when an allocation higher or equal to 8-16 man-hours/week takes place).

Major findings of this research work, conclusions, and recommendations for further investigation are dealt with in the next chapter.

CHAPTER SIX

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 Summary of Findings

The flexibility of the Building Research Establishment activity sampling package combined with graphical forms of data presentation allowed an in-depth appreciation of the progress of work on site. However, this method of acquiring production-related information presented 3 major difficulties for the analyses of the duration of activities; the need for proper definition of activities; the lack of statistical accuracy of the small allocations of man-hours; the lack of an indication of the continuity of effort due to the instantaneous nature of the observations. The latter 2 problems were solved by the method of measuring durations put forward in this research work. The method involves data aggregation and hence greater accuracy. It also makes it possible to take into account only weeks with high labour allocations, that is, weeks in which, most probably, the work was done continuously.

Very little could be done in respect of the problems caused by the definition of activities at such a low level of work breakdown as to make the process of building appear inevitably discontinuous. This is not to say that the discontinuity of work observed on the 3 sites was caused by the way in which operations were defined, but that it was not possible to separate the discontinuity of work caused by this factor from other possible causes. In theory, only the definition of operations at its highest possible level of breakdown will produce sound information in accordance with network programming concepts. In practice, this refinement in the level of observations is of academic interest, because the trades concerned with each stage of work will continue to

see the process of building as discontinuous, given the existing design practices in the construction industry.

The models to estimate durations and the pattern of allocation of resources presented in this research work were valid for a wide range of levels of work breakdown; they can be tentatively extended to the lowest level, that is, truly operationally-defined activities.

The graphical and statistical analyses were able to confirm the long duration of activities, the discontinuity of work, the spreading of work to various blocks, the overlapping of work within and between blocks, and the high proportion of external works found by different authors while observing the progress of work on actual house building sites. There is nothing to suggest that the results were atypical; to the contrary, the 3 sites were the object of a rationalised design. The design rationalisation was partially successful in reducing the number of visits and the discontinuity of work, mainly for the Pitcoudie Project.

It was demonstrated that the duration of activities should not be seen in isolation; long durations, discontinuity of work, spreading of work, and overlapping precedence were interrelated characteristics of the progress of work on the sites investigated.

The fact that it was possible to treat without distinction the 90 completely different activities of the 3 sites shows that common rules were governing the allocation of resources to the activities and their durations. The models for the pattern of resource allocation were useful for describing the magnitude of the string of allocations (and associated durations) that took place for every activity on site; however, they were not able to predict the order in which the components of the string of allocations occurred. The models for the estimation of durations were capable of explaining why activities with large labour content took comparatively less time than activities with small labour content; the former activities used a comparatively larger weekly allocation of resources than the latter.

Both sets of models converged to virtually the same figures while predicting the durations associated with each magnitude of the weekly allocation of man-hours. Both sets of models can be used to provide indications on the low intensity of work (man-hours/week) allocated to the activities on the 3 sites.

The models for the estimation of durations showed a strong correlation between the duration of activities and the amount of resources they consumed; this correlation has not been established by previous research work. Despite the high correlation coefficients, part of the variability of durations remained unexplained. Therefore, stochastic differences will occur between the estimated and actual duration of activities if the latter are estimated for new sites using labour content as the independent variable.

The best correlation coefficient and model behaviour were obtained when durations were measured by taking into account only the weeks in which 8 or more man-hours were allocated to the activity. It is suggested that allocations around or greater than this figure can be taken as an indication that significant effort was devoted to the activities during the week.

6.2 Conclusions

This section addresses itself to the applicability of the concepts developed in this research work to the programming of house building projects.

The estimation of the duration of activities is dependent on the estimation of their labour content; the review of the literature showed the inaccuracies and biases in estimating the latter. Apart from this inaccuracy in the independent variable, the regression models produce errors and biases for the estimation of the dependent variable as well. This second source of inaccuracy in the regression

models as a predictive tool was of the same order as that of the already mentioned inaccuracy in estimating labour content.

The resource allocation models are highly sensitive to the correct estimation of total duration and total resource consumption. Both variables are subjected to high inaccuracies in their estimation. Completely different patterns of resource allocation emerge with slight differences in the total duration and total resource consumption. Therefore, the resource allocation models can only be used to provide rough indications on the string of allocations and respective durations that can be expected; their actual use for scheduling is restricted due to the high sensitivity of the models.

This research work provided data on the variability of durations that can be expected on house building sites. It also set figures for the accuracy that can be achieved for the estimation of durations in the presence of good activity sampling feedback data. It is beyond the scope of the work developed so far to categorically conclude that the variability of durations and the inaccuracy of their estimation, (assuming that they are representative of the house building industry as a whole), affected the applicability of network techniques to construction sites.

In addition, it is not possible to assess whether the availability of information at this level of accuracy can produce benefits for the progress of work on site derived from the application of programming techniques; it remains to be investigated if these variability and inaccuracy are already above the limits beyond which no benefit can be gained from the scheduling of work on site. However, this research work makes available a substantial part of the information needed to produce simulation exercises to examine the usefulness of scheduling under the stochastic conditions discussed above. High variability and inaccuracy cannot be judged on their own, but only in respect of their effects on programming and site management.

Similarly, the relatively high costs of obtaining activity sampling data with the frequency of observation rounds used in this research work can only be analysed in the light of possible benefits arising from their use in practical applications. It was observed that even at the high frequency of observation rounds used, accuracy was attained only at high levels of data aggregation. It seems that at these levels other methods of collecting production information, like production cards and operationally annotated pay-rolls, can be as useful as activity sampling, but at a smaller cost.

The framework for the proposed simulation exercises cannot be taken directly from the present network programming techniques. These techniques cannot accommodate the long durations, discontinuity of work, overlapping and spreading of work to various construction units. In particular, the notion of a constant rate of deployment of resources to the activities should be abandoned in favour of varying patterns of resource allocation.

6.3 Recommendations for further Work

Three broad areas of research are suggested for further work. The first area deals with complementing the developments presented in this thesis. Investigation in this area will complete the set of data needed for comprehensive simulations of the progress of work on site. Proceeding on the lines pursued in Chapters Four and Five, it would be interesting to:

- conduct in-depth studies on the overlapping factors between identical activities on different construction units and between different activities on the same unit;
- derive the "s" shaped resource allocation curves to compliment the knowledge obtained through the pattern of allocation models obtained in Chapter Five;

- calibrate the proposed method of measuring durations using continuous methods of production observation;
- extend the regression models for the estimation of durations to any level of work breakdown; for example, it would be possible to adjust the models in such a way as to obtain the duration of entire projects based on their total labour consumption;
- derive the models for the estimation of durations and for the resource allocation patterns from the viewpoint of the output of crews, rather than considering the labour requirements as was done in this research work;

The second area of research deserving attention is related to modifications of the existing programming techniques. It would be worth:

- investigating the interrelationship between strategic schedules and management of the site on a short term basis;
- analysing the usefulness of the project milestones detected in this research work to the setting of strategic schedules;
- separating programming and control of work from the physical progress on site; techniques that do not impose locational constraints, like bar charts and "s" curves, would be the first to be investigated under this heading. In particular, the concept of pools of work ahead and behind each trade could be specially suited to overcome the programming difficulties caused by discontinuity and spreading of work.

Finally, once the complete set of models are available to provide data for the programming of work, and suitable techniques are devised to accommodate the actual production characteristics of building sites in scheduling exercises, it would be possible to investigate the correct strategy to deal with production problems in house building sites. It seems that research in this area would possibly lead to:

- an increase in the applicability of programming techniques through a systematic gathering of production-related information. Very little is known about the actual production

process on house building sites. Initially the costs of observation studies similar to the one carried out in this research work could be afforded only by research organizations, that would collect, organize and analyse information for the construction companies. One of the more promising areas is the reduction of variability in the building process, in order to increase the possibility of successful application of schedules of work;

- abandonment of the search for improvements in house building construction through site programming, concentrating instead on other areas like design, short term site management, industrial relations, and training. While feedback information would still be needed to assess the influence of decisions taken in these areas, the actual progress of work on site would be looked on as another component of risk in the construction industry; the effects of risk could be mitigated by techniques other than site programming.

APPENDIX

SITE HIERARCHY FOR THE PITCOUDIE 2 SITE

A complete description of the Pitcoudie 2 site is given, together with the site hierarchy formulated by the house building production analyst. It is hoped that this information would help prospective users of activity sampling methods to define the site hierarchy for new projects. This appendix is also intended to allow a deeper appreciation of the physical characteristics of the Pitcoudie 2 site and their likely influence on the findings reported throughout the main body of the thesis.

A.1 Site Description

The Pictoudie 2 scheme had been developed in consultation with architects and engineers in the Scottish Development Department responsible for Housing Standards, engineers in the Fife region, and the Department of Engineering in the Glenrothes Development Corporation. The information reproduced in the next paragraphs was taken from an internal project report (see Scottish Development Department in the bibliography).

"Pitcoudie 2 is a continuation scheme from Pitcoudie 1, on a bigger scale of operations. The objectives of the Pitcoudie projects are to study possible savings of time and money caused by the rationalization of traditional house building construction. These objectives are to be achieved by:

- the sequence of operations being identical in each house;
- the standardization of building components (windows, floor joists, partitions, etc.);
- the use of a simplified form of construction: concrete floors, which are not common in Scotland, are finished smooth to receive thermoplastic tiles without the use of an inter-

mediate screed; walls are of a thick single concrete block and internal plasterboard lining in Pitcoudie 1, and the traditional cavity brick/block wall with a thermal lining board in Pitcoudie 2;

- the coordination of dimensions;
- the careful attention to plumbing, electrical and joinery work to require fewer, larger, and more independent trade operations;
- the contract documents and drawings allowing improved communications between design and building teams.

A special consideration in Pitcoudie 2 is the re-examination of the relationship between houses, roads, footpaths and courtyards.

Seven different housing types are used:

- 2 persons single-storey south aspect;
- 2 persons single-storey north aspect;
- 4 persons two-storey;
- 5 persons two-storey south aspect;
- 5 persons two-storey north aspect;
- 7 persons three-storey;
- 9 persons three-storey.

The 7 person and 9 person houses are 4 person houses with an additional storey, 9 person houses having an additional annexed room on the first and second floors. There are also 2 three-storey and 2 four-storey blocks of flats providing mixed accommodation for 2 persons, 3 persons, and 4 persons.

Some special houses and flats for the disabled are provided. The differences between south aspect, north aspect, and disabled houses are mainly in the positions of doors and windows, and in increased sanitary facilities for the latter.

Singe and two-storey houses have ducted warm air systems (equally divided between houses with gas and electric systems). Three-storey houses have either wet radiator gas systems or electric storage heaters. Flats use electric warm air ducted partial systems, with bedrooms heated by electric storage heaters in 3 person disabled flats.

Apart from these differences in heating systems, position of doors and windows, and increased facilities in disabled dwellings, the houses can be considered identical as far as the construction process is concerned. Obviously the blocks of houses differ in size, because each one has a particular mix of housing types. Flats employ a different construction method involving intermediate precast floors".'

Pitcoudie 2 specifications are given in table 13. The general site layout, dwelling mix, and area of blocks are given in figure 04 and table 06 produced in the main body of the thesis.

A.2 Site Hierarchy

The house building production analyst used the following hierarchy of headings to record the snap observations;

- Level 1:
  55 blocks of dwellings, corresponding to 49 blocks numbered from 1 to 49 comprising houses only, 4 blocks numbered from 50 to 53 comprising 2 three-storey and 2 four-storey blocks, and 2 dummy blocks; block 60 is used to record all stage-related external work that cannot be associated with particular blocks; block 0 is used to record observations that can neither be assigned to particular blocks (including block No. 60) nor to particular stages of work;
- Level 2:
  houses within each block; some blocks (like No. 15) are very small containing only 2 dwellings for 2 persons, others (like block No. 31) have 10 dwellings; when it is not possible to relate information to any particular house inside the block the heading "apportionable to block only" is used;

Table 13

Pitcoudie 2

General Specification Notes

Foundations:	houses generaly 570 x 190 mm; flats generally 750 - 800 x 230 mm. concrete strip foundations (1:2:4) with 450 mm. minimum ground cover at all external and party walls. Foundations to flats have bottom mesh reinforcement.
Sub-Floor:	consolidated site fill to within 350 mm. of floor level, thereafter 175 mm. well consolidated hardcore with 50 mm. sand blinding finished smooth to receive dpm.
DPM: "Visqueen 1200" damp-proof membrane in sub-floor.	
Ground-Floor Slab:	125 mm. concrete slab with mesh reinforcement; 600 mm. perimeter insulation 25 mm. thick; surface of slab floated to a smooth surface and finished with pvc floor tiles on "Dunlop Smoothfloor" latex screed.
DPC: "Nurlene" damp-proof courses in walls.	
Underbuilding:	Houses - 255 mm. thick "Thermalite" concrete blocks laid with 50 mm. vertical coursing and 1/3 bond horizontally; Flats - non-loadbearing 255 mm. overall thickness with 102.5 mm. outer skin, 52.5 mm. cavity concrete filled up to dpc and 100 mm. "Russlite" concrete blocks (7.0 N/sq. mm.) inner skin; for loadbearing walls the inner skin is 140 mm. "Russlite" concrete blocks (7.0 N/sq. mm.) and overall thickness thus 295 mm.
External Walls:	Houses: 255 mm. overall with 102.5 mm. brick, 52.5 mm. cavity and 100 mm. "Russlite" concrete block (4.12 N/sq. mm.) inner skin; Flats: non-loadbearing 255 mm. thick overall with 102.5 mm brick, 52.5 mm. cavity and 100 mm. "Russlite" concrete block inner skin (7.0 N/sq. mm. on ground floor of 3-storey floors and ground-floor plus first-floor of 4-storey flats; 4.12 N/sq. mm. blocks on first and second-floor at 3-storey flats and second plus third-floor of 4-storey flats); for loadbearing walls the inner skin is 140 mm. "Russlite" blocks and overall thickness thus 295 mm.; finished externally with 20 mm. dry dash render; internal lining in "British Gypsum

	Vapourcheck Thermal lining" fixed by modified "Thistlebond" method (25 mm. thick board) and nailed with 3 rows of 3 nails per sheet; U value of 0.67 W/sq. M deg C for 255 mm. wall; 2 person houses only have Cape "U Foam Plus" cavity insulation.
Party Walls:	two skins of 100 mm. "Russlite" concrete block (4.12 N/sq. mm., 1250 kg/c. m. density) generally with 55 mm. cavity; both sides of wall with 8-12 mm. render and 12.5 mm. plasterboard fixed by "thistlebond" method; party walls between flats and houses will in some instances have higher density and thicker blocks (see above).
Intermediate Floors:	Houses: 200 x 50 mm. joists at 450 mm. centres, built into walls- where built into party-walls, joists are fire-stopped with 12.5 mm. "Asbestolux" plates; 19 mm. chipboard flooring with higher density grade in bathrooms; 9.7 mm. plasterboard ceilings for 2-storey houses and 12.5 mm. plasterboard for 3-storey houses; Flats: prestressed precast concrete units, 200 mm. thick; design certificate to be supplied by manufacturers; 22 mm. T. and G. flooring on 50 x 50 mm. battens on sound insulating quilt (battens not fixed to floor units); 12.5 mm. plasterboard ceilings on 50 x 38 mm. battens fixed to timber inserts in concrete floor units.
Roof:	"Redland Delta" tiles on 50 x 25 mm. impregnated battens, breather felt type 1A on 12.5 mm. bitumen impregnated black top fibreboard sarking on "Fink" type roof trusses at 600 mm. centres generally; 100 mm. fibreglass roof insulation immediately above ceiling; top floor ceiling to be 12.5 mm vapour-checked plasterboard
Internal Partitions:	50 mm. "Paramount" partitions.
Loadbearing Partitions:	75 x 50 mm. studs at 400 mm. centres lined with 12.5 mm. plasterboard.
Glazing:	2 person house type only to be double-glazed with "Pilkington's Plyglass" sealed units; all other house types to be single-glazed.
Water Storage:	7 person and 9 person house types (3 storeys) to have 180 litres capacity combination "Elson" tanks; all other dwellings to have 135 litre capacity "Elson" tanks.

Heating:	single and two-storey houses to have ducted warm air system (approximately 50% split between gas and electric); three-storey houses to be either wet radiator gas system or electric storage heaters; flats (all electric) to have warm air ducted partial system plus bedrooms heated in 3-person disabled flat by electric storage heaters.

Table taken from Scottish Development Department, Urban Design and Research Division, Pitcoudie Housing Development for Glenrothes Development Corporation, Edinburgh, Scottish Development Department, March 1979.

- Levels 3 and 4:

  stages of work and operations: each house building process is divided into 42 stages of work and each stage of work is further divided into operations; whenever it is not possible to relate an observation to a particular operation within a stage of work, the heading "apportionable to stage only" is used; a complete listing of the stages and respective operations is given below.

Stages of work	Operations
1) Foundation	A - excavate trenches B - concrete C - shuttering D - reinforcement K - apportionable to stage only
2) Substructure	A - brickwork B - blockwork C - lintels and service entry ducts K - apportionable to stage only
3) Ground-floor slab	A - fill, hardcore and blinding B - slab, dpn, edge insulation, and reinforcement C - flooring D - precast concrete floor units E - precast concrete stair units F - machine guide and shuttering G - slip steps K - apportionable to stage only
4) First-storey superstructure and also: 6) Second-storey 8) Third-storey 10) Fourth-storey superstructure	A - brickwork to external walls B - blockwork to external walls C - blockwork to party walls D - door and window frames E - dpc, lintels, and window cills F - stud partitions G - rendering to party walls and stair wells H - temporary buttresses for brickwork J - cavity wall insulation K - apportionable to stage only

5) Second-storey flooring and also 7) Third-storey, 9) Fourth-storey flooring	A - floor joists and ties C - flooring D - precast concrete floor units E - precast concrete stair units K - apportionable to stage only
11) Roof carcassing	A - trusses, wall plates, fascia, ties, and braces B - sarking C - asbestos cavity closers D - ceiling insulation K - apportionable to stage only
12) Eaves to apex superstructure	A - brickwork to flank walls B - blockwork to flank walls C - blockwork to party walls K - apportionable to stage only
13) Roof covering	A - felt, battens, tiles, and roof lights K - apportionable to stage only
14) Scaffolding	A - bricklayers scaffolding B - external scaffolding K - apportionable to stage only L - carpenters scaffolding
15) Glazing	A - glaze doors and windows B - mastic pointing around doors and windows K - apportionable to stage only
16) Harling	A - harling and metal trims B - expansion joint filler C - mastic pointing to expansion joints D - remove efflorescence K - apportionable to stage only
17) Stairs	A - timber stairs, balustrade, trim, and soffit B - metal handrails and balcony balustrades K - apportionable to stage only
18) Dry-linings	A - plasterboard to external walls B - plasterboard to party walls and partitions C - plasterboard to ceilings D - paramount partitions K - apportionable to stage only
19) Doors	A - external doors B - internal doors sets C - door and window reveals D - ironmongery K - apportionable to stage only

20) Joinery	A - timber skirtings and door facings B - plastic skirtings C - kitchen units D - bath panels, trims, shelving, and boxing pipes E - tiling showers K - apportionable to stage only
21) Plumbing	A - gutters, down pipes, and roof flashings B - soil and ventilation pipes C - hot and cold water pipes, tank, cistern, and lagging D - wash basin, bath, and WC E - radiators and pipes F - gas pipes K - apportionable to stage only
22) Electrical	A - wiring B - socket outlets, switches and fittings C - conduit and meters K - apportionable to stage only
23) Heating and ventilating	A - gas heating unit and ducts B - electrical heating unit and ducts C - air extract unit and ducts K - apportionable to stage only
24) Decoration	A - artex B - tape and fill joints in plasterboard C - emulsion paint to walls D - gloss paint to internal surfaces E - gloss paint to external surfaces F - sigma coating (stairs, landing, etc.) K - apportionable to stage only
25) Floor finishes	A - screed B - floor tiles K - apportionable to stage only
26) Cleaning and snagging	A - clean out prior to execution B - snagging after occupation C - clean out during construction K - apportionable to stage only
27) Additional sound insulation	K - apportionable to stage only
28 and 29) not used	
30) Reduce levels	A - strip topsoil, reduce levels, and cart away B - tidy earthworks around site C - cover up courtyard areas for protection

	D - clean off courtyard areas
	E - break up and cart away rock
	K - apportionable to stage only
31) Soil drains	A - excavate trenches and backfill
	B - lay pipes and granular material
	C - construct manholes
	K - apportionable to stage only
32) Surface water drains	A - excavate trenches and backfill
	B - lay pipes and granular material
	C - construct manholes
	K - apportionable to stage only
33) Gardens	A - garden paths and steps
	B - bin stores
	C - fencing
	D - screen and retaining walls
	E - vine supports
	F - replace topsoil
	G - rotary dryers - all work
	K - apportionable to stage only
34) Landscaping	A - return topsoil and form mounds
	B - public seats and play equipment
	C - play areas - all work
	D - cobbled edging to courtyards
	E - fencing
	F - concrete blocks for fire paths
	K - apportionable to stage only
35) Roads and public footpaths	A - kerbs, base, and surfaces to roads and courtyards
	B - kerbs, base, and surfaces to footpaths
	K - apportionable to stage only
36) Site establishment	A - erect and maintain offices, sheds, and compounds
	B - temporary fences, access, and utilities
	C - visits to stores and offices
	D - plant maintenance, cleaning, and refueling
	E - general cleaning up around site
	K - apportionable to stage only
37) Gas, and also 38) Water, 39) Electricity	A - excavate trenches for main cable/pipe, and backfill
	B - lay main cable/pipe and fittings
	C - excavate trench for house connection, and backfill
	D - lay house connection cable/pipe and meter
	K - apportionable to stage only

40)	PO telephone	A - all work
41)	TV relay	A - all work
42)	Street lighting and name boards	A - street lighting, all work B - street name boards, all work

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- Level 5:
  all observations were recorded against one of the following activities, no matter what headings were used for higher levels in the hierarchy:

  - F1 - making the building grow (adding materials and components to the house in a productive way)
  - U1 - unloading
  - H1 - handling around the site
  - H2 - handling from stack to workplace
  - Su - supervision
  - T1 - setting out and measuring
  - T2 - testing hot water pipes, drains, etc.
  - P1 - preparation of materials
  - C1 - cleaning tools or clearing up
  - N - not working while at the workplace
  - I - not working while around site
  - W - walking
  - Bk - meal breaks
  - Ro - work stopped due to the weather
  - A - operative not seen during the round
  - Rt - work repeated
  - F2 - lay bricks/blocks to rule
  - F3 - lay bricks/blocks to line
  - F4 - spread mortar bed
  - P2 - cut bricks/blocks
  - P3 - prepare mortar
  - P4 - set up line

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