MAINTENANCE MODELLING OF A MAJOR HOSPITAL COMPLEX

A thesis submitted to the University of Salford

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June 1993

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ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, professor A.H. Christer, for his untiring interest, motivation, encouragement, and support for this research project.

My thanks also goes to the maintenance management and staff at Withington Hospital for their help and support to this project, specially Mr. W. McMaster the Works Office manager.

My thanks also goes to Mrs. E. Heaton, Miss S. Sharples, and Dr. W. Wang, at the University of Salford, for checking the final copy.

Finally I must thank my parents for their encouragements and support, and I am greatly indebted to my wife and children for encouragement and enduring the production of this thesis, it is to them all that this thesis is dedicated.

Notwithstanding all the assistance given to the auther, the errors and shortcomings of this work are his alone.

ABBREVIATIONS

List of abbreviation used in activity cycle diagrams

The activity cycle diagrams of the simulation models have used abbrevations to entities, activities, and queues. These are in below.

A. Entities

There are four classes of entities being used in the simulation, these are:

(1) JOBS (red) : Jobs are either defects, breakdowns, services or modification.

(2) TRADSM (blue) : Tradesmen are either electicians, fitters, plumbers, or joiners.

(3) SUPRVS (green) : Supervisors are responsible for scheduling jobs, allocating resources, ordering spares, and monitoring the work.

(4) SECRY (megenta): Secretary is recieving the jobs either by telephone call or through internal post.

B. Queues

Each class of entities has its set of queues, these sets of queues, some of them are dummies, are listed in below.

B.1. Jobs (red)

PJ	: Pooled jobs queue.
EM	: Emergency jobs queue.
DLYD	: delayed non-urgent jobs queue.
ONDESK	: Non-emergency jobs queue.
PBOARD	: Scheduled jobs on the plan board queue.
JC	: Collected job waiting to gain access queue.
JATR	: queue of collected jobs are waiting for collecting spares and tools, when no previewing to jobs is necessary.
JATWRK	: collected jobs waiting to be diagnosed or repaired.

B.2. Tradesmen (blue)

FREE	: Free tradesmen queue.
VW	: Tradesmen are waiting to travel to preview jobs
CA	: Tradesmen are waiting to gain access to preview jobs.
DG	: Tradesmen are waiting to diagnose jobs.
BK	: Tradesmen are waiting to travel back to the maintenance department.

SP	: Tradesmen are waiting to request spares for previewed jobs.
TNS	: Tradesmen are waiting to travel from the store to the maintenance department because of no spares in stock.
TR	: Tradesmen are waiting to travel to the job location.
CAR	: Tradesmen are waiting to gain access to job location in order to repair.
RP	: Tradesmen are waiting to repair jobs.
F	: Queue of tradesmen finished repairing the defect.
T	: Queue of tradesmen have finished repairing jobs
TRS	: Tradesmen are waiting to request and collect spares and tools to not previewed jobs.
TRVL	: Tradesmen are waiting to travel to job location.
GAAR	: Tradesmen are waiting to gain access to repair jobs.
G	: Queue of tradesmen are waiting to travel back to the maintenance department because of failing to gain access.
DGR	: Tradesmen are waiting to diagnose a defect.

B.3. Supervisor (green)

SUPRVS	: a free supervisor queue.

B.4. Secretary (magenta)

SECRY : a free secretary queue

C. List of activities

ARIVE	: Interarrival time between jobs.
EMERGY	: Emergency activity.
DLYDJR	: Repairing the delayed non-urgent jobs.
SCHEDL	: Scheduling and allocating resources.
COLECT	: Collecting job(s) from the plan board.
TTVW	: Travelling to preview a job.
GAV	: Gaining access to preview a job.
DIAG or DIAGNS	: Diagnosing a defect.
TBAK or TRAVL	: Travelling back to the maintenance department.
RSPR	: Requesting spares.
TRTR	: Travelling to repair a defect.
GATR or GARP	: Gaining access to job location in order to perform a repair.
REPAR	: Repairing a defect.
FSHJOB	: A dummy activity used to control the number of jobs repaired.
RS	: Requesting and collecting spares.
TRVEL	: Travelling to a job location.
GTRVL	: Travelling back to the maintenance department because of failing to gain access to job location.

ABSTRACT

By its nature, building maintenance requires an ability to respond to a demand that is random in time, random in nature and random in location. This in turn creates complex operational and logistical problems for management, specially if the property complex is large.

The objective of this research is to assess the scope for and effectiveness of quantitative modelling, and the prediction of the outcome of alternative management action (policy), to assist in the management of building maintenance complexes of the size of a hospital. Both building and engineering equipments are encompassed within the study as appropriate.

The research issues are split into three related phases; a demand study; a defect reduction study; and a maintenance management model.

1 - The maintenance demand study

Based upon general statistics obtained, attempts have been made to identify and quantify both the major problems areas (in terms of cost and frequency of maintenance activities), and the nature and cause of the demand for maintenance. They have revealed no coherent picture in that the demand from wards and buildings seems independent of the patient throughput and the age of buildings. The demand for maintenance, for the main trades involved, has been estimated and used in the simulation models mentioned in below.

2 – Demand reduction model

Accepting the current demand situation for maintenance, it was proposed to identify what is the cause of the demand and what possible actions could reduce the demand: Possibly through design modification, changes in materials used, change in practice of service/building user, development of Preventive Maintenance 'PM' or inspection system for component. Despite considerable effort, it proved not possible to progress this aspect of the study and the reasons are discussed.

3 – Maintenance management models

Simulation models to the maintenance activities within the hospital has been developed using, Extended Control and Simulation Language, ECSLPLUS, to model the maintenance policies, and assessing any changes in operating procedures. The advantage of modelling is that the magnitude and nature of changes can be assessed and contemplated prior to any actual change in operating procedures. This is generally recognised as being most valuable.

For specific problems and areas of operation identified, development of specific methods of deployments have been attempted. For instance, 'recieving one job at a time'; 'recieving a batch of jobs at a time'; and 'delaying non-urgent jobs and grouping them in time'. A number of maintenance management policies have been assessed using the above models, these are: 'Previewing' and 'not previewing' most of the defects before repair to identify the required resources; 'employing extra part-time tradesmen during the busy days'; 'working 7 days instead of 5 days a week'; 'no sickness policy'; and 'employing multi-skilled tradesmen option'. These models should be capable of indicating to management the gains and consequances, in terms of measures of interest to them such as the workforce and manhours required to meet the demand for maintenance per trade, changing operating practice, customs and timescales. That is, their decision variables.

Chapter 1

INTRODUCTION

1.1. Introduction

Building maintenance has until recently been a neglected field of quantitative modelling and of academic study. It has not attracted very much attention despite being regarded as underfunded, unproductive and poorly managed, or the recognition that many of its managerial problems are demanding more research and skills than those of new works. Large backlogs of maintenance are acknowledged in both the public and private sectors, running into £billions, and the resulting poor state of the national building stock is expected to have serious current and future social and economic effects. Neglect of building maintenance has cumulative results with rapidly increasing deterioration of the fabric and finishes of a building accompanied by possible harmful effects on the contents and occupants or users. In excess of one-third of the total output of the construction industry is devoted to building maintenance, inadequate though it is to keep the nation's buildings in a satisfactory condition (Seeley 1987). Better management and work planning would result in a more economic use of resources and a corresponding reduction in the total cost of maintaining property to a standard.

As far as hospital buildings are concerned the Davies Report (1983), commissioned by the Department of Health and Social Security, DHSS, estimated that in England alone there was a backlog of maintenance work of £2 billion. Quoted examples of short-term patching of defective flat roofs, hardware not being replaced, and painting often being regarded as a luxury. There was a generally expressed view among health authority officials that in order to cope with restricted maintenance expenditure allocations, measures were being taken which were not cost-effective, and were building up severe difficulties in the years ahead (Seeley 1987).
The maintenance of relatively new hospitals was also being neglected. Because of excessively tight cost limit and the experimental methods under which many were constructed, hospitals built in the 1960s and 1970s can cost up to three or four times as much to maintain as older hospitals (Royal Institute of British Architects 1985).

1.2. Maintenance definition

British Standard Institution (1984), defines maintenance as:

> *"The combination of all technical and associated adminstrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function".*

There are two processes envisaged: *"to keep"* i.e. work carried out in anticipation of failure, which is usually referred to as "preventive maintenance"; and *"to restore"* i.e. work carried out after a failure, which referred to as "corrective maintenance". The requirements for maintenance must not be less than those necessary to meet relevant statutory requirements, Seeley (1987).

The Building Maintenance Committee (1972) has recommended the following version of the British Standard Institution definition for maintenance of buildings which includes a reasonable element of improvement:

> *"Work undertaken in order to keep, restore or improve every facility, i.e. every part of a building, its service and surrounds, to a currently acceptable standard and to sustain the utility and value of the facility".*

This building maintenance definition refers to a *'currently acceptable standard'*, since most buildings have long life expectancy, therefore it is assumed that the currently acceptable standard to be higher than the initial standard when the building first constructed. There may, of course, be cases where buildings are put to a less demanding use for which a lower standard would be acceptable, Lee (1987). There is also reference to *'utility and value'*, which are important factors to take into account when fixing an acceptable standard.

The Woodbine Parish Report (1970) gives the following version of British Standard definition of building maintenance of hospitals:

> *"Work undertaken to keep or restore hospital premises to acceptable standards of safety and efficiency having due regard to the needs of patients and staff within their immediate environment, the requirements of the NHS and the resources available".*

Clearly the *'acceptable standard'* would be related to safety and efficiency and the work done in such a way as not unncessarily to disrupt services or inconvenience staff and patients. The reference to *"available resources"* is interesting in that it suggests that some arbitrary sum of money is set a side for maintenance and that this cannot be exceeded even though to achieve an acceptable standard would involve a greater expenditure (Lee, R. 1987). Thus the standard is really determined by the amount of money allocated rather than as a result of assessing the benefits obtained from maintaining the building to a particular state.

1.3. Withington Hospital

Withington is a large South Manchester district general teaching hospital of some 1,131 beds allocated to serve most of the medical specialities. The annual budget of the Works Office, including the maintenance of Withington hospital, Duchess of York hospital and 14 near by clinics is about £3 million pounds. About 65 tradesmen and supervisors of 7 different trades are employed, namely 6 electricians, 7 fitters, 5 joiners, 4 plumbers, 4 builders, 6 gardeners, 12 painters and a number of assistance, supported by 3 technicians, 2 works stores, 4 stockers and 2 planner estimaters. The management of the Works Office estimated the total work load of the seven trades plus the planned preventive maintenance jobs as about 600-700 jobs per week. However, records indicate that the day-to-day work load of the four key trades, namely, electrical, mechanical, plumbing, and joinery is about 200-300 jobs per week.

1.4. Process and building maintenance

For the last three decades there has been growing interest in the study of maintenance models for systems with stochastic failures. These studies are concerning with applying Operational Research techniques to the maintenance of industrial processes where the main objective is to keep the machines in productive operation for as much of the time as possible (Cho & Parlar 1991). It was recognised that a failure based interruption at one part of an industrial process may bring the whole process to a halt. Gereards (1983), and Gits (1984) make a number of observations which are useful in highlighting the similarities and differences between process and building maintenance, these are summarised by Grimshaw & Poole (1990) as follows:

1. The maintenance of industrial processes can be generated by failure, by the end of a specific period of use, or by the assessment of condition against a pre-determined scale of condition triggers.

   Failures of buildings can also be triggered by the failure of a component, or the assessment of condition of an element or component against a pre-determined scale.

2. The failure of plant can be due to primary cause, i.e. not caused by any other failure; secondary causes, which are the result of a primary failure; or by external causes, which are unrelated to the operation of the plant.

   Failures of building components can also have the same causes.

3. Plant has two states: Uptime when it is working and downtime when it is not working at a time when it should be. The utilisation factor is the ratio of the time a production unit is operable to the uptime available. The availability of the plant is the ratio of uptime to the uptime plus the downtime.

   Buildings or sections of buildings can either be in use (uptime) or out of use due to major repair (downtime).

4. There is a distinction between corrective/emergency maintenance of plant which follows failures, and preventive maintenance which precedes failure and, perhaps, reduces its probability. The same distinction can be made between corrective/emergency and preventive maintenance of buildings. Buildings can also be taken out of commission for major or turnaround maintenance, where turnaround maintenance is carried out while the plant or building is not in operation (Mann and Bostock 1982).

The objective of the maintenance of industrial processes is to reduce downtime to a minimum but at reasonable cost. The key decisions are what level of resources to be allocated and the level of inspection or preventive maintenance or replacement which should be carried out in order to reduce the downtime and the unexpected failures to an acceptable level.

Having considered the similarities of plant and building maintenance, it is necessary to highlight the possible areas of differences:

a. It is important to include the improvement of the building facility. The concept of a currently acceptable standard is necessary because of the nature of the use of buildings. The requirements that users place on a building change over time, some times quite rapidly, which means that merely keeping a building in its original state would not be an acceptable maintenance policy. Gereards (1990) argues that the introduction of new technical systems in an industrial organisation and the replacement decisions do not belong to the core of maintenance theory; such decisions actually concern investment considerations which can be handled by well established methods for replacement decisions. Eitherway, such replacement decisions are part of the maintenance problem.

b. Building maintenance has distinctive features of having longer timescales involved. Frequently, building defects do not lead to major damage or disruption for several months or even years, giving the maintenance manager a considerable time window in which to effect repairs. This time element opens up the possibility of economic in repair both by the clustering of jobs in time according to their locations, and by the careful routing of tradesmen, specially when the size of the building complex is large.

c. Defects may also have an effect on only one function of a building and not on others: for example, stonework defects might affect only the aesthetic qualities of building rather than its structural stability (Grimshaw & Poole 1990).

1.5. The objectives

The objective of the maintenance management of hospital buildings is concerned with achieving the best balance between the allocation of maintenance resources and the achievement of the hospital aims of delivering better health care and service to patients. Audit Commission (1986) stated that wages are a significant component representing about 70% of the building maintenance costs, the remaining 30% cover the transportation, materials and/or spare parts cost. Therefore the key to secure maximum value for the investment in maintenance is through managing the workforce productively.

This research has been carried out as a PhD project with the objective of assessing the scope for and effectiveness of quantitative modelling. In particular, we are interested in the prediction of the outcome of alternative management actions (policies), in the management of maintenance of building complexes of the size of a hospital. Both building and engineering equipment are encompassed with the study as appropriate. The set of maintenance management policies selected for specific study at Withington hospital are:

(1) Previewing a defect before repair, by collecting one job at a time, to identify the required resources. (This procedure is standard policy, which is recommended by the South Manchester District Health Authority).

(2) Not previewing policy; depending on the experienced supervisor's knowledge in identifying the required spares and resources of most of the defects (jobs);

(3) Issuing a batch of jobs instead of one job at a time.

(4) Delaying non-urgent jobs and grouping them in time.

(5) No sickness model: Sickness is a serious cause of lost days. To assess the impact of this, we consider a no-sickness model.

(6) Employing extra part-time tradesmen during busy days (Mondays and Tuesdays).

(7) Working 7 days instead of 5 days a week.

(8) Employing multi-skilled tradesmen.

These models should be capable of indicating to management the gains and consequences, in terms of measures of interest to them such as, the manhours and the minimum workforce necessary to meet the daily demand for maintenance, of changing operating practice, customs and timescales. That is, their decision variables.

The following chapter, Chapter two reviews the Operational Research contributions to maintenance and replacement. Chapter three concentrates on the maintenance demand study which based on general statistics obtained to identify and quantify the major problem areas in terms of cost and frequency of maintenance activities.

Chapter four studies Data/information systems and the possibility of reducing the demand for maintenance through identifying the cause of the demand and to propose actions to reduce the demand for maintenance.

Chapter five concentrates on the input data of the hospital maintenance management models, through fitting appropriate distributions and estimating their parameters.

Chapter six explains the hospital maintenance management simulation models and their structures.

Chapter seven concentrates on the analysis and interpretation of simulation output data.

Chapter eight gives the summary, conclusions and the recommendation for future work.

The Appendix in the end of this thesis includes a number of tables showing some statistics measures of the simulation output data, discussed in chapter 7.

Chapter 2

LITERATURE REVIEW

2.1. Introduction

One of the aims of the research in maintenance management, of production plant and/or buildings, is to provide decision making tools for the maintenance manager. Operational Research techniques are among the tools which can help maintenance decision making (Pintelon & Gelders 1992). They allow subjective decision to be replaced by objective decisions taking into account clearly formulated objective functions and a complex set of constraints. Operational Research techniques have long been used and appreciated in areas like production and inventory management (Pintelon & Gelders 1992). Although the need for such a decision support models is growing in the maintenance management field, as can be judged by the number of major surveys of the published literatures, reviewed by a number of authors recently, such as, Pintelon & Gelders (1992), Cho & Parlar (1991), Valdez-Flores & Feldman (1989), Thomas (1986), Jardine & Buzacott (1985), Christer (1984), and Sherif & Smith (1981). But it is felt that little of the available Operational Research techniques has been used in the industrial maintenance field (Ford & Bradbard & Ledbetter & Cox 1987). However, some Operational Research techniques are being adopted and implemented in the industrial maintenance areas as reported by several authors such as, Jardine (1970), Christer (1984b, 1987), Chilcott & Christer (1991), and Desa & Christer (1993), but comparatively few applications can be found in the area of building maintenance. Those which do exist, (Christer 1976, 1981, 1982, 1988, and 1990), are predominantly theoretical in nature with a shortage of case material.

Operational Research papers trying to optimize specific maintenance decisions are appearing more frequently. Some describe case studies which report on the application of a given Operational Research methods to a specific case. These methods provide some insight into the situation and the complexity of the maintenance decision, but they often can not be generalized (Pintelon & Gelders 1992). Despit the gap between Operational Research theory and practice, it is slowly narrowing, but still remains large in maintenance management, (Dekker 1989). Pintelon & Gelders (1992) advanced several reasons for this problem; (1) There is a lack of awareness of available quantitative techniques due to the mostly exclusive technical training of maintenance managers; (2) The time pressure most maintenance managers have to face does not leave much time for additional training in Operational Research techniques and their applications; (3) The stochastic character of maintenance activities are additional complication to the maintenance management problems; (4) Lack of appropriate data for maintenance modelling.

There are a growing number of maintenance management information systems, MMIS, introduced to record maintenance historic data. The MMIS could help in promoting the use of quantitative techniques for modelling purposes, if they exist and are properly used. An attempt has been made in the maintenance management area, Alzubaidi (1987), and Kobbacy (1988), to integrate maintenance management information system with quantitative models and thus create a system capable of recognising data patterns per equipment and choosing an appropriate general model for that pattern of data in order to introduce automatic preventive maintenance schedules on the basis of historic data. However, the process of validating the historic data, fitting and validating the chosen model is an important issue to avoid the model from misrepresenting the real system, (Baker & Christer 1993).

The purpose of this chapter is to introduce the main features of the contributions that Operational Research has made to date in the general area of industrial equipment maintenance and replacement which is thought to be equally applicable, in principle, to the maintenance of buildings and their contents such as a hospital complex, a factory complex, or housing estates.
It is convenient to refer to topics classified by Christer (1984), according to the following sections titles: (1) Management problems; (2) Overhauls; (3) Inspection procedures; (4) Preventive maintenance; (5) Capital equipment replacement; and (6) Stochastic maintenance and replacement.

After describing briefly the typical nature of each problem type, the underlying theory or model will be presented in its simplest form and the nature and variety of these models discussed.

2.2. Management problems

There are a number of areas which exist within the maintenance function where Operational Research can make immediate contribution along well proven lines (Christer 1984). These areas related to decision problems of, inventory control, depot location and routing problems, determining the workforce size and in the scheduling of both men and materials. Most of these problems are generally referenced within any standard Operational Research text book. Therefore, only the general aspects of the maintenance management problems are indicated in this chapter.

2.2.1 Stock control

Most maintenance models discussed in the literature assume the availability of infinite stock of spare parts and materials. However, in some real life situations, the availability of spare parts is an important factor in determining an optimal policy for the whole system (Cho & Parlar 1991). Maintenance and repair of industrial plants and/or buildings require many different spare parts and consumable goods, where the maintenance management has to guarantee their availability. It includes the management of special tools, materials requests, material deliveries, supply requests, price and lead time inquiries, and order and materials recipts (Pintelon & Gelders 1992). These inventory problems concern high-volume low-cost items with near deterministic lead time such as, nuts, bolts, washers, and grease, to the high cost sporadic items with considerable outage cost and variable lead time (Christer 1984). However in maintenance, the majority of items show slow to very slow demand, and their price is usually high, leading to high investment (Geraerds 1991). In order to optimize investment in spare parts, it is important to choose the right reorder policy. Numerous models for these decisions can be found in literature (Pintelon & Gelders 1992). Spare parts are classified according to their rotation (fast, normal, and slow moving items), or may be classified according to their repairability or criticality (Howard 1984). The problem of finding the right trade off between stocking, that is how many parts do we need in stock, and stock out for slow moving items is a difficult but encountered problem in spare parts inventory management (Gelder & Groeneweghe 1985). In a recent paper, Sani (1993) examined verious periodic policies, of problems arising in the control of low demand items such as, vehicle spare parts and other machine spare parts, from the classical system to the various heuristic policies, reported in the literature. The performances of the studied systems are compared, and attempts have been made to determine which is better, in terms of a number of performance measures, and under what conditions. The aim, of the ongoing research, is to modify the exisiting policies or develop new methods that suit the problems arising in the control of low demand items.

2.2.2. Manpower and scheduling problems

Scheduling problems in which manpower and materials are organised to meet the demands for maintenance action are amongst the most common applications of Operational Research within industrial maintenance (Christer 1984). A number of decision concerning the maintenance workforce scheduling within an organisation can be taken into account. Typical aspects to be taken into consideration are centerisation versus decenterisation, technological trade groups versus groups specialised in specific plants units or technical systems,

and mono-skilled versus multi-skilled tradesmen (Geraerds 1991). Accepting the need to schedule, the task is one of identifying the schedule which satisfies the constraints of a problem in most cost-effective way (Christer 1984).
As the level of sophistication of equipment technology advances and the impact of breakdowns increases, the need for highly trained maintenance technicians grows, where maintenance workers will need more diagnostic skills to cope with complex equipment, and have to rely on information systems which provide technical and historical data (Pintelon & Gelders 1992).

As far as manpower problems are concerned, problems of manpower or gang size arise in numerous forms. In structure, they often resemble the standard queueing situation in a store where interest is in the performance of various numbers of cash-out locations, assuming both stochastic arrivals and service time. It is not surprising, therefore, that simulation is a frequent tool here (Christer 1984). A number of case studies published recently concerning the manpower and scheduling problems of industrial plants. Duffuaa & Raouf (1992) developed a simulation model to determine the optimum number of maintenance crew, where the model is applied to a soft drink plant. The downtime of the plant has been estimated using the simulation model, and the optimal level of maintenance crew is chosen to maximise the output of the production process. Poulsen (1984) developed a simulation model to determine the optimum number of maintenance men in a fully loaded machine shop. The optimum number of maintenance men corresponds to the minimum of the total cost, made up of the machine downtime cost and the wages of maintenance men. Basker & Husband (1982) consider the multi-skill question within a single service branch of a large engineering manufacturer. A simulation model was developed and used to present the results of experimenting with five combinations of skill mix options out of the three skills involved, and comparing the outcome of the considered options. Mann & Bostock (1982) discussed how a number of variables might influence maintenance manpower requirements and a procedure for forecasting those requirements have been presented. Christer (1981) proposed an alternative form of schedule modelling to the existing reactive mode for attending to building maintenance repairs over a large geographic area. The outcome of this model is compared with the current practice.

2.3. The overhaul problem

Jardine & Buzacott (1985) define the overhaul as

> "*a maintenance action taken to improve the condition of an item before the item has failed*".

Thus it is a form of preventive maintenance but, in general, it does not return the item to the 'as new' condition which a replacement does (Jardine & Buzacott 1985).

Some types of equipment are characterised by a decrease in operating efficiency with time, where the efficiency may be totally or partially restored by an overhaul (Christer 1984). Typical examples are the industrial boilers whose burning efficiency deteriorates as fuel jets become corroded with combustion deposits, and as a result more fuel is needed to produce the same unit output of steam. The overhaul problem is also applicable to some high speed production machinary which requires fine tuning, since as time advances vibrations within the plant slowly cause a slackening of the settings. This in turn increases the probability of a product being produced outwith the customer's tolerance specification which is essentially increasing the expected proportion of scrap (Christer 1984). Therefore, from time to time, major adjustments or surveys need to be performed. Between these surveys the operating cost of the equipment increases due to the deterioration of certain parts of the equipment. Some of these deteriorating parts can be overhauled, thus reducing the operating cost of the equipment. A balance is required between the money spent on overhauling, such as materials and wages, and the saving obtained by reducing the operating cost. We wish to determine an optimum overhaul policy which minimises the sum of operating cost and the overhaul cost between surveys.

2.3.1. Basic overhaul model

In any practical sitation, data collection and analysis is required both to identify the problem and specify the initial set of assumptions of a model. However, here we will be content to review the assumptions and the basic model presented by Christer (1984). The assumptions made in the analysis of the overhaul model, which contain considerable engineering input and interpretation, are as follows:

(1) An overhaul returns the equipment to a post-survey condition;

(2) The cost per unit time of operating the plant t time units after an overhaul is $g(t)$, a known function;

(3) The cost of an overhaul, C_O, is constant and the time required, d, is negligible;

(4) The policy is to perform n equally spaced overhauls at intervals of s time units between surveys;

(5) The equipment operates between surveys every T time units;

(6) The objective is to select n to minimise the operating cost over the survey period.

Under these assumptions, the situation is as depicted in figure 2.1

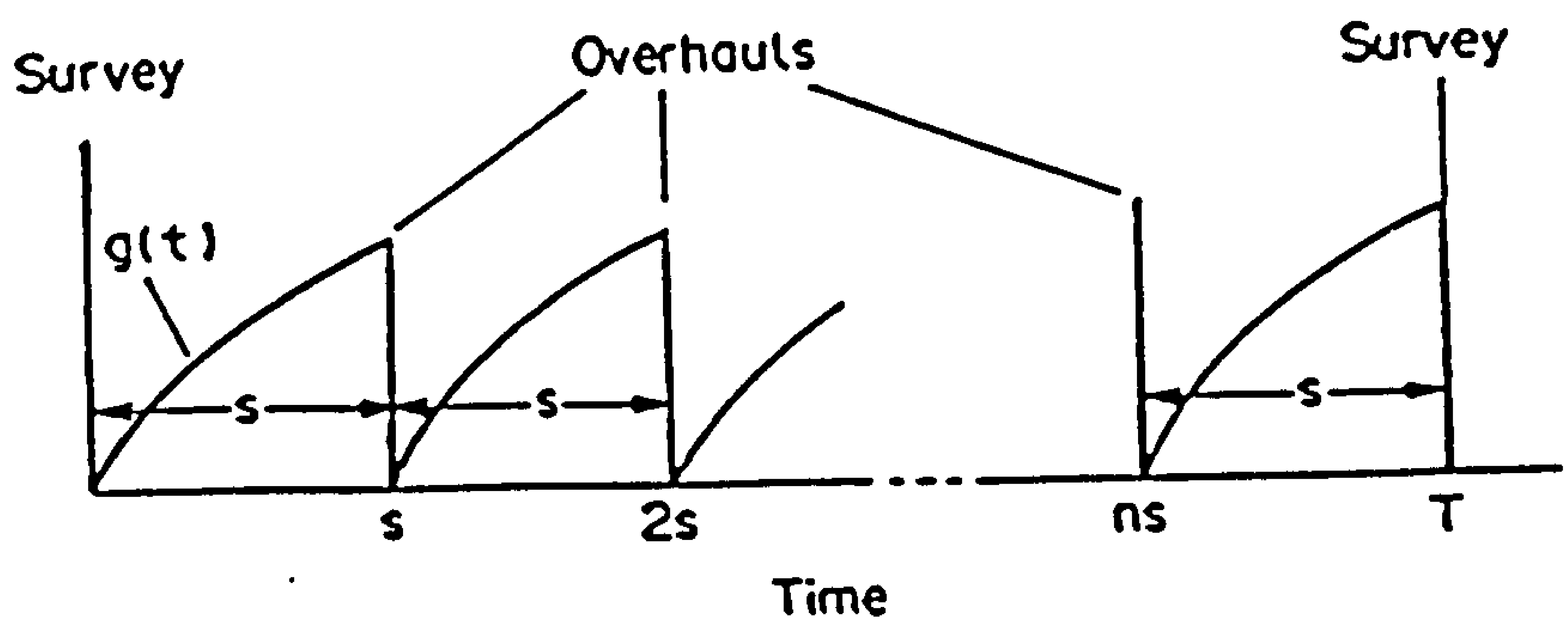


Figure 2.1: Shows the assumption of an overhaul situation

Clearly, since the overhaul period stretchs across the survey period, we have

$$s(n+1) = T \quad . \tag{2.1}$$

The total cost between surveys, $C(n)$, is given by

$C(n)$ = (total operating cost) + (total overhaul cost)

= $(n+1)$(operating cost over s) + (n)(overhaul cost)

$$= (n+1) \int_0^s g(t)dt + n\, C_o \quad . \tag{2.2}$$

Using equation (2.1) to eliminate s from (2.2) we have for $C(n)$,

$$C(n) = (n+1) \int_0^{T/(n+1)} g(t)dt + n\, C_o \quad , \tag{2.3}$$

which is the model of the process. The choice of n is made to minimise $C(n)$ and is usually best achieved by a numeric search over n, selecting a starting value based upon the n of current practice, or perhaps management's intuition as to a likely optimal region. Christer (1984) presented numerical example to illustrate how to solve an overhaul problem using this model.

It is noted that most text books reffering to this problem suggest eliminating n between equations (2.1) and (2.2) to obtain an overhaul model in terms of the operating period s, namely

$$C(s) = \frac{T}{s} \int_0^s g(t)dt + \frac{(T-s)}{s} C_o \quad , \qquad (2.4)$$

where s*, the solution, is given by $dC(s)/ds=0$.

Christer (1984) argues that what is required from model (2.3) is actually the practical choice of s which agrees with the time scale of the organisation, be it shifts, days, or seasons. Christer (1984) advanced two reasons in faviour of using equation (2.3) and not equation (2.4). These are: first, equation (2.4) is likely to prove a much more complex task to solve than the integer search of $C(n)$. Second, the probability of obtaining an answer to (2.4) which is consistent with the assumption of the model is zero, that is, having an integer value to n. It must be noted that s is not a free variable but constrained to be of the form T, $T/2$, $T/3$, .., and consequently differentiation is not a valid process (Christer 1984).

In most situations $g(t)$ will not be known in analytic form, but will be required to be determined from a discrete set of data points obtained perhaps from one unit observed over several cycles, or several units observed over one cycle (or both).

2.3.2. Variations in the basic overhaul model

There are some variations on the basic overhaul model considered by Christer (1984). The basic model assumes, assumption (1), that the overhaul returns the plant to a post-survey condition. If the assumption of totally effective overhauls cannot be sustained, because of insufficient data, or because the analysis suggestes otherwise, the model needs to be adjusted. It is necessary, therefore, to model the cost curves subsequent to an overhaul. Two case studies have been reported, the first case study, by Davidson (1970), is to solve the overhaul problem for an industrial boiler, in which the overhaul produced a partial improvement; and the second, by Hastings & Thomas (1970), is to determine an imperfect overhaul policy for fork lift trucks over their life. If the non-perfect overhaul complication arises in practice and cannot be engineered out, a dynamic programming formulation of the problem is likely to be the most convenient, (Hastings 1973).

The basic model assumes, assumption (3), that the cost of an overhaul, C_O, to be constant. This assumption is neither necessary nor, in many applications, very plausible (Christer 1984). A more realistic formulation, discussed by Christer (1984), would be to have the overhaul cost as a function of the time since last overhaul that is, $C_O = C_O(s)$. For instance, overhauling a boiler last overhauled a week ago usually entail less effort that had it been untouched for a year. The only change this make to the basic model (2.3), is in the last term, when $C(n)$ is now given by

$$C(n) = (n+1) \int_0^{T/(n+1)} g(t)dt + nC_O\left(\frac{T}{n+1}\right) \quad . \qquad (2.5)$$

The second part of assumption (3) of the basic model, assumes that the downtime, d, is negligible. Although it is known that an overhaul will require time, d, it is often appropriate to take d as zero in an overhaul model since it is ideally undertaken at down-periods such as evenings and weekends. For continuous production process, the downtime period d may need to be taken into account explicitly. The policy of ignoring d, in the case of $d<<s^*$, is not fully justifiable at the outset since s^* is unknown until the model is formulated and solved (Christer 1984). The simplest option here is to formulate d within the model. Therefore, if we assume that $d=d(s)$, then the only change to the basic model (2.3) is through the time-spanning condition (2.1) which now becomes

$$(n+1)s + nd(s) = T \qquad (2.6)$$

which may be solved to provide $s = s(n)$. Therefore, $C(n)$ is as follows:

$$C(n) = (n+1) \int_0^{s(n)} g(t)dt + n\, C_o(s(n)) \quad . \qquad (2.7)$$

Two other variations to the basic model have been thoroughly discussed by Christer (1984). These are: First, the assumption of n equally spaced overhauls is replaced by non equi-spaced overhauls. It is expected that in most cases, the assumption of equi-distributed overhauls is appropriate unless particularly large sums or risks are involved. Second, relaxing the assumption (5), by considering what happens when no fixed and known time zone T exists within which to overhaul. If there is no known or anticipated survey time T, the survey period become effectively infinite and model (2.3) is invalid. In this case, the decision variable is the operating periods between overhauls which is chosen to provide the minimum operating cost per unit time.

2.4. Inspection procedures

One of the most common methods employed to manage building maintenance is to wait until a defect is reported to the maintenance orgnisation by the building user (Christer 1982). This is called a contingency system and it is directly analogous to a breakdown system for industrial plant. Some aspects of maintenance such as external painting (Christer 1976) and programmes for property improvement of housing estates are performed on planned cycles, but the majority of the workload is characteristically of a responsive contingency type (Christer 1982).
Inspection decisions in maintenance tend to be centred around determining the optimal interval between checks on equipment and interpreting the results obtained from the checks, Jardine & Buzacott (1985).

A notion called delay-time analysis, arose as a side issue in modelling building maintenance, Christer (1982), and developed, by Christer & Waller (1984a), for modelling the consequences of an inspection policy for industrial inspection maintenance. The delay-time technique considers a piece of equipment subject to defects which can be identified by an inspection, perhaps periodically. Inspection procedures could be manual, some form of condition monitoring or a mixture of both. The principle of an inspection policy is that it does not prevent faults arising within the equipment, but it does identify faults before failure and, therefore, the subsequent repair cost is likely to be less. As a consequence of an inspection policy a large proportion of building maintenance work is identified and clustered at a specific point in time (Christer 1982). The maintenance organisation has, therefore, the opportunity to allocate its resources appropriately and so can rectify the defects in a more efficient manner than would other wise be the case.

2.4.1. Delay time modelling

A central concept in the delay-time modelling is the delay time, *h*, of a defect, which is the time lapse from when a defect could first be noticed until the time when its repair can be delayed no longer because of unacceptable consequences. A repair may, therefore, be undertaken any time within this period. It has been proven possible to obtain a subjective estimate of the probability density function *f(h)*, Desa & Christer (1993), Christer (1982, 1984), of the delay time *h*. This has in turn enabled the construction of models of the expected relationship between the inspection period, *T*, and the consequence variables such as, the expected downtime per unit time, or the expected operating cost per unit time. At a repair be it due to breakdown or a fault identified at an inspection, the following questions may be asked:

(1) How long ago could the fault have first been noticed at an inspection or by an operator *(=HLA)*;

(2) If the repair was not carried out, how much longer could it be delayed *(=HML)*.

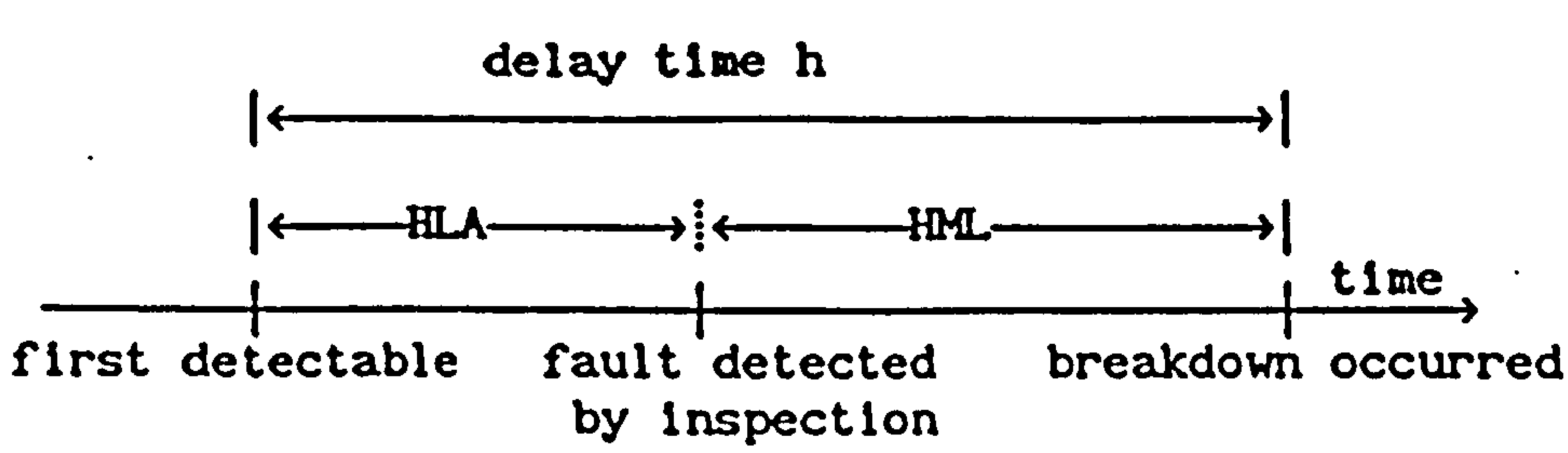


Figure 2.2: Shows how to estimate the delay time.

The delay time for each fault is estimated by

$$h = HLA + HML.$$

By observing sufficient defects, a prior distribution for h, $f(h)$, may be obtained. Here, it is assumed that defects are independent. The aim of the delay time analysis is to determine $b(T)$, the probability of a defect arising as a breakdown repair. As the inspection period T increases, then the probability $b(T)$ increases as well, and vise versa. Once $b(T)$ is available, the function may then be used to estimate the cost or downtime consequences of different inspection procedures.

2.4.2. Basic delay time model

It is possible to construct a maintenance inspection model if the delay time distribution is established. In this basic model of an inspection policy the following assumptions are made (Christer & Waller 1984a);

(1) An inspection takes place every 'T' time units, cost 'I' units, and requires 'd' time units to be carried out where $d<<T$.

(2) Inspections are perfect in that any defect present will be identified at inspection time.

(3) Defects identified at an inspection will be repaired within the inspection period.

(4) The time of origin of a fault, i.e. the instant at which a defect may be assumed to first arise, is uniformaly distributed over the time since the last inspection and is independent of h, the delay time.

(5) Faults arise at a rate of 'k' per unit time, on average.

(6) The probability density function of delay time, $f(h)$, is known.

The assumption '$d<<T$' in (1), and assumption (3), that defects identified at an inspection will be repaired within the inspection period, may for the first

time seem to be contradictory, but assumption (3) would seem to be reasonable if adequate maintenance staff were available to perform repairs simultaneously. Assuming $d<<T$ implies that the downtime due to breakdown may be ignored, since the error introduced by this simplification will be kept small when calculating the expected number of failures over a period of time T. Variation on assumptions (2) of perfect inspection, and (4) of uniform time of origin are discussed later.

First, it is necessary to determine the form of the probability function of a defect arising as a breakdown repair, $b(T)$.

Any defect with a delay time $h>T$ will never arise as a contengency repair, but assuming inspections are perfect, defects are always identified at an inspection. Therefore, those defects with delay time '$h<T$' are only considered. Suppose a defect arising within the period $(0,T)$ has a delay time in the interval $(h,h+dh)$. The probability that the delay time lies in this interval is $f(h)dh$. This defect is repaired as a breakdown repair if the defect arises in the period $(0,T-h)$, see figure 2.3, otherwise the defect is considered as an inspection repair.

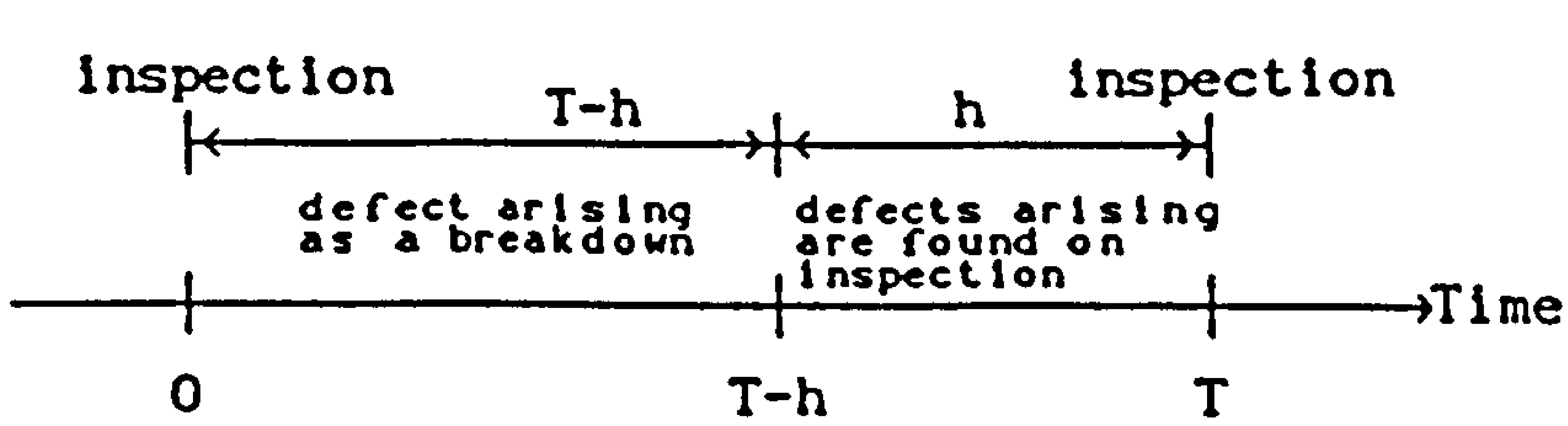


Figure 2.3: Shows breakdown, and inspection repairs using delay time inspection policy.

The probability of a defect arising before $(T-h)$, given that a defect will arise is $(T-h)/T$. Therefore the probability that a defect with delay time in the interval $(h,h+dh)$ is repaired as a breakdown is

$$\frac{(T-h)}{T} f(h)dh \quad .$$

Allowing h to vary from 0 to T and integrating over h, then the probability, $b(T)$, of a defect arising as a breakdown is given by

$$b(T) = \int_0^T \left(\frac{T-h}{T}\right) f(h)dh \quad . \qquad (2.8)$$

In equation (2.8), if inspection period T tends to 0, $b(T)$ converges to 0, which corresponds to no breakdowns. At the other extreme, when inspection period T tends to infinity, i.e. no inspection is performed, $b(T)$ coverges to 1, which corresponds to the probability of all defects will be arisen as breakdown maintenance. From assumptions (5) and (6), and considering negligiable downtime due to breakdown, the number of defects arising during the period $(0,T)$ is 'kT'. If the period of downtime can not be assumed very small, or subsequently proves not to be acceptably small, it is relatively simple to modify the basic model to allow for the downtime, Chilcott & Christer (1991).

Defining $N(t)$ as the expected number of contingency repairs arising between inspections, it follows that

$$N(T) = k \int_{h=0}^{T} (T-h) f(h)dh \ ,$$

the proportion of defects identified at an inspection, before causing a breakdown is

$$\frac{Tk-N(T)}{Tk} = \left[1 - \frac{1}{T} \int_0^T (T-h)f(h)dh \right] \quad . \qquad (2.9)$$

Equations 2.8–2.9 refer to a steady state of regular inspections at interval T. Clearly, when switching for the first time from a contengency repairs system to an inspection repair sytem a 'surge' of repairs would be identified at the first inspection. An estimate of the number of repairs at this inspection is (Christer 1982)

$$\int_0^\infty k.h.f(h)dh = k\bar{h}$$

where h is the mean value of the delay time.

To determine $D(T)$, denotes the expected downtime per unit time inspecting on period T, we note that the expected downtime between the end of one inspection and the end of the next is

$$kT \; d_b \; b(T) + d \quad ,$$

where d_b denotes the expected downtime per breakdown repair. Since this is measured over a complete period of length $T+d$, the downtime per unit time measure, $D(T)$, becomes

$$D(T) = \frac{1}{(T + d)} \left\{ kT \; d_b \; b(T) + d \right\} \quad . \qquad (2.10)$$

This model assumes that all defects identified at an inspection are repaired within d. The cost function is determined in a similar way. Let c_b be the average cost of repairing a breakdown, and c_i the average cost of repairing a fault found at inspection. The expected cost of the repair of a defect is therefore,

$$c_b\, b(T) + c_i(1 - b(T)),$$

and the expected cost per unit time is given by

$$C(T) = \frac{1}{(T + d)} \left[kT(c_b\, b(T) + c_i(1-b(T))) + I\right] . \qquad (2.11)$$

Equations (2.8) to (2.11) constitute the basic inspection model. This basic model may be modified according to need, (Christer & Waller 1984a).

2.4.3. Some variations on the basic delay time model

Two variations of the basic model assumptions are presented in this section. Suppose that there are insufficient staff available to complete all repairs at an inspection (assumption 3), or that inspections are not perfect. Here we investigates the changes to the basic model that such considerations will make. For instance, if assumption (3) above was invalid and there were only enough maintenance staff to identify defects during the inspection period d, and further time is required to perform inspection repairs following the inspection, with each inspection repair causing additional downtime. The formulation of $D(T)$ would be modified as follows:

If d_i is the expected downtime due to an inspection repair, then assuming repairs are performed sequentially, the total expected downtime at an inspection is

$$d + kTd_i\{1-b(T)\} \quad . \tag{2.12}$$

Therefore the downtime per unit time over an inspection cycle is

$$D(T) = \frac{1}{T+d+kTd_i[1-b(T)]}\left[kTd_b\ b(T) + d + kTd_i(1-b(T))\right]$$

$$= \frac{1}{T+d+kTd_i[1-b(T)]}\left[kT\left\{d_b b(T)+d_i(1-b(T))\right\} + d\ \right] . \tag{2.13}$$

Note that d_i must be less than d_b for the inspection to be worthwhile.

2.4.4. The case of non-perfect inspection

It is unrealistic to expect a perfect inspection every time. It is more likely, in many cases, that the probability of a fault being detected at an inspection is dependent to some extent on the value of I, the expenditure on the inspection. Such dependence would need further investigation/experimentation in a particular context. However, here we will be content to review the simpler model used by Christer and Waller (1984a).

Let there be a fixed probability that a specific defect will be identified at an inspection, which is independent of how long the defect has been present. Let the value of this probability be β, and the corresponding probability be $(1-\beta)$ that the defect will not be detected. The effect of this assumption will be to change the form of $b(T)$ (2.8) with consequence changes to $D(T)$ and $C(T)$ (2.10 and 2.11 respectively).

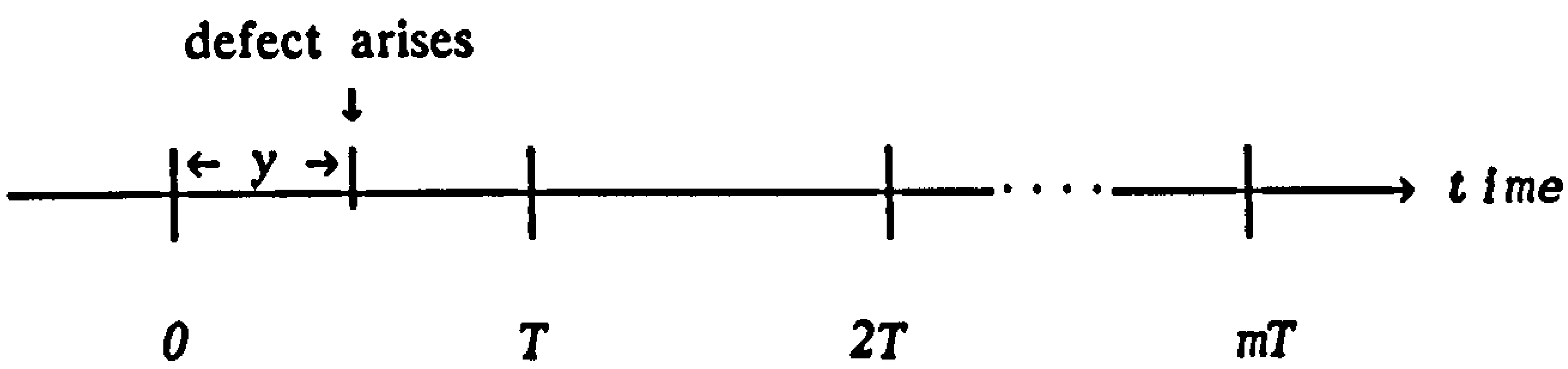


Figure 2.4: Shows the case of non-perfect inspection.

Consider a defect arising at time y after an inspection at time zero, as shown in figure (2.4). Depending on the delay time of the fault and β, it is possible to calculate the probability of this defect being identified at an inspection. It could be the inspection at T *if* $h>(T-y)$, or at $2T$ *if* $h>(2T-y)$, or failing this, at the inspection at $3T$ *if* $h>(3T-y)$, and so on. We have, therefore the defect arising at point y,

Prob(defect identified at T)

$$= \text{Prob(defect does not result in a breakdown before } T) \times \text{Prob(being identified at } T)$$

$$= \text{Prob}(h>T-y) \times \beta$$

$$= \beta \int_{T-y}^{\infty} f(h)dh$$

$$= \beta R(T-y) \qquad \text{where } R(x) = \int_{x}^{\infty} f(h)dh$$

Similarly,

Prob(defect identified at $2T$)

$=$ Prob(defect does not result in breakdown before $2T$)x Prob(being missing at time T and being identified at $2T$)

$=$ Prob$(h>2T-y)$x$(1-\beta)$xβ

$=$ $\beta(1-\beta)\ R(2T-y)$

In general, the probability that a defect initiated at point y will be identified at the inspection nT is

$$\beta(1-\beta)^{n-1}\ R(nT-y),\ n=1,2,\ \ldots$$

Adding all these probabilities we obtain the probability that a defect will be identified at an inspection as

$$\sum_{n=1}^{\infty}\ \frac{\beta}{T}\ (1-\beta)^{n-1}\ R(nT-y),$$

where it is assumed the defect arises at time y. Since y can vary uniformly between 0 and T, integrating over y therefore, we have the probability that a defect arises as a breakdown $b(T)$,

$$b(T)\ =\ 1-\Big[\ \int_0^T \sum_{n=1}^{\infty}\Big\{\frac{\beta}{T}\ (1-\beta)^{n-1}\ R(nT-y)dy\Big\}\Big]\ . \qquad (2.14)$$

In equation 2.14, for β=0 or 1, $b(T)$ corresponding to the failure probability for the conventional failure system or the basic inspection model with perfect inspection.

2.4.5. Non uniform distribution of time of origin

The effect of altering assumption (4) in the basic inspection model, when a perfect inspction was assumed, is to modify the formula for $b(T)$, so producing consequent changes in the expressions for $D(T)$ and $C(T)$. Here, it can be assumed that the instantaneous rate of fault occurrence at time y after an inspection is not uniform but is given by $g(y)$. Assumption (5) will now have to be modified as follows: The expected number of faults in the small interval $(y,y+dy)$ is $g(y)dy$ and, therefore, the expected number of faults arising in the interval $(0,T)$ is

$$K(T) = \int_0^T g(y)dy \quad . \qquad (2.15)$$

Assume perfect inspections. The expected number of faults arising in the interval $(y,y+dy)$ and resulting in a subsequent breakdown, which must have a delay time of less than $T-y$, is

$g(y)dy$ x (the proportion of these faults with $h<T-y$)

$$=g(y)dy \int_0^{T-y} f(h)dh = F(T-y)\ g(y)dy$$

where $\quad F(x)= \int_0^x f(h)dh \quad .$

Therefore, the expected number of breakdowns during the time period 0 to T is

$$B(T) = \int_0^T F(T-y)g(y)dy \quad . \tag{2.16}$$

The proportion of faults occuring as breakdown is $b(T)=B(T)/K(T)$. Further, assuming the downtime caused by breakdown and inspection repairs is small, the downtime per unit time is given by

$$D(T) = \frac{1}{T+d} \left[d_b \ B(T) + d \right] \tag{2.17}$$

since the number of repairs arising in $(0,T)$ which are performed at an inspection is $K(T)-B(T)$, the cost model in its simplest form is, assuming inspection repairs are performed at cost during the inspection period d,

$$C(T) = \frac{1}{T+d} \left[c_b \ B(T)+[K(T)-B(T)] \ c_i+I \right] \quad . \tag{2.18}$$

Christer & Waller (1984a) give numerical examples for comparison of the results for these three models in terms of the expected proportion of defects arising as breakdowns and the expected downtime. As far as the expected proportion of defects arising as breakdowns is concerned, the model for non–perfect inspections shows, as would be expected, a higher percentage of breakdowns than the basic model. Also, the model for non–uniform distribution of initial point shows a lower percentage of breakdowns than the basic model. This result is because the assumed distribution has lower fault frequency earlier in the cycle. Again, the expected downtime figures show that the models with the lowest and highest occurrences of breakdowns have the lowest and highest downtime respectively, which again is an expected result.

2.4.6. Updating prior Delay-time models and distributions

The prior delay-time models and distributions have been updated in later papers by Christer & Redmond (1990, 1992). The prior model assumes that delay-time distribution could be found using techniques of subjective estimation. If the subjective estimates indicate a bias or error, that is, the fraction of defects ending in failure would not agree with the observed value for maintenance policy actually in use, it is necessary, therefore, to consider a possible revision of both the prior delay-time distibution and the subsequent delay-time model.

Suppose the decision variable is the inspection period T, and the probability of a defect arising as a breakdown conditional upon T *is* $b(T)$.

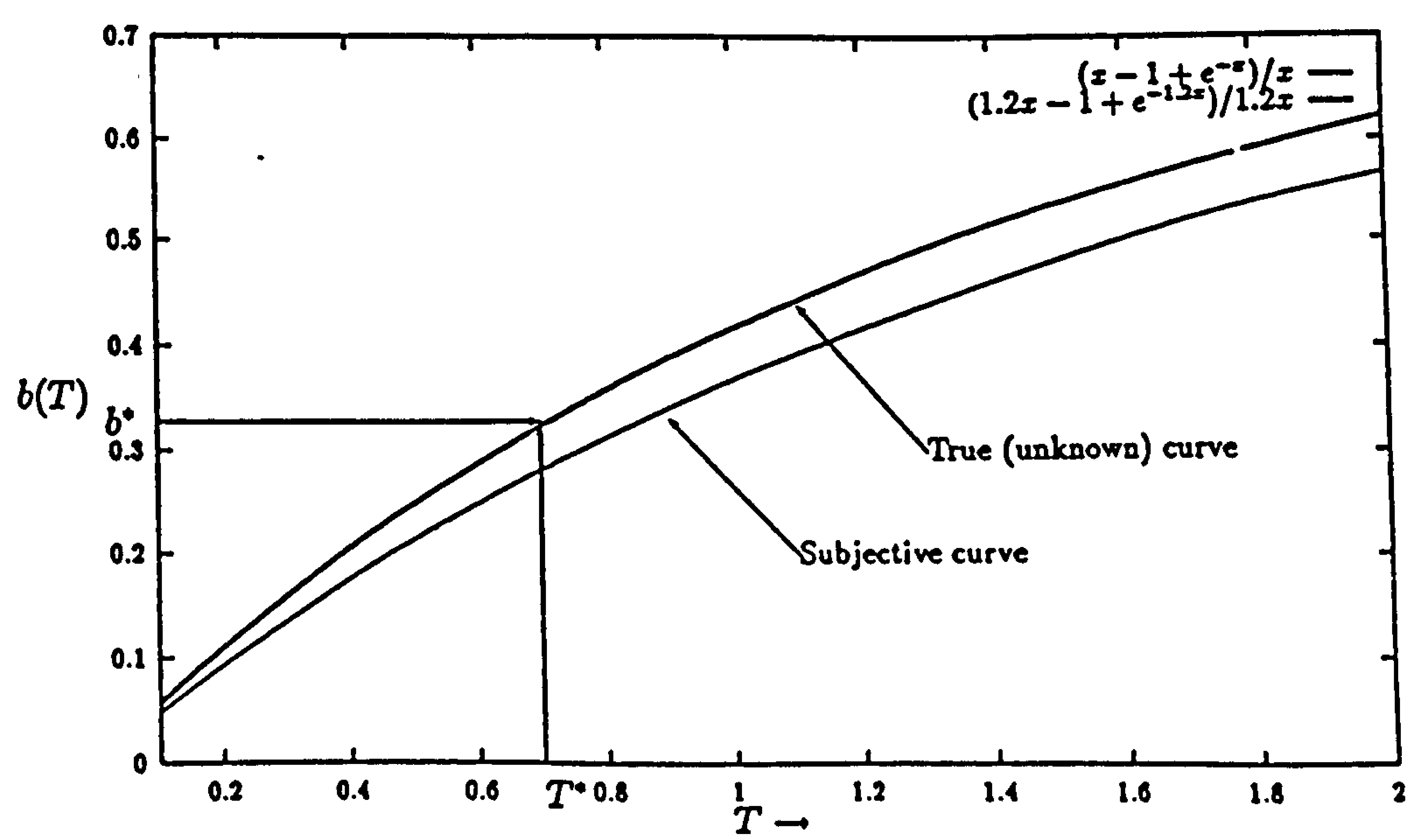


Figure 2.5: shows the subjective and a revised estimates of $b(T)$, (after Baker & Christer 1993).

The curve in figure 2.5, illustrate the prior estimate of $b(T)$ which has been obtained based upon a prior probability density function of delay-time $f(h)$. This curve should pass through the observed point b^* corresponding to the current practice period T^*. The problem is to revise $f(h)$, perhaps $g(y)$ and may be the assumption of perfect inspection measured by β, so that the subjectively derived curve $b(T)$ passes through the status quo point (T^*,b^*) (Baker & Christer 1993).

The simplest method proposed for such revision was a scaling of the subjective estimates of h. It was pointed out (Christer & Redmond 1990) that estimates of h derived from subjective estimates of HLA at failure tended to be biased downwards, as smaller delay-times are more likely to cause a failure before being picked up at the next inspection. Similarly, estimates of h from $HLA+HML$ at inspection tend to overestimate h. The pooled distribution from failures and inspections is unbiased. Theoretical distributions for observational bias in h were developed by Christer & Redmond (1990), and techniques for removing the bias proposed. Christer & Redmond (1992) considered scaling and other methods of revising subjective estimates in the context of a reanalysis of older case studies. A problem has arisen recently (Desa & Christer 1993), in connection with a bus fleet that required the use of the updated delay-time model. Initial estimates based on carefully collected data have previously proved to be close enough to the status quo point not to require revision of the prior distributions or model (Baker & Christer 1993).

In their latest review paper, Baker & Christer (1993) review the development in the delay-time analysis as a means of modelling engineering aspects of maintenance, refering to the current state of knowledge and research in this area such as, updating delay-time models and distributions, condition monitoring using delay-time modelling, its relationship with other models of preventive maintenance and its analogy with medical screening, extentions to the basic model, and parameter estimation and model validation.

2.5. Stochastic maintenance and replacement

Stochastic maintenance and replacement studies tend to relate to relatively minor components of non-repairable or maintainable equipment, or equipment which is not repaired *in situ*, which is subject to chance failure, Christer (1984). Although minor in terms of relative cost, such items as electric motors or switching valves can be key components within major plants in terms of failure consequences. In considering models that have been proposed and used, we first consider stochastic replacement processes where equipment subject to failure is replaced upon failure, or before failure on preventive replacement basis. There are two principal replacement processes here, *a block replacement process and an age-based replacement process.* Before examining the two replacement policies for items subject to sudden failure, it is necessary to first mention two conditions that must be met before preventive replacement is likely to be worthwhile (Jardine & Buzacott 1985). They are: (1) The total cost associated with a failure replacement must be greater than the total cost associated with a preventive replacement; (2) The hazard rate, $r(t)$, of the equipment must be increasing; where the hazard rate is

$$r(t)= f(t)/R(t)$$

$f(t)$ is defined as the probability density function of the time to failure of an equipment, and $R(t)$ is the reliability function of the equipment, defined as

$$R(t) = \int_t^\infty f(t)dt .$$

The block replacement policy has a preventive replacement carried out at fixed intervals of time T, $2T$, $3T$,.. and also upon failure. It is possible that a components replaced upon failure just before a block replacement epoch will be replaced again at the epoch. This could arise with the light bulb block replacement policy in a large shop or factory. This policy contrasts with the age-based process where failure replacements take place as before, but preventive replacements occur only when component attains age t_p. Clearly an itemised data recording system is necessary in both policies, specially in the later one if it is to operate and does, therefore, restrict application of the policy. Whereas the data recording helps the former policy to avoid some of the apparently less efficient aspects of a block replacement policy, it has an associated cost.

2.5.1. Block replacement, basic model

Block replacement policies are usually associated with large groups of relatively minor items (Christer 1984). It may be preferable for a variety of reasons such as, ease of implementation or economic of scale, to replace an item at constant intervals of length T, with failure replacement occuring when necessary. The model for this policy if the objective is total cost minimization is:

$$C(T) = \frac{Cp + C_f \; H(T)}{T}, \tag{2.19}$$

where, $H(T)$ is the expected number of failures in the interval $(0,T)$. This function is the solution of the renewal integral equation

$$H(T) = F(T) + \int_0^t H(t-u)\, du \ ,$$

where

$F(T)$: is the density function of failure time;

C_p : is the total cost associated with a preventive replacement;

C_f : is the total cost associated with a failure replacement;

$C(T)$: is the total cost per unit time associated with a policy of making replacement at intervals of length T, irrespective of the age of this item.

It is possible, in practical situations, that the block replacement problem, represented by equation (2.19) can be investigated without the need for mathematical calculation or even knowledge of $f(t)$, Christer (1984).

2.5.2. Age-based replacement

Age-based replacement is similar to that of block replacement except that instead of making preventive replacements at fixed intervals, thus incurring the possibility of performing a preventive replacement shortly after a failure replacement, the time at which the preventive replacement occurs depends on the age of the equipment. Therefore, operating an age-based replacement implies a component is replaced upon failure and upon attaining age t_p . Usually cost measures C_p, C_f are associated with preventive and failure replacement. The problem is to balance the cost of the preventive replacement against their benefits and we do this by determining the optimum preventive replacement age for the equipment to minimise the total expected cost of maintaining the equipment per unit time (Jardine 1973).

Over a period of time, say T, the total cost of operating with replacement age t_p, $C(T)$, is a random variable, therefore, on any specific occasion the cost experienced per unit time is $C(T)/T$. An appropriate objective function here would be $Ex\{C(T)/T\}$, Christer (1984). A typical curve $C(T)$ which depends, of course, on the decision variable t_p, is shown in figure 2.6, which depicts a set of discontinuing arcs with decreasing discontinuity and converging gradient (Christer 1984).

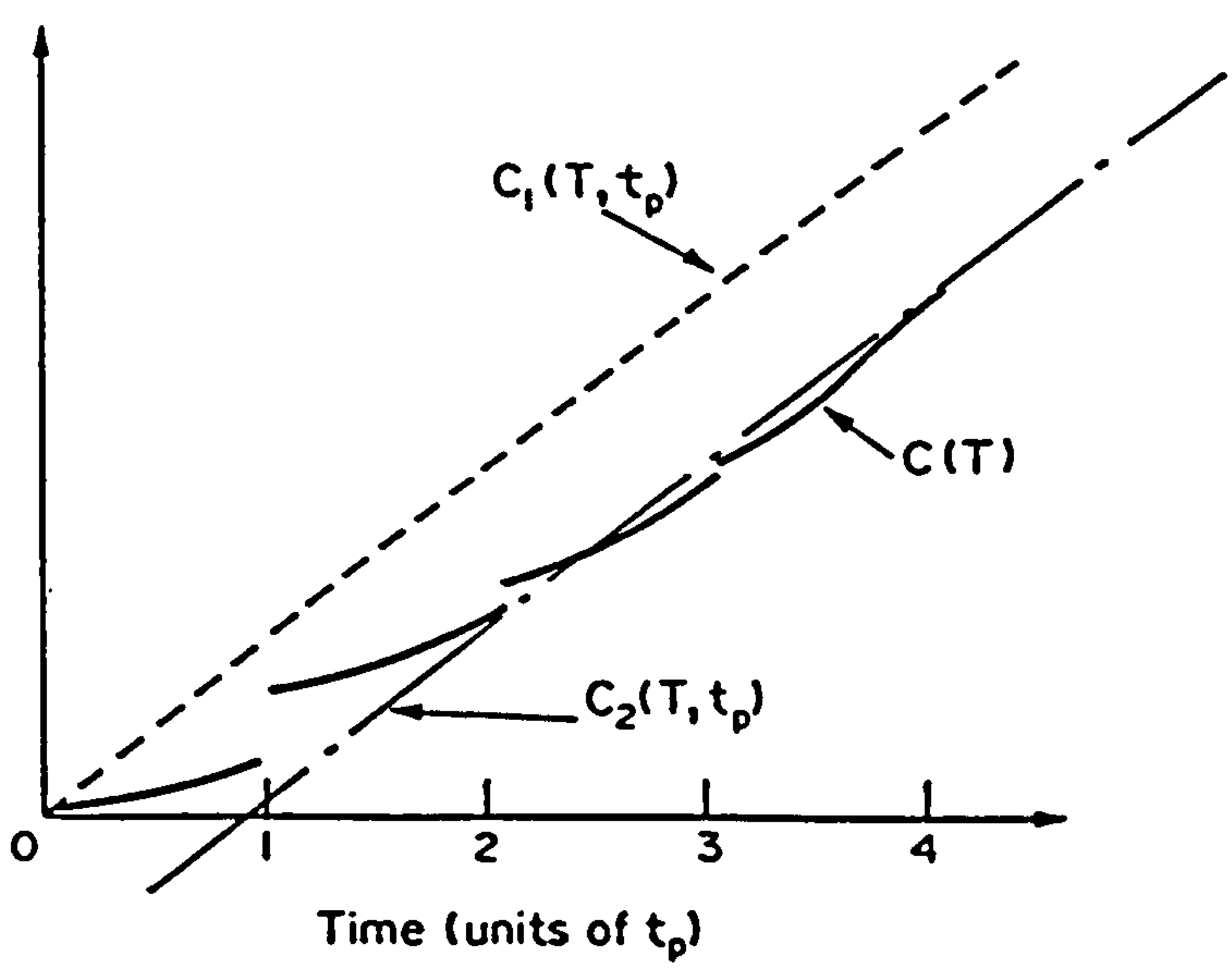


Figure 2.6: Shows the operating cost, asymptotic and alternative approximation of the operating cost, for the age-based replacement problem.

Although $Ex\{C(T)/T\}$ is a complex quantity, the long term time average is relatively simple, namely, (Ross 1970).

$$\lim_{T\to\infty} \left\{ \frac{C(T)}{T} \right\} = \frac{Ex(\text{cost per cycle})}{Ex(\text{cycle length})} \quad . \tag{2.20}$$

Defining $R(T)$ as the reliability function

$$\int_t^\infty f(t)dt \quad ,$$

the model relating preventive replacement age to the long term total cost per unit time is

$$C(t_p) = \frac{C_p\, R(t_p) + C_f\, (1-R(t_p))}{t_p\, R(t_p) + M(t_p)(1-R(t_p))} \quad , \tag{2.21}$$

where $C(t_p)$ is the total cost/unit time if preventive replacement are made only when the item has been in use for a period of length t_p and $M(t_p)$ is the mean time to failure of the item given that preventive replacements are made once the item is of age t_p.

$$M(t_p) = \frac{\int_0^{t_p} tf(t)dt}{1 - R(t_p)}$$

Therefore the objective is to find the optimal value of t_p, the replacement age, such that the total cost per unit time $C(t_p)$, in equation (2.21), is minimized.

One practical problem here is that costs do change, and even the perceived need for the process has a finite time limit. If this limit is, in some sense, relatively short or if costs are changing rapidly, either a dynamic formulation of the problem might be contemplated or, alternatively, the criterion function could be modified (Christer 1984). This has been achieved through considering for the moment the asymptotic total expected cost formulation $C_1(T,t_p)$, (Christer 1984),

$$C_1(T,t_p) = \xi(t_p).T$$

represented by equation (2.20) where ξ is the objective function ratio. This estimation of the cumulative cost is represented by the dotted line in figure 2.6 and is, of course, parallel to the limiting asymptotic form of $C(T)$. Christer (1978) extended the expansion of $C_1(T,t_p)$ to two terms, i.e.

$$C_2(T,t_p) = \xi(t_p)T + \zeta(t_p) \ ,$$

which provides an altervative approximation to $C(T)$, see figure 2.6, which coincides with the asymptotic part of $C(T)$ exactly. For practically all the range of T, excluding the origin, $C_2(T,t_p)$ gives more accurate measure of the cost than $C_1(T,t_p)$, as would be expected.

2.6. Replacement of capital equipment

Replacement decision of equipments are usually viewed from a life cycle costing viewpoint where a balance is required amongst the three costs of, (Jardine & Buzacott 1985): (1) operation and maintenance, (2) ownership, and (3) fixed. Many reasons may be advanced for considering replacement, Christer (1984), of such equipment and could include the following:

(i) Performance of current plant declining; output or operating costs increasing;

(ii) High plant performance required, response to an increased demand for quality or quantity of product;

(iii) To offset chance of decreasing performance; safety equipment and perhaps fleet cars;

(iv) Obsolescence; computer hardware, computer software, medical equipment, defence systems.

Jardine (1973) & Christer (1984) gave details of models of replacement of capital equipment. In this review section, we will concentrate on reviewing the latest paper by Christer & Scarf (1993) concerning 'a robust replacement model with application to medical equipment'. Christer & Scarf (1993) model is attempting to resolve some of the concerns highlighted by Christer & Waller (1987) by attempting to identify and address the actual issues of a replacement decision. The model takes into account subjective considerations which, while difficult to quantify, nevertheless influence replacement decision making.

The prototype model presented by Christer & Scarf (1993) is a general model, developed in the context of medical equipment. Some reasons have been advanced for this choice (Christer & Scarf (1993). First, the replacement of medical equipment is a particularly complex problem to model since it embraces on occasions emotive and behavioural considerations along with value judgements. Secondly, equipment within a hospital group is often of high-tech and rapidly developing nature representing a multi-million pound investment, with the annual maintenance cost being of the order of 10% of replacement value. The prime aim of Christer & Scarf's model is to aid replacement decision-making by identifying a 'good' replacement decision and the consequences of alternative decisions.

There are some features characterising the replacement decision problem for medical equipment (Christer & Scarf 1993), these are:

(1) The existing item being considered for replacement is not new but N, say, years old. The decision is therefore whether or not to replace it now, in one year, .., or in K years, or only when forced by technical obsolescence. Technical obsolescence is reached when spare parts are no longer available or when it is unacceptable to use the equipment.

(2) Equipment is unlikely to be replaced with like equipment. It is possible that the replacement decision is being driven by technical obsolescence, or by changing medical requirements, or by technological developments. In all these cases, the like with like option is not even a candidate.

(3) The replacement age of equipment should be related to its usage. Christer & Scarf (1993) argue that, if there are two items of equipment, one used once a week and the other twice a day, a straight age-based replacement decision based upon average costs may not be appropriate. Also, new equipment may have a higher usage by choice or by design. In this case, although the observed cost per unit of usage could be less than that of the existing item. Since the study is concerned with equipment usage the objective is to seek to optimise the total cost per unit of usage.

(4) The influence on patient care of equipment's proper operation must be considered. Failure of, or a lack of availability of, medical equipment is possibly associated with consequences to patient care, requiring perhaps different treatment, or greater medical resources, or worse. Therefore the patient care consequences, here called penalty, need to be considered.

(5) The puchase of new equipment subsequent to a replacement decision does not imply equipment is replaced. Equipment is often not a unique item

but one of a pool of equipment. In this case, there is evidence that old equipment may not be scrapped, but be retained in use. Indeed, in some cases old equipment appears to be subject to a major overhaul before rejoining the pool of equipment or retiring as 'spare'. The real implication here is that what are sometimes viewed as replacement decisions are really purchase decisions.

Christer & Scarf (1993) discussed the usage and the penalty concepts in order to clarify the proposed format of the prototype replacement model. The usage is the measure of time that equipment is actually being used to serve patients. Operating cost, failure rates and equipment downtime are expected to depend upon the level of equipment usage. Usage of equipment will in turn depend upon the demand for equipment.

The penalty concept appears to be readily recognised and accepted, but difficult to quantify. Its existence can be influential in replacement decision processes, though not in an objective quantitative fashion. To what extent a patient suffers through being treated by one type of machine rather than another, or through having the treatment delayed, is not easily quantified for a particular case, and is even more complex in general. Although penalty may not be known, Christer & Scarf (1993) have modelled it as a cost parameter p, and the sensitivity of a decision to this parameter has been explored for a particular equipment.

2.6.1. The prototype replacement model

The criterion function, of Christer & Scarf's prototype replacement model, is to minimise the total expected discounted cost per unit of usage over (K,L), and this is done with respect to K *and* L. Only K is considered as a decision parameter which would influence action. The L cycle and the replacement at the end of the L cycle are introduced to influence the optimal K by the ongoing need to retain an operating equipment. The terms used in the model are defined as follows:

$c(i)$	equipment expected operating cost in its i^{th} year of operation;
$m(i)$	expected maintenance cost per year for equipment in its i^{th} year;
$C(i)$	total expected maintenance and operating cost per year for equipment in its i^{th} year of operation, $(m(i) + c(i))$;
$u(i)$	usage of an equipment in year i relative to usage in year 1;
$p(i)$	penalty measure for equipment in its i^{th} year;
$S(i)$	scrap value or resale value of equipment i years old;
'o', 'n'	suffix 'o' denotes old equipment; suffix 'n' denotes new equipment;
R	purchase cost of equipment. R_n is the purchase cost of the new item;
r	discount factor;
K	remaining life of existing plant, expressed in months or years;
L	economic life of new replacement plant measured in years;
N	age of existing plant in years;
$C(N;K,L)$	total expected discounted cost incurred over time $K+L$ for equipment currently N years old.

All costs are based upon current day values. That is $m_o(3)$ and $m_n(1)$ represent the maintenance cost today of operating an item of old equipment aged 2 years for one year, and a new item of replacement equipment for one year. The total cost of operating and maintaining new replacement equipment for one year in, say, 4 years time will, of course, be larger than $C_n(1)$ because of inflation. This being so, an underestimate of the discounted maintenance costs actually incurred for a new item of plant in its i^{th} year of operation is given by

$$C_n(i)\ r^{i-\frac{1}{2}} \qquad (2.22)$$

Here, the costs have been modelled as being incurred mid year. If inflation was constant at $q\%$, the actual discounted sum necessary to meet the total maintenance and operation cost in its i^{th} year of operation is

$$C_n(i)\ \left[\ r\ \left[1 + \frac{q}{100}\ \right]\ \right]^{i-\frac{1}{2}}$$

If the discount factor $r = \left[\frac{1}{1+(j/100)}\right]$,

when j is the internal rate of return (or an equivalent measure), the total discounted cost allowing for inflation and discounting becomes once again

$$C_n(i)r^{i-\frac{1}{2}}$$

where now $r = (100+q)/(100+j)$. This means that in the subsequent model, any given value of the discount factor r does, in fact, correspond to a multitude of different inflation and discounting senarios.

It can be noticed that the above parameters have been written as functions of year of operation i, which is appropriate if C, m, p, *and* S could all be functions of usage, either the usage in the year i or the cumulative usage to date.

The replacement decision situation being modelled, is shown in figure 2.7, where the time unit is taken as a year. The existing equipment is N years old and will be operated for further K years before being replaced. The new equipment is assumed to be of a different type, which will be replaced with like plant after L years.

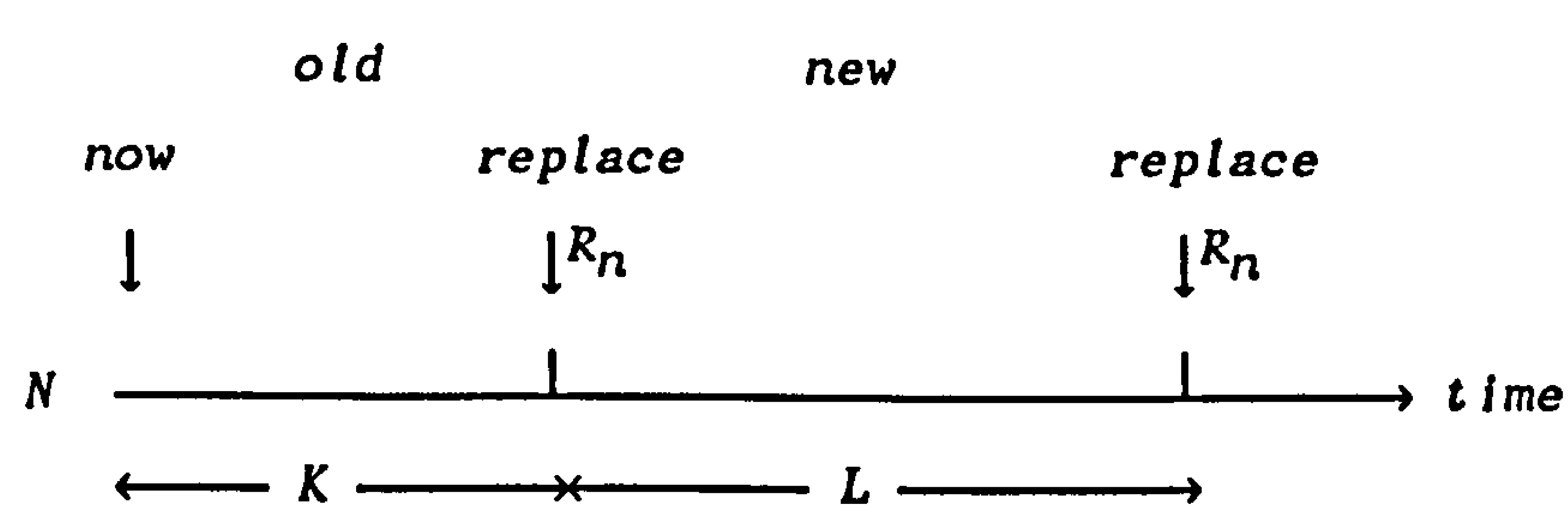


Figure 2.7: Shows the replacement decision situation being modelled where the time unit is taken as a year.

Measuring i in years and restricting K *and* L to integer numbers of years, the total discounted cost incurred by replacing the existing equipment of age N after K years and again after a further L years is denoted by $C(N;K,L)$. We note that

$$C(N;K,L) = \left[\sum_{i=1}^{K} (C_o(N+i) + p_o(N+i))\, r^{\,i-\frac{1}{2}} + \right.$$

$$\left. r^K \left\{ R_n - S_o(N+K) + \sum_{i=1}^{L} (C_n(i)+p(i))r^{i-\frac{1}{2}} + (R_n - S_n(L))r^L \right\} \right] \quad . \qquad (2.23)$$

If the usage is assumed constant, i.e. $u(i)=1$, the objective function becomes

$$\left\{ \frac{C(N;K,L)}{K+L} \right\} , \qquad (2.24)$$

and the objective is to find K and L which minimise this function.

Figure 2.8 displays the significant of this criterion measure. The servovent ventilatores at Liverpool Royal Hospital was used as an example for demonstration, see figure 2.8.

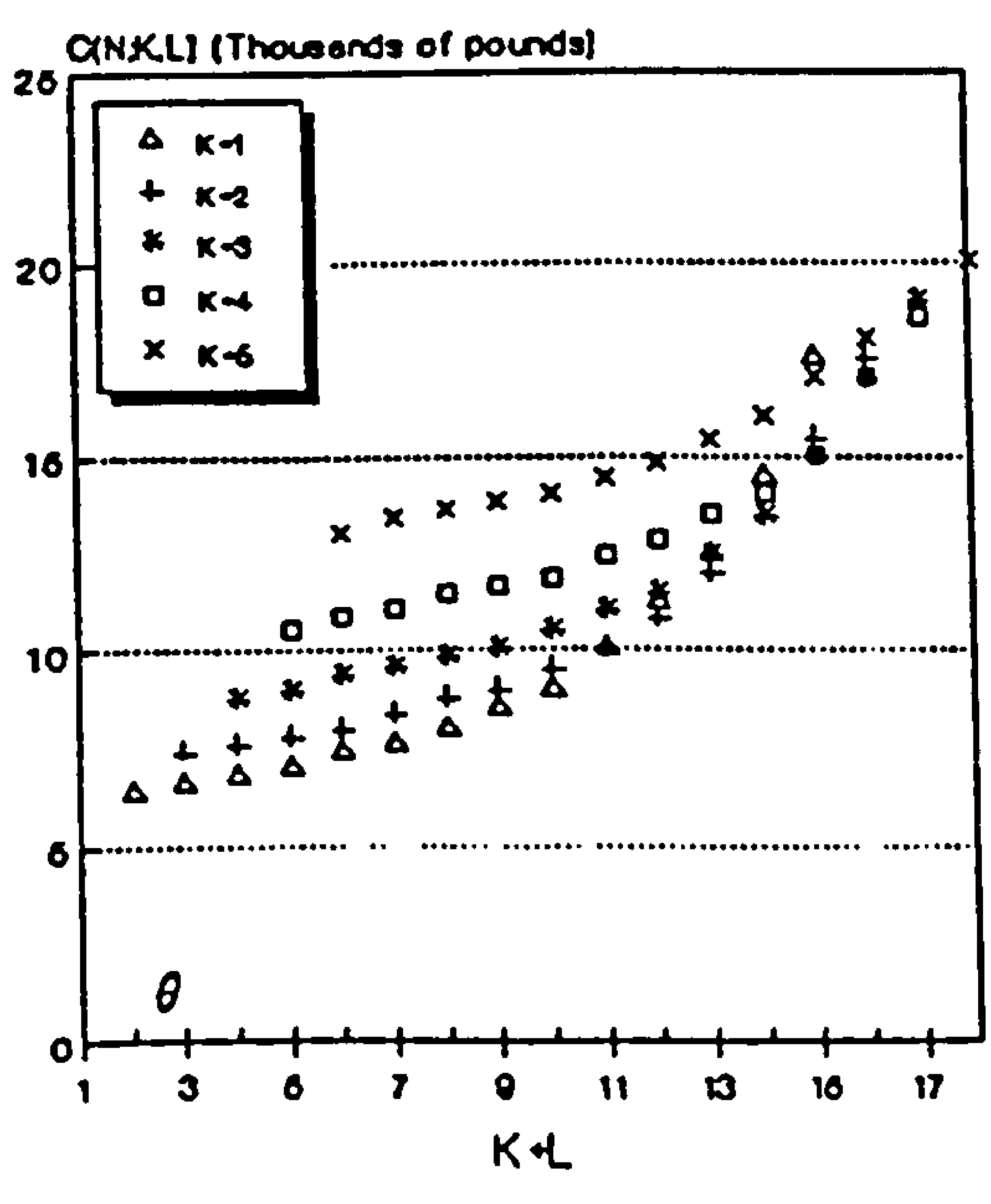


Figure 2.8: Total discounted cost against the length of replacement cycle $K+L$ for machine currently aged 8 years.

for machine currently aged 8 years.

For any value of *(K+L)* when *K and L* are integers, there is a set of values of *(K and L)* each of which is expected to produce a different value of *C(N;K,L)*. The column of points in figure 2.8 represents these values. The tangent of the angle between the origin and any point representing a *{K,L}* pair and the horizontal axis has the value of the objective function (2.24) for the *{K,L}* pair.

Optimising function (2.24) with respect to *K and L* is equivalent to picking from the set of possible *{K,L}* pairs that which makes the minimum tangent angle θ. When it cannot be assumed that $u(i)=1$, the criterion becomes

$$\left[\frac{C(N;K,L)}{\sum_{i=1}^{K} u_o(N+i) + \sum_{i=1}^{L} u_n(i)}\right] \qquad (2.25)$$

The significance of criterion (2.25) can still be deduced from figure 2.8, though with a change of interpretation. On the time axis, *K+L* now changes to total usage over *(K+L)* whilst the discounted cost axis remains as before. Each point now represents for a specific *(K,L)* pair the resulting discounted cost and total usage level. The criterion selects one *{K,L}* pair from the set by again selecting the minimum tangent option.

So far, both these formulations have assumed the old item is scrapped. Should it be retained and fully used for the remaining *L* years, the problem becomes a purchasing option and the above objective function would be modified to

$$\left[\frac{C(N;K,L)\left[\sum_{i=1}^{L}\left(C_o(N+K+i) + p_o(N+K+i)r^{i-\frac{1}{2}} + S_o(N+K)\right)\right] r^K}{\sum_{i=1}^{K+L} u_o(N+i) + \sum_{i=1}^{L} u_n(i)}\right] .$$

The actual behaviour of these objective functions are demonstrated in an example about the serovent ventilators at Liverpool Royal Hospital. It reveals that they behave as one would expect. As penalty measures increase, K *and* L values decrease; as equipment cost R_n increases, the remaining life K increases; and as maintenance costs m_n increases in relation to m_o, K increases.

2.6.2. Cost of delayed optimal replacement

For reasons of budgeting constraints, recommended replacement after a period K may not be possible. In such cases, an indication is required of the extra cost to be incurred in revenue expenditure because of lack of capital expenditure, that is the marginal extra cost of delayed action.

If using criterion function (2.24) the optimal replacement strategy for an N years old piece of equipment was (K^*,L^*), the resulting total discounted cost is $C(N;K^*,L^*)$. Assuming for convenience that usage is measured by time with $u(i)=1$, K^* *and* L^* are given by

$$\min_{K,L} \left\{\frac{C(N;K,L)}{K+L}\right\} .$$

If the first replacement was delayed one year from K^* to K^*+1, discounted cost for the extra year beyond the optimal strategy is given by

$$[C(N;K^*+1,L^*) - C(N;K^*,L^*)].$$

Since the averaged discounted cost for a year under the optimal strategy is

$$\frac{C(N;K^*,L^*)}{K^*+L^*},$$

a measure of the marginal discounted cost of delaying the replacement decision by one year is given by

$$\left\{ [C(N;K^*+1,L^*) - C(N;K^*,L^*)] - \frac{C(N;K^*,L^*)}{K^*+L^*} \right\} . \qquad (2.27)$$

If only one of the choice of replacement options was possible, other things being equal, the choice could presumably be based upon minimising the above measure of additional cost. If the replacement purchases were delayed a further period k years beyond the optimal K^*, a measure of the additional discounted cost would be the increased discounted cost over the additional period k, less k times the unit discounted cost under the optimal policy, that is

$$\left\{ [C(N;K^*+k,L^*) - C(N;K^*,L^*)] - \frac{kC(N;K^*,L^*)}{(K^*+L^*)} \right\} . \qquad (2.28)$$

It is suggested by Christer & Scarf (1993), that such marginal considerations could be of assistance when having to deside a portfolio of replacement decisions across equipments from a constrained budget.

2.7. Preventive maintenance

Technical systems, be it a production system of goods and delivering services or be it a building, are subject to deterioration with usage and age. System deterioration is often reflected in higher production costs and lower product quality. To keep the production cost down while maintaining good quality, preventive maintenance is often performed on systems subject to deterioration. The growing importance of maintenance has generated an increasing interest in the development and implementation of preventive maintenance models for deteriorating systems, (Valdez-Flores & Feldman (1989).

In most organisation planned maintenance (PM) consist of regular routine servicing and adjustment with the objective of both reducing the number of faults arising and their consequences when they do arise. At any PM intervention the action to take is prescribed by an itemised schedule for the plant concerned which can contain well over 100 service and check points, (Christer 1984). Also, different schedule on different cycles can operate concurrently on plant. Although planned maintenance is important if it is used properly, it has its pitfalls. Parkes (1970) stated that

> *"there was a belief that planned maintenance will eliminate all accidents, ensure a hundred percent availability of all plant and guarantee undisturbed nights for maintenance staff. Indeed some organisations have spent a great deal of effort on this sort of complete scheduling exercise only to discover that it can be a*

Christer (1984) argues that, suppose a PM schedule is carried out every 4 months, *(T=4)*, with the objective of reducing the total operating costs. Clearly, the total unit time cost *C(T)*, where *C(T)* includes costs of downtime. PM and breakdowns, will be dependent upon *T*, whether the PM is influential or not. Conceptually the curve for *C(T)* could be one of the two forms indicated in figure 2.9. This being so, if *C(T)* corresponds to curve PRQ, the ideal PM period is given by *T**. Should the current practice correspond to T_1, P is the only known point of this curve. Alternatively, if no PM activity takes place, the asymptotic point Q representing $T=\infty$ is known. When PM is totally ineffective, the curve *C(T)* takes the shape SQ with the optimum being at Q, that is don't PM. Knowing only one point of the curve *C(T)*, it will not be obvious which of the two curve types may apply. To model a PM process is to model this curve, or its equivalent, for a stipulated schedule of PM tests.

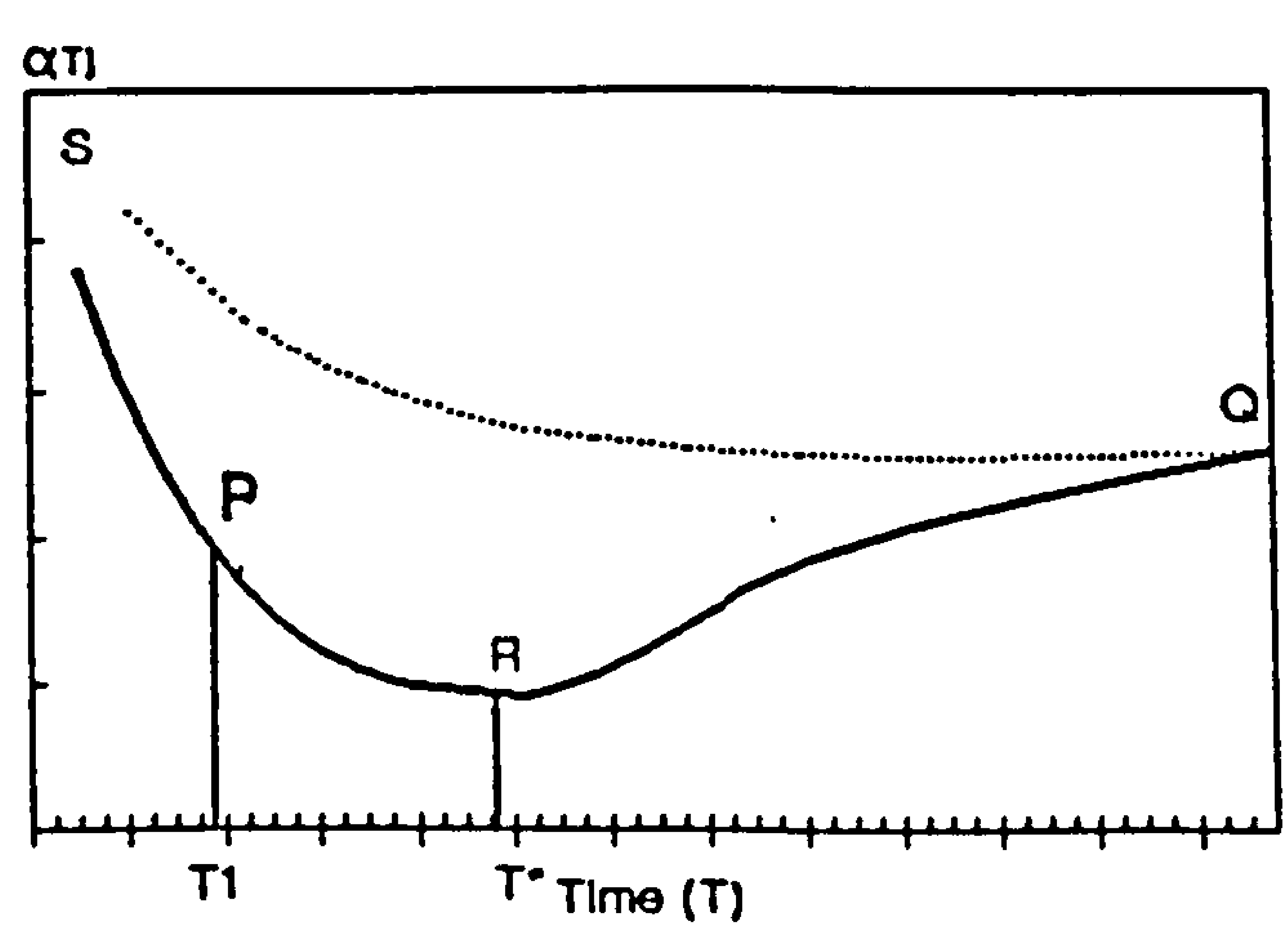


Figure 2.9: Periods of planned maintenance.

Planned maintenance models are available in the literature. Typical are the models of Handlarski (1980), and Kay (1976). Handlarski argues that, in most PM studies, improvement was sought through maximising of availability and minimising of cost. This, in his opinion, inevitably resuts in suboptimization. To avoid suboptimization, Handlarski (1980) developed a model to maximize the average profit per unit of total time taking into account the revenue gained per unit time of operation, the cost of breakdown and maintenance repair as well as the downtime. Maximisation of profit function leads to optimal scheduling of PM. Handlarski has distinguished between two types of maintenance, type I policy, which is a maintenance repair is done when the operating time of the equipment since last planned or corrective maintenance reaches the maintenance interval L, i.e. age-based maintenance. Type II policy whereby maintenance is done at fixed interval and upon failure, i.e block type maintenance. Handlarski developed mathematical models assuming the corrective and planned maintenance return the equipment to 'good as new' condition, and also for the case where PM repair is superior in quality to corrective repair. The efficiency of age and block maintenance policies are compared which show that the profit yield of type I policy is never worse that that of type II policy.

Kay (1976) has adopted the same idea relating the net earning per unit time to the availability and cost function. Maximiztion of the net earning leads to optimal scheduling of PM. Kay assumed that Planned and corrective maintenance, return the equipment to 'as new' state, and have the same life to failure distribution.

One interesting attempt to capture the interaction between a PM and plant performance is due to Watson (1970), who considers the maintenance policy for a sinter plant of British Steel Corporation, which were concerned about rising cost of maintenance, coupled with falling trend in availability. Watson used the availability as a criterion and developed a model relating the downtime of a unit to PM intervals. The repair was performed in a block type maintenance, that is at fixed interval of time. The analysis revealed that the time of failure after a PM was longer than that after a breakdown repair for the same unit. for different components, the ratio of these means was called the 'improvement factor *(I)*' for the component, which is defined as

$$I = \frac{\text{(expected life following PM repair)}}{\text{(Expected life following corrective repair)}} .$$

The improvement factor should be greater than unity to justify the planned maintenance. This was incorrect because it takes no account of sampling bias. He further suggested that a unit which contains many components can be divided into sets, where all components in each set have the same improvement factor I. Assuming a negative exponential distribution of time to failure for components after a PM, knowing the I factor the time to failure distribution subsequent to repair could be estimated, so enabling plant availability to be formulated as a function of PM frequency.

Accepting this, Christer (1984) argues that, in modelling such problem, it seems that the difference in life expectation after a PM and a repair of the same component (which is the basis of the model) needs further investigation and should not be too readily attributed to beneficial aspects of PM. For example, Baker & Christer (1993) reported that in the hospital study, it was discovered that infusion pumps were often examined by engineers in response to what later transpired to be user-error. There were many such false alarms. However, at each such incident, some maintenance activity was carried out.

To neglect this activity, they argue, when deriving an optimum policy would have led to the recommendation of an unduly short PM or inspection interval.

Chapter 3

MAINTENANCE DEMAND STUDY

3.1. Introduction

A prime aim of building maintenance is to preserve a building in its initial effective state, as far as practicable, so that it efficiently serves its purpose. The increase in sophistication and complexity of medical services within the health service is reflected in the sophistication and complexity of buildings, their finishes, fittings, contents and services. Not only do the buildings and their contents comprise increasingly complex technical systems with interrelating parts or elements, but there are now considerable financial, legal and organisational constraints affecting maintenance activities which pose management and logistic problems. The task of maintaining the existing building stock and their contents is wide in scope and has to be carried out against a background of restraints and constraints. Often, buildings cannot be closed for operations even for relatively major works, and medical facilities have to be kept in good condition or restored to a functional condition as fast as possible. For instance, a defective bed in a hospital can cost up to £350 per day if it is not available. Therefore the maintenance management has to achieve its goals without disrupting staff and patients. This has led to the recognition, (Ministry of Works, Emmerson Report 1962; The Chartered Institute of Building 1990), that maintenance operations of premises require dedicated maintenance management. Emmerson Report noted the lack of people with appropriate management skills throughout the construction industry and that those who have the necessary qualifications are attracted more to new work than to maintenance. This point was emphasized in the Woodbine Parish Report (1970) in relation to maintenance supervisors in the hospital service. Of the 240 or so building supervisors employed by the service in 1969, 85 of them held no technical qualifications and only 63 had a higher National Certificate or higher qualification. It was reported by the hospital authorities that those with higher qualifications did in fact achieve better standards of maintenance and improved organisation (Lee 1987).

3.1.1. Purposes of building maintenance

Some of the main purposes of maintaining buildings in general are (Seeley 1987): (1) retaining value of investment; (2) maintaining the building in a condition in which it continues to fulfil its function; and (3) presenting a good appearance. These all apply to varying degrees to hospital buildings, but there is a particular ordering priority with hospital buildings. A number of factors which may be considered to have some degree of priority for rating in establishing an order of priority for the many and varied jobs in the health service are listed, which compete for place in the programme of work. These factors are presented below in their approximate order of priority (Bushall 1984):

(1) Safety;

(2) Essential service;

(3) Statutory requirements;

(4) Security;

(5) Initial cost;

(6) Revenue saving;

(7) Spares availability;

(8) Alternative source of supply;

(9) Delivery time;

(10) Manpower; and

(11) Public relation.

In his case study (Nicholson 1990), has asked each departmental representative in The Edith Cavell Hospital at Peterbourough to rank the priority of each item of medical equipment in terms of it's importance to health care. That is, the highest priority was given to the equipment upon which life or the efficient running of the department depended, and repairs or replacements which had to be immediately effected. At the lowest end of the scale came items which, although useful, were not essential to the function of the department and a period of up to seven days downtime could elapse without disrupting the health care. It was interesting to know that the equipment which had the highest priority was not medical, as one might expect, but a washing machine. That means the users should have greater control in setting up priorities for the facilities in their departments.

3.1.2. Categories of building maintenance work

The Local Government Operational Research Unit Report 144 (1972) had classified hospital building elements by first, concentrating on those elements that, as a result of high unit cost or extensive use, or both, account for a significant proportion of total health service expenditure; and secondly by grouping elements with similar functions, similar replacement and maintenance costs, and similar life times. The analysis of one year data in The Royal Berkshire Hospital has identified three separate categories of hospital building maintenance work: (1) Fabric maintenance; (2) Improvement and modification; and (3) Day-to-day repairs.

An efficient maintenance programme depends upon and is responsive to building condition. To draw up a long-term maintenance programme for the fabric of buildings, a maintenance manager must decide which of the various components or elements of the building, such as walls, floors, roofs, windows and doors, need detailed inspection for assessing their condition. To make decisions, concerning what to inspect, how often, and the response to an observed condition, the maintenance management must not only know the cost implications of the various alternatives but must also know the minimum acceptable condition of the element. The Local Government Operational Research Unit Report 146 (1972) study had analysed one year data for different types of floor and roof covering in The Royal Berkshire Hospital, which are, as the report concluded, not untypical of other hospital estates; For instance, although only 17% of floors are carpeted, they account for 43% of flooring cost (excluding cleaning). This is because they require relatively high maintenance and replacement expenditure. By contrast, PVC sheet which covered 35% of the total floor area, accounts for 27% of the flooring cost.

Similar analysis to roof covering had shown that 45% of roof covered by felt which accounts for 7% of total maintenance and replacement cost of roofs, whereas 26% of roof covered by slate, account for 9% of total roof cost.

Maintenance is not simply a mixture of running repairs and replacing like with like when individual components wearout. Periodically, it will be necessary to invest in refurbishment or improvement in order to maintain a property to a standard appropriate for its intended use or to bring it into line with current standard and thereby maximise its asset value.

Day-to-day repairs differ from fabric maintenance and improvement and modification jobs in that they are mostly small jobs in nature carried out in response to specific requests from the users of the buildings, usually with an urgency associated with a short time scale of the requested response. The work ranges from emergency call-out caused by, perhaps, serious electrical or plumbing problems in terms of potential cost and/or safety to building users, to a request for standard and straight forward jobs like replacing a defective light bulb. Although they are small jobs, they do cater for a significant proportion of the building maintenance time and, therefore, building maintenance budget since maintenance is labour intensive. Day-to-day repairs are important in that the users of buildings often judge the efficiency of the maintenance department by the service they receive when they make requests.

The National Economic Development Office (1985) reported that the surge of new hospital buildings in the 1960s encouraged an *emergency cover only* for the maintenance of older hospital buildings, partly to conserve scarce resources for much needed medical staff and equipment, but also because of a belief that these buildings would probably be replaced in the foreseeable future. In consequence a large backlog of maintenance work has built up, and many districts report that it is still growing (National Economic Development Office 1985). The cost of the work required to bring properties in England up to the level regarded by health authorities as the minimum acceptable standard has been estimated as of the order of £2bn (Davies 1983).

3.2. Forecasting maintenance demand

Forecasting the demand for maintenance is a key process in supplying the information which forms the basis for maintenance planning. A demand forecast, therefore, subsequently leads to the specification of what maintenance should be carried out at what instants of time during the life of the technical system in the organisation concerned. Forecasting the demand for maintenance might primarily be based on the study of the failure behaviour, the distribution of delay-time, the distribution of time to failure of the equipment to be maintained or the failure rate, which could be increasing, decreasing or constant, specially if the equipment is subject to one major failure process. If the system to be maintained consists of a large number of parts and is subject to a large number of failure processes, for instance, failure processes in hospital buildings, then we can usually assume that a large number of renewal processes are being superimposed (Ascher 1984). Drenick (1960) has shown that as the number of parts or equipments, n, in the system approaches infinity and the sampling can be considered to be asynchronous, i.e. the process starts up at time $t=-\infty$ but observation begins at time $t=0$, then the superposed process approaches an Homogeneous Poisson Process HPP as shown in figure 3.1. Superposed renewal process assumes that each of the 'n' superimposed processes was in the equilibrium (i.e. the equipment had been placed there infinitely long ago and had not been observed during $(-\infty,0)$), under the condition that $n \to \infty$, it shows that in the time of equilibrium, very complex system case, the interarrival times are independent and identically exponentially distributed (i.e. the system is modelled by an HPP). The failure arrivals rate which may depend upon the repair time and subsequently upon the downtime, may be considered as a constant.

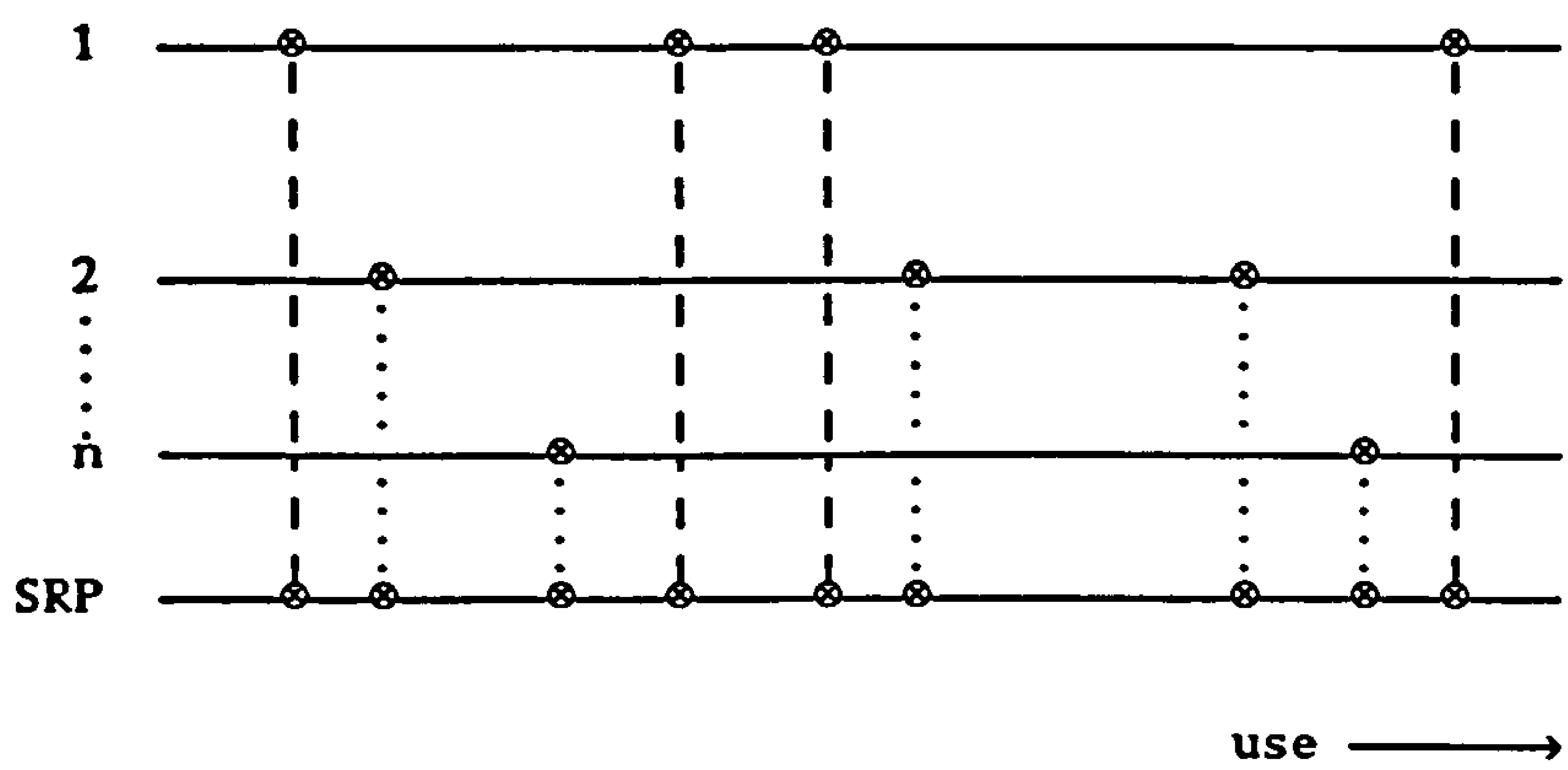


Figure 3.1: superposition of renewal processes SRP.

3.3. Data gathering

In order to evaluate the source of and nature of maintenance demand for a hospital complex, specific types of data are needed to assess the size, nature and cost of maintenance work as well as the possible relationship to the use of buildings and their contents. Key issues of concern and interest here are considered below:

1. *Size of maintenance work*:

   In order to start to evaluate the maintenance problem in terms of size and frequencies of maintenance work, the following minimal data are needed:

   (a) Date, day and time of job arrivals to the maintenance department;

   (b) Job description;

   (c) Job location; and

(d) Number of tradesmen and trades involved.

Availability of such data, for a sufficient period of time, is vital to identify the major maintenance problems in terms of frequencies and percentages of the total maintenance work during the period studied, and the possibility of predicting the demand for maintenance. To achieve this prediction, there is a need to collect reliable data for a sufficient period to identify the demand for maintenance and to predict the seasonality and the fluctuation in maintenance work during the months and/or seasons of the year, and the overall trend in maintenance work. Such analysis will be the basis of forecast of maintenance work for the coming years.

2. *Nature of maintenance work*:

In order to identify the nature of maintenance work, there is a need to collect data about the description, cause, consequences and the possible ways of prevention of a defect within a building element or the building contents. Through the identification of the cause of defect, it is possible to investigate maintenance options to reduce the occurrence of defects or to reduce or eliminate their consequences. Possibilities here are re-designing the equipment, changing users practice, considering planned maintenance, inspections and undertaking preventive replacement, perhaps periodically. Developing a maintenance practice in response to recognised maintenance problems and equipment use is very much in the spirit of maintenance concept design (Gits 1984), and snapshot modelling (Christer & Whitelaw 1983).

3. *Cost of maintenance work*:

Cost of maintenance work can be classified into long-, medium- and short-term estimates. Long-term estimates of maintenance cost may extend over a number of years and be required for a variety of purposes, including financial planning for hospital buildings. The characteristic feature of long-term maintenance estimates is that the precise nature of the individual items of work is not known and the estimate must be based on the average cost of maintenance. The medium- and short-term estimates need more accurate maintenance cost estimates based on the actual work which is undertaken, i.e. there is a need to estimate the marginal cost for specific defect. The accuracy of the maintenance cost estimates depend upon the amount of information available on; the nature and extent of the work; the conditions under which the work will be executed and the mode of execution; the cost of employing labour; and, the material cost (Lee 1987).

Small jobs can be broken down directly into their labour and material costs. These are usually single-trade jobs which consist of a straight forward uninterrupted work sequence. Larger jobs can be broken down into a series of separate tasks representing discrete parts of the whole. The tasks usually incur both labour and materials and may refer to a single trade operation or multi-trade operation. Defects in building elements or facilities can cause specific penalties either because the equipment is not available when it is needed, or because of the inconvenience to patients or staff. Such cost is very subjective. To what extent a patient suffers through having the treatment delayed, is not easily quantified for a particular case, and is even more complex in general (Centre for Operational Research And Applied Statistics 1990). Data required to evaluate cost of maintenance which can be readily available are the time spent in doing a job and the spares and materials needed. These usually consist of the following component costs:

(I) The labour time spent in each job can be divided into:

(a) Time spent in diagnosing and repairing a defect (productive time).

(b) Time spent travelling between maintenance department, store and job location.

(c) Time spent collecting spares and to gaining access to building or work site.

(II) Cost of spare or materials needed for each job per trade.

4. *Usage measure*

Usage is the measure of time that the equipment is actually being used to serve patients. For some equipment such as fire extinguishers and locks or padlocks in drug stores, usage will be the actual time the equipment is available in working conditions since these "insurance" equipments serve through their presence (Centre for Operational Research and Applied Statistics 1990). Other equipment such as beds is in use only when used by patients or staff.

Operating costs, failure rates and equipment downtime can be expected to depend upon the level of equipment usage. Usage of equipment will in turn depend upon the demand for equipment, which is generated by the number of patients, number of beds and the medical specialities. General data concerning the use of buildings, and presumably their condition can be measured by collecting the following data:

1. Number of beds per ward;
2. Patient discharges; and
3. Speciality in each ward.

Patient throughput can be calculated as a measure of the extent of use of the building.

An attempt to collect the data required for this study utilised different means targeted at different sources which had been collected for different uses such as budget control or accounting. The data available are history data, physical condition survey data, general data, and day-to-day jobs data. These are discussed in the following sections.

3.3.1. History data

At Withington hospital, maintenance jobs data are collected on a routine basis stored in the " Works Information and Manangement System" (WIMS) since 1982. The maintenance management at Withington used the system as a register of assets (i.e. buildings, components, plants/equipments), to record details of planned work, and to schedule the work and record details of work done in order to create financial/technical history of the assets. Data covered a 12 months period, starting from the 1st of September 1987 until 31st of August 1988, collected and stored in a computer system on a routine basis by the maintenance department. Data was divided into the *building group and the engineering group*, and consisted of the following details:

(1) Asset identification number, which is used to identify a group of similar equipments or elements in a ward or pavilion, but surprisingly is not a unique number for each equipment or element;

(2) Date of reporting a defect;

(3) Trades involved;

(4) Labour cost; and

(5) Brief description of fault.

This data was not particularly suited to the task of maintenance modelling for three reasons; Firstly, the data of the *engineering group* covers the whole pavilion (building) without the asset number being broken down into components (i.e. individual wards). This contrasts with the *building group* data where the asset number identifies individual wards within the pavilion; This mis-match is an obstacle hindering the intended analysis to identify and forecast a ward's demand for maintenance as a function of it's use, and therefore the effect of medical speciality on the demand for maintenance. Secondly, the data included many duplicated records caused either by a computer or an operator error, as well as a considerable amount of missing records attributed to a shortage in staff time (secretarial time). In consequence, though some computer based records do exist, they can be expected to give an inaccurate picture of the number of jobs and total labour cost for a given ward or pavilion. Thirdly, the material cost was not included in the full history, but is accounted for as a variable overhead cost by maintenance department in a weekly report to the Works Office which does not refer to the actual jobs or trades involved.

3.3.2. Physical condition survey data

In order to determine the condition of the buildings and their elements a physical condition survey proposed, by the National Health Service NHS, to be undertaken, every five years and to be updated annually, for each hospital building within the Health Authority Districts. A physical condition survey was assessed, for each building at Withington hospital, by the South Manchester District Health Authority in 1984, and has been updated annually since that date as part of physical inspection reporting. A physical condition survey data, updated in 1985, was made available to this study. This physical condition survey is a limited inspection of 19 elements of perceived greatest risk and most likely to fail or disrupt the provision of the health service. These elements are: structure, external fabric, roof, internal fabric, internal fixtures and fittings, external works and grounds, electrical installation, heating system, steam system, ventilation, phones and paging, alarms and safety systems, drainage, piped medical gas and vacuum, hot and cold water systems, lifts, boilers/calorifier plant, fixed plant and equipment, and fuel storage and distribution. The survey was carried out for each of the 19 elements and was based on an assessment of the remaining life of each element. Each element is given one of a range of condition categories A, B, C and D. The criteria used for determining these categories of each element was as follows:

A : Denote that the element is 'as new' and can be expected to perform adequately to its full normal life.

B : The element is sound, operationally safe and exhibits only minor deterioration.

C : The element is operational but major repair or replacement will be needed soon within say three years for a building element and one year for an engineering element.

D : This category would cover those elements where there is a serious risk of imminent breakdown.

X : A rating added to D category to indicate that it is impossible to improve without replacement.

Consequently only *building elements* with remaining life of 3 years or less, and 1 year or less *(engineering elements)* are considered to be less than category B. There are further data in the physical condition survey which are:

(1) Age of the building;

(2) An estimate of the remaining life of the element based on the year of the physical condition survey;

(3) An estimate of cost to repair, which need to be put in hand in order to ensure that the element attains the assessed remaining life. Day-to-day repairs are not included; it is work of an irregular nature which evaluated and costed; and

(4) An estimate of cost to upgrade, if the remaining life is 10 years or less then the current cost to upgrade/replace the element is estimated.

A general condition for a particular building as a whole was assessed in the survey by adding the condition categories of all of the elements of the building surveyed. Usually, because some elements cost more than others initially, and/or because of failure in some elements is more crucial than in others, such as roofing versus internal fabric, then it may be necessary to apply further weighting factors in order to get a better general condition to the building as a whole.

The objective of the physical condition survey is to give a general and subjective assessment of the state of the buildings, from which the approximate cost of repair or replacement of failure work can be estimated and planned. Sahai (1987) has listed five criteria which are necessary in deciding upon upgrade a property, these are:

(a) The function of the building;

(b) Utilisation;

(c) Location;

(d) Condition/safety;

(e) Economic factors.

These criteria are not isolated, but interact one with the other and therefore must be viewed as a whole, e.g. economic consideration may be sacrificed to location, or whether the property is worth upgrading at all. A property may not be worth maintaining; it may be worth letting it run down because of the developmental potential of the site. The land upon which the property stands may be worth a great deal more because of it's location than the property after upgrading.

Condition of the buildings is not something with merely physical attributes, it must be related to use of a building or part of it (e.g. is the space in question is director's suite, or cleaners room). For this reason there is no absolute standards for maintenance, because it is people who determine standard (Sahai 1987). In the National Health Service, training modules titled "Mereworth" have been developed in association with Leicester Polytechnic, Sahai (1987), for integrating the various types of information about building before deciding how much, if any, money should be spent on maintenance. These involve not only the technical professionals, but also doctors, nurses, accountants, administrators and others. Jointly, they look at ways in which best value for money may be obtained from the NHS estate.

3.3.3. General data

General data, related to the patient throughput activity in each ward or medical speciality collected by the medical record office (statistical division) on a daily basis are:

(1) The number of beds in each ward allocated to each medical speciality;

(2) The number of beds occupied, with occasional borrowing and lending of beds to other medical speciality, this data covers each individual ward

and its medical specialities;

(3) Patient discharges/deaths in each ward referring to the medical speciality by the initials of the medical consultants;

(4) Patient throughput is calculated, (Marshall 1980), to represent the average number of patients who have been treated in each bed during the period.

The patient throughput is used here as a measure of the extent of use of the building; there are some factors affecting the patient throughput as a measure of usage these are: the number of empty beds, the length of stay and the number of visitors per patient. It was felt that the patient throughput measure is reasonable to represent the usage of the building, in that a lot of activities are usually accompanying the new patients such as X-Ray or other examinations and the requirement to use general facilities, whereas the long stay patients may be due to the preparation to operation or monitoring the recovery after an operation which require less activities than the short stay patients. That is why the number of beds alone cannot give a good indication about the activities within the ward.

3.3.4. Day-to-day jobs data

It was realized that the history data was not suitable for the task of maintenance modelling for the reasons explained in section 3.3.1. The necessary data required for the task of maintenance modelling can be collected through snap-shot modelling (Christer & Whitelaw 1983), and was proposed to be collected by means of questionaires, see section 4.5.1., to be completed by the operative who performs the repair. The data collection exercise had faced a lot of difficulties and reluctance from the trade unions at Withington hospital, see section 4.5.2., and the exercise has failed to collect the necessary data. To overcome this problem it was proposed to collect day-to-day jobs data via a limited snap-shot data collection exercise with the help of the maintenance department secretary, the data was in simple form and has not included what was planned to be collected for the study to recognise the size, nature and means of prevention of the maintenance problems, as well as the possible use of snap-shot data in the maintenance modelling. this was for two reasons. First, in order to establish a basis to quantify the size of maintenance activities in Withington hospital, since the available history data was unreliable and will likely under estimate the volume of work; and, second, to estimate the job arrivals pattern during the days of the week as an input to the maintenance management simulation models. Data covering more than two and a half months period, from 12th of February 1990 until the 30th of April 1990, were collected by recording the date of job arrivals, location, trade involved and brief description of the defect for the jobs arriving during the period. This data was felt to be very reliable in that it represents the day-to-day job arrivals during that period with a high degree of accuracy, since all jobs arriving to the maintenance department, and scheduled by the supervisors, were received by the maintenance department secretery.

3.4. Day-to-day demand for maintenance

To reduce the demand for maintenance, it is first necessary to identify the causes of the need for maintenance. In order to identify the causes of the demand for maintenance, an attempt has been made to identify and quantify the key trades and the major problem areas in terms of cost and frequency of maintenance activities using the available historic records and day-to-day jobs data. The majority of maintenance jobs are, or can be considered to be, single trade repairs such as plumbing or joinery in the *building group* and electrical and mechanical in the *engineering group*. Table 3.1 shows the percentages of number of jobs to the total maintenance activities of the four key trades at Withington hospital using history and day-to-day jobs data. There is an obvious difference between the percentage of plumbing trade jobs in the history data, extracted from computer information system, data collected over one year, (25.11%), and the percentage of plumbing jobs based upon day-to-day jobs data, collected over two and a half months (34.58%). This difference is believed most likely due to the unreliable history data and different sampling periods. The maintenance management felt that the four key trades can operate virtually as 90% autonomous group within its parent maintenance department, and more than 80% of the jobs are single trade jobs. The history data was summarised by showing the jobs description, frequencies, percentage of jobs appearance to the total maintenance activities in each key trade and the total labour cost in the four key trades, see tables 3.2-3.5. Day-to-day jobs data were also summarised by showing the jobs decription, frequencies, percentage of jobs appearance to the total maintenance activities in each key trade, see tables 3.6-3.9.

A simple comparison between table 3.2 of historic data, and table 3.6 of day-to-day jobs data for plumbing jobs can show that the most frequent jobs are the same in both tables with the difference in their percentage which is related to missing records in the historic data. Indeed the extent of missing data is evident by the frequency of occurrence, 189 in a year versus 784 in two and a half months. The more frequent jobs are simple jobs in terms of time needed for the actual repair such as sink blocked (15.5%) or rewasher a tap (15.2%). A possible reduction in sink cleaning jobs can possibly be

Trade	History data %	Day-to-day jobs data %
Plumbing	25.11%	34.58%
Electrical	27.83%	25.16%
Joinery	23.01%	24.29%
Mechanical	11.67%	8.02%

Table 3.1: The percentages of the number of jobs to the total maintenance activities at Withington Hospital using *history data and day-to-day jobs data.*

Job description	Frequency	% Freq	£Total cost
Sink blocked	42	22.2%	155.65
Rewasher & repair tap	42	22.2%	66.97
Clinimatic faulty	24	12.7%	159.87
Repair WC	21	11.1%	68.80
Blocked or leak on sluice	16	8.4%	25.38
Repair geyser	13	6.8%	132.19
Repair boiler	10	5.3%	25.81
Repair shower	4	2.0%	21.83
Smell of gas	2	1.0%	35.80
Repair radiator	2	1.0%	4.57
Others	13	6.8%	136.17
Total	189		

Table 3.2: Summary of one year *computerised history* records of the *plumbing jobs*, at Withington hospital, showing the description of most frequent jobs, their frequencies and the total standard labour cost.

Job description	Frequency	% Freq.	£Total cost
Change light bulb and clean shade	101	51.7%	767.48
Repair blug, socket and fuse	25	12.8%	56.48
Repair domestic equipment (toaster, vaccum .. etc)	14	7.1%	41.20
Nurse call faulty	9	4.6%	68.56
Repair lift	9	4.6%	35.45
Repair TV	9	4.6%	9.53
Adjust clock time	7	3.5%	5.52
Repair bed	7	3.5%	42.05
Water boiler faulty	4	2.0%	7.92
Investigate burning smell	1	0.5%	4.49
Others	9	4.6%	71.93
Total	195		

Table 3.3: Summary of one year *computerised history* records of the *electrical* jobs, at Withington hospital, showing the description of most frequent jobs, their frequencies and the total standard cost.

Job description	Frequency	% Freq.	£Total cost
Repair bed	21	23.3%	232.50
Repair and check heating	17	25.7%	167.20
Suction equipment faulty	10	15.1%	76.63
Repair ogden pump	3	4.5%	159.50
Leaking & blockage	5	7.5%	41.20
Insurance work	2	3.0%	93.76
Others	8	12.1%	384.49
Total	66		

Table 3.4: Summary of one year *computerised history* records of the *mechanical* jobs at Withington hospital showing the description of most frequent jobs, their frequencies and the total standard labour cost.

Job description	Frequency	% Freq.	£Total cost
Move/fit shelves	42	23.3%	232.50
Repair cupboard	31	17.2%	89.83
Fit/replace curtains	22	12.2%	99.48
Repair doors	22	12.2%	264.08
Repair locker	18	10.5%	25.70
Repair chair	9	5.0%	9.81
Repair lock	9	5.0%	44.60
Repair trolly	8	4.4%	13.69
Fix towel dispensers	5	2.7%	7.97
Repair/open window	3	1.6%	7.42
Repair floor	2	1.1%	29.22
Others	9	5.0%	18.74
Total	180		

Table 3.5: Summary of one year *computerised history* records of the *joinery* jobs at Withington hospital showing the decription of most frequent jobs, their frequencies and the total standard labour cost.

Job description	Frequency	% Freq.
Sink or basin blocked	122	15.56%
Rewasher tap	119	15.17%
Toilet blocked	103	13.13%
Pipe leak	80	10.20%
Reglaze window & Window draft	57	7.27%
Cieling (roof) leak & drain blocked	46	5.86%
Clinimatic blocked	43	5.48%
Geyser faulty	34	4.33%
Flush faulty	25	3.18%
Sink leak	25	3.18%
Remake/fit towel rail	18	2.29%
Loo collapsed or secure loo	17	2.16%
Loo seat faulty	17	2.16%
Shower tray blocked	13	1.66%
Overflow geyser flooding	12	1.53%
Door faulty	10	1.27%
Shower faulty	8	1.02%
Cooker pilot	7	0.89%
Bad smell	7	0.89%
New sink plug	5	0.63%
Plumbing alteration	5	0.63%
Others	11	1.40%
Total	784	

Table 3.6: Summary of 2½ months records of the most frequent ***plumbing jobs in day-to-day jobs data***, showing the description of jobs, their frequencies and percentage of frequencies. The labour cost was not recorded.

Job description	Frequency	% Freq.
Replace a light bulb	322	55.90%
Nurse call buzzer	41	7.12%
Repair fuse or plug	38	6.59%
Socket faulty	23	3.99%
Adjust clock time	23	3.99%
Vaccum cleaner faulty	15	2.60%
TV faulty	14	2.43%
Longer lead required	10	1.73%
Buffer faulty	10	1.73%
Clinimatic system faulty	9	1.56%
Replace battery	7	1.21%
Kettle faulty	7	1.21%
Fan faulty	7	1.21%
Repair fridge-freezer	5	0.86%
Repair heater	5	0.86%
Washing machine faulty	4	0.74%
Others	37	6.66%
Total	577	

Table 3.7: Summary of two and a half months records of the most frequent *electrical jobs in day-to-day jobs data*, showing the description of jobs, their frequencies and percentagies frequencies. The labour cost was not recorded.

Job description	Frequency	% Freq.
Repair door handle	172	31.88%
Fit or supply shelves	82	14.96%
Relocate cupboard	49	8.94%
Fitting partion	43	7.84%
Repair window	42	7.66%
Fit lock & key	33	2.92%
Refit ceiling tiles	16	2.92%
Repair (blind) curtain	16	2.92%
Refit curtain rail	13	2.37%
Repair drawer	9	1.64%
Dismantle wall panel	9	1.64%
Repair floor	9	1.64%
Repair chair	8	1.46%
Repair desk	8	1.46%
Repair garden fence or barierr	8	1.46%
Fit hasp & staple	6	1.09%
Others	25	4.56%
Total	548	

Table 3.8: Summary of two and a half months records of the most frequent *joinery jobs in day-to-day jobs data*, showing description of jobs, their frequencies and percentages of frequencies. The labour cost was not recorded.

Job description	Frequency	% Freq.
Bed or cotside faulty	38	20.65%
Fit trolly wheel	32	17.39%
Mobile suction faulty	19	10.32%
Radiator faulty or leaking	18	9.78%
Auto-clave pump	14	7.61%
Repair door/window frame	12	6.52%
Repair wheel chair	10	5.43%
Oxygen point	10	5.43%
Heater faulty	5	2.71%
Lock faulty	4	2.17%
Dish washer wheel faulty	3	1.63%
Auto lift faulty	2	1.08%
Cabinet drawer	2	1.08%
Vaccum cleaner	2	1.08%
Potato peeler & washer	2	1.08%
Others	11	5.97%
Total	184	

Table 3.9: Summary of two and a half months records of the most frequent *mechanical jobs in day-to-day jobs data*, showing their description, frequencies and percentages of frequencies. The labour cost was not recorded.

achieved by a redesign or modernisation of the sink or changing the users practice. In the case of defective washers, a possible action to eliminate these types of failures is block replacement to tap washers. A few cases of emergency repairs were reported in the plumbing jobs, such as smell of gas, which represent about 1% of the total number of jobs observed. Similar analysis to electrical, mechanical and joinery jobs observed in the history data (table 3.3 - table 3.5) and day-to-day jobs data (table 3.7 - table 3.8) can lead to the same conclusion, namely the more frequent jobs tend to be small jobs such as replace a light bulb, which represent (55.9%) of the total electrical jobs, and repair a nurse call buzzer (7.12%) in the electrical jobs, repair bed (20.6%) or fit trolly wheel (17.4%) in the mechanical jobs, and repair door handle (31.4%), or fit or move shelves (14.9%) in the joinery jobs. These types of defects can be reduced by implementing the appropriate and effective maintenance action such as a block replacement to light bulbs or introduce a periodic inspection, perhaps to nurse call buzzer, trolley wheels and/or to door handles if such maintenance action proved to be effective and efficient.

First, however, to clarify the situation, some questions concerning the nature of the demand for day-to-day maintenance has been addressed in an attempt to identify some explanatory variables and relationships between measures. For instance:

(a) Is the demand for maintenance dependent upon age or use of buildings?

(b) Is there a difference in the trend and pattern of jobs arriving per day over the days of the week?;

(c) Is the number of jobs arriving in any working day correlated with the number of jobs arriving during the next, or the previous working day?;

(d) Is there any difference in the average number of jobs arriving during week days?;

(e) Is there any evidence of an accumulation in jobs during a weekend?; and

(f) What is the expected number of jobs arriving for each working day of the week?

These are necessary questions which need to be addressed in order to define relationships and estimate important parameters which can be used as an input to the maintenance management models (simulatiom models).
These and similar questions are investigated on the basis of such data as has been collected along with judgemental input. The issues will be considered in turn.

3.4.1. The influence of age and usage of building upon the demand for maintenance

In order to answer this question, the history data at Withington hospital was analysed. All day-to-day jobs and small improvement jobs such as fitting new hooks, locks and shelves, but excluding all large improvement jobs, were included in the history data, i.e. all jobs that would normally be carried out without being put on a special annual programme. To assess the extent to which the age of the buildings as an independent variable influences the demand for maintenance in both the *building and* the *engineering groups*, similar buildings, in terms of size, type and number of storeys, but differing in age were selected for comparative study. The seven chosen buildings were pavilions 2–4 and 6–9 at Withington hospital, representing a very old group

(75+ years) because data were not available about other age groups, such as 20-50 years old buildings; some of these pavilions were built in the same year (i.e. they have the same age), therefore there are some duplicated measures of age in the analysis of age as an independent variable influencing the demand for maintenance.

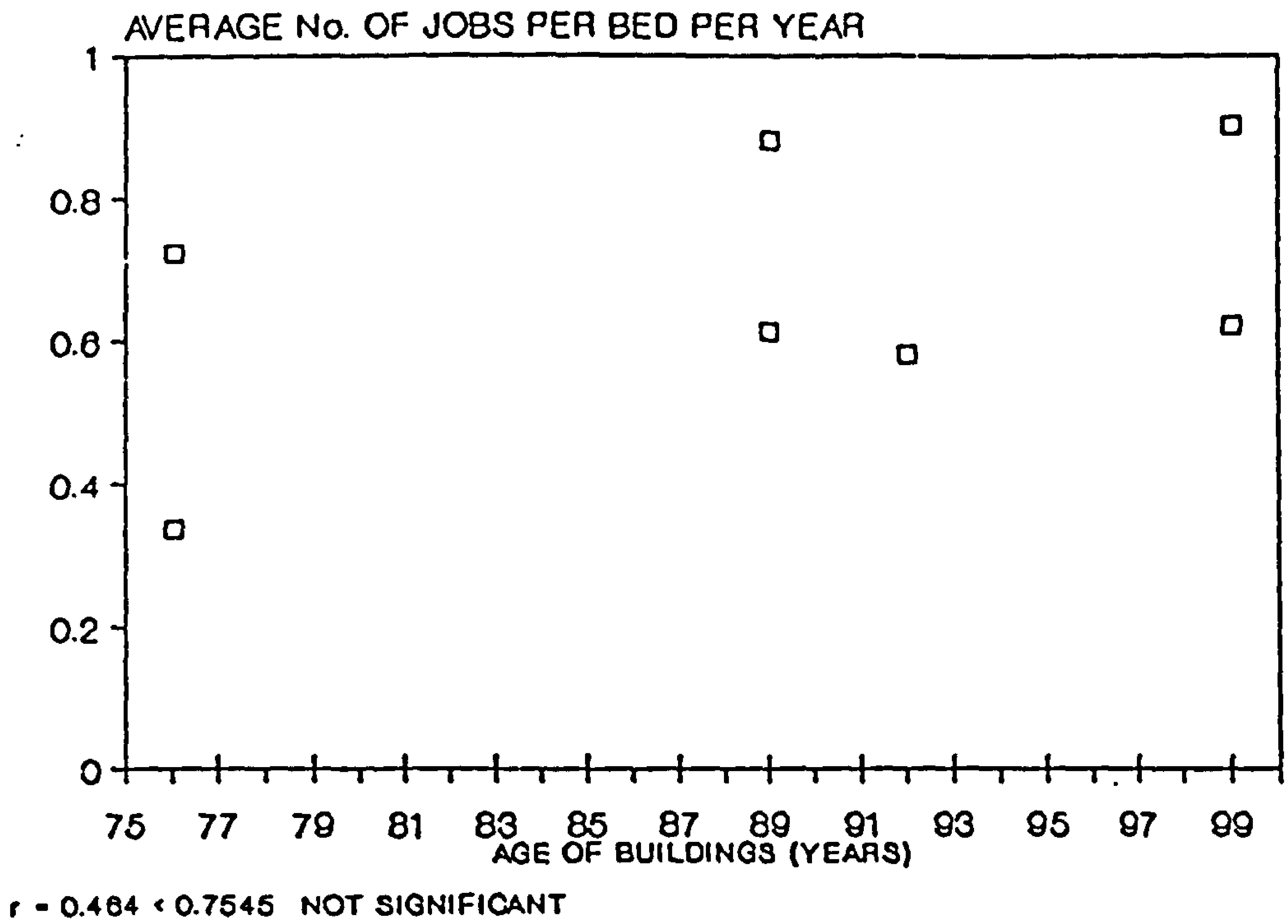
By comparing the demand for maintenance, as measured by the average number of maintenance jobs per bed in the *building group* with the age of buildings (figure3.2a), the correlation coefficient, which measures the linear association between two or more variables, was not significant at the 90% confidence level. Also the correlation coefficient of the average labour cost per bed in the *building group* with the age of the building (figure 3.2b), was not significant at the 90% confidence level. Likewise the average number of jobs per bed and the average cost per bed in the *engineering group* versus the age of building were not significant at the 90% confidence level (figure 3.3).

In the same way, the patient throughput as an independent variable was considered to provide a measure of the extent of use of a building. The available information was analysed, to see if it influenced the demand for maintenance. The correlation coefficients of the total number of jobs per bed, and the total cost per job per bed of the *building group* (figure 3.4), the average number of jobs per bed and the average cost per job per bed of the *engineering group* (figure 3.5) versus the patient throughput were again not significant at the 90% confidence level.

It was concluded that the age and use of the set of buildings considered gave no significant statistical evidence of influencing either the average number of jobs per bed, or the average labour cost per job per bed in either the *building* or *engineering groups*.

Whatever influenced the demand for maintenance, it was not explained simply by the building age or patient throughput for either the building or

(a)



(b)

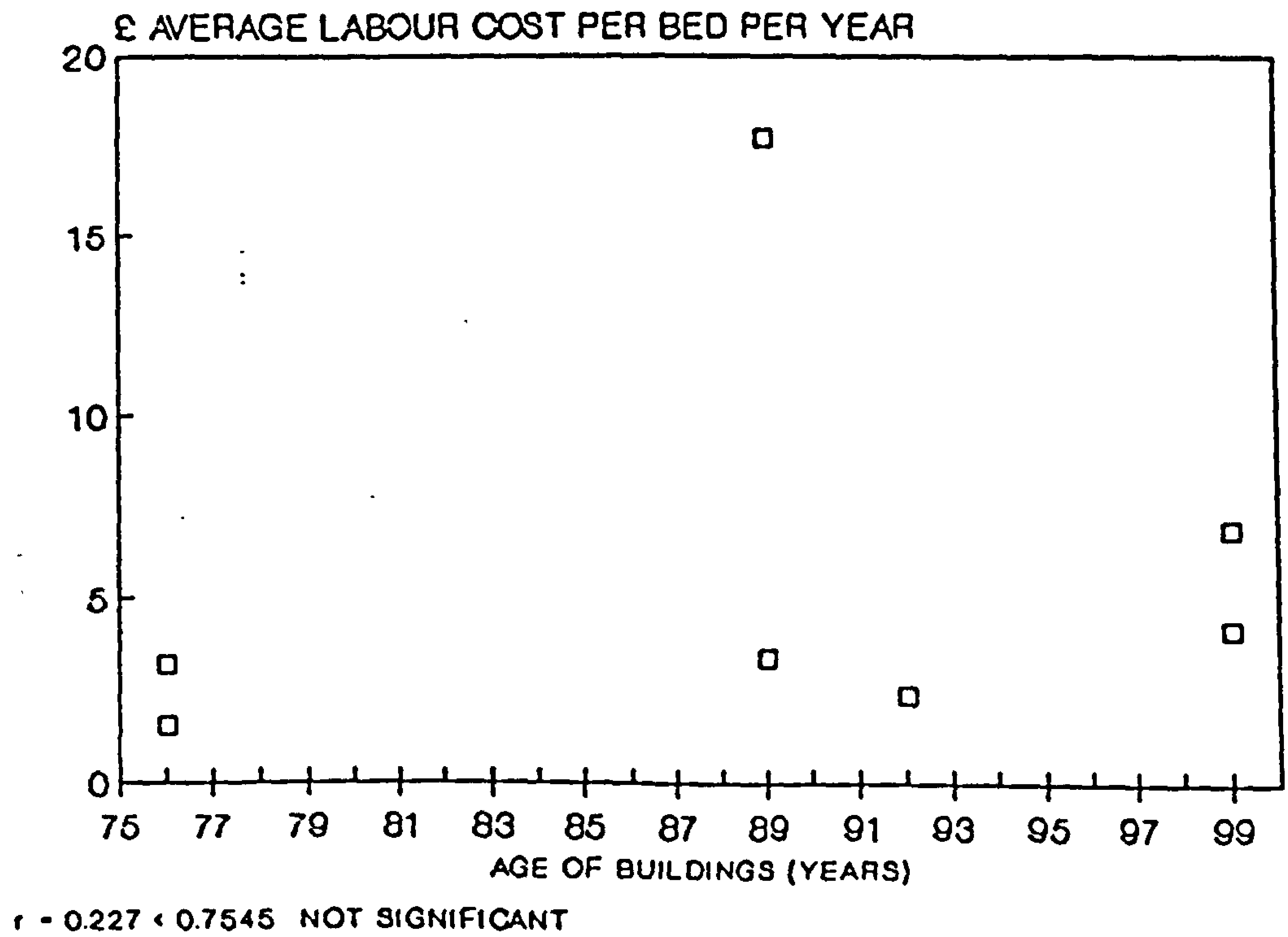
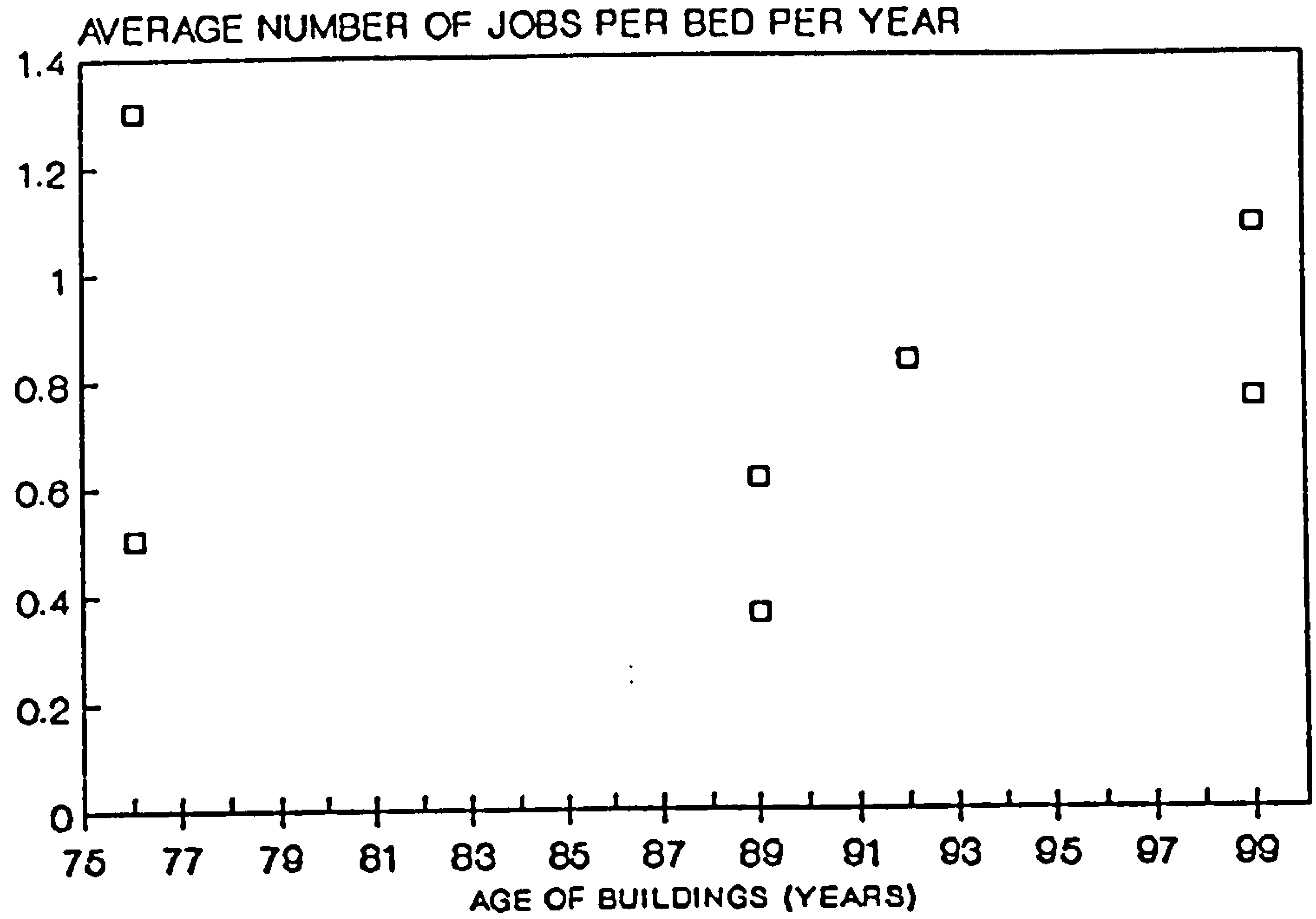


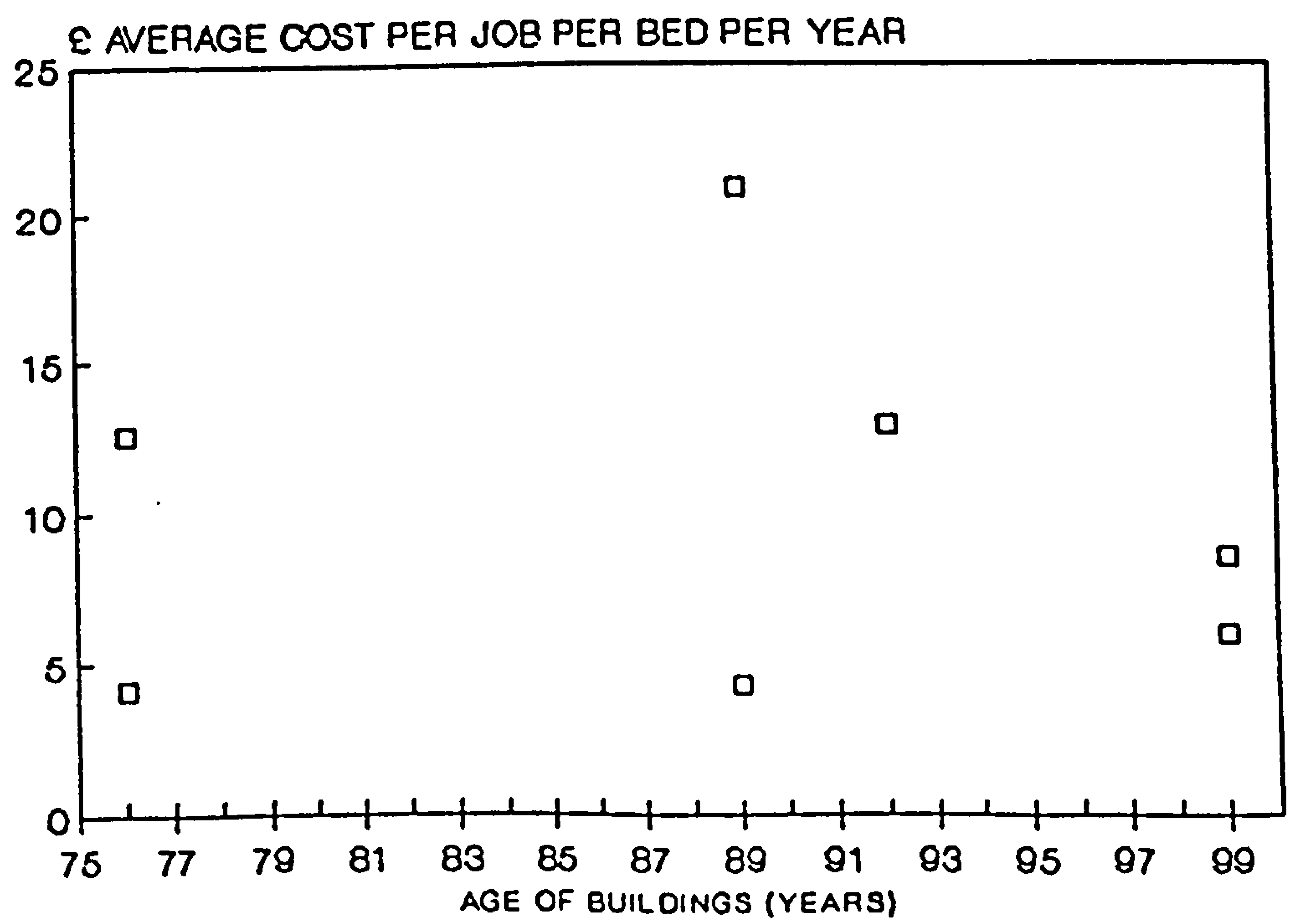
Figure 3.2: (a): Average number of annual building jobs per bed versus age of buildings. (b): Average annual cost per building job per bed versus the age of building.

(a)



r = |-0.01| « 0.7545 NOT SIGNIFICANT

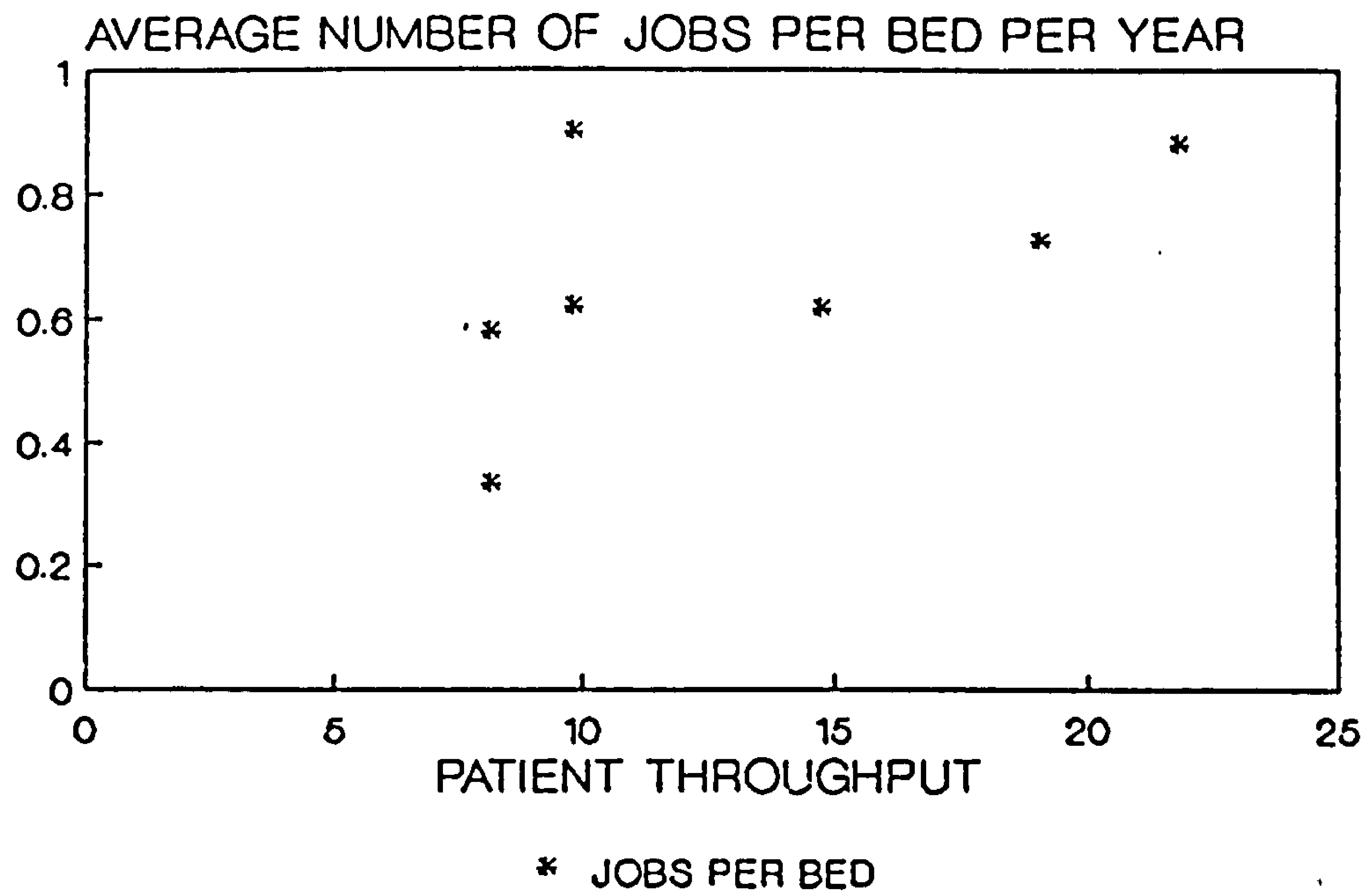
(b)



r = -0.016 « 0.7545 NOT SIGNIFICANT

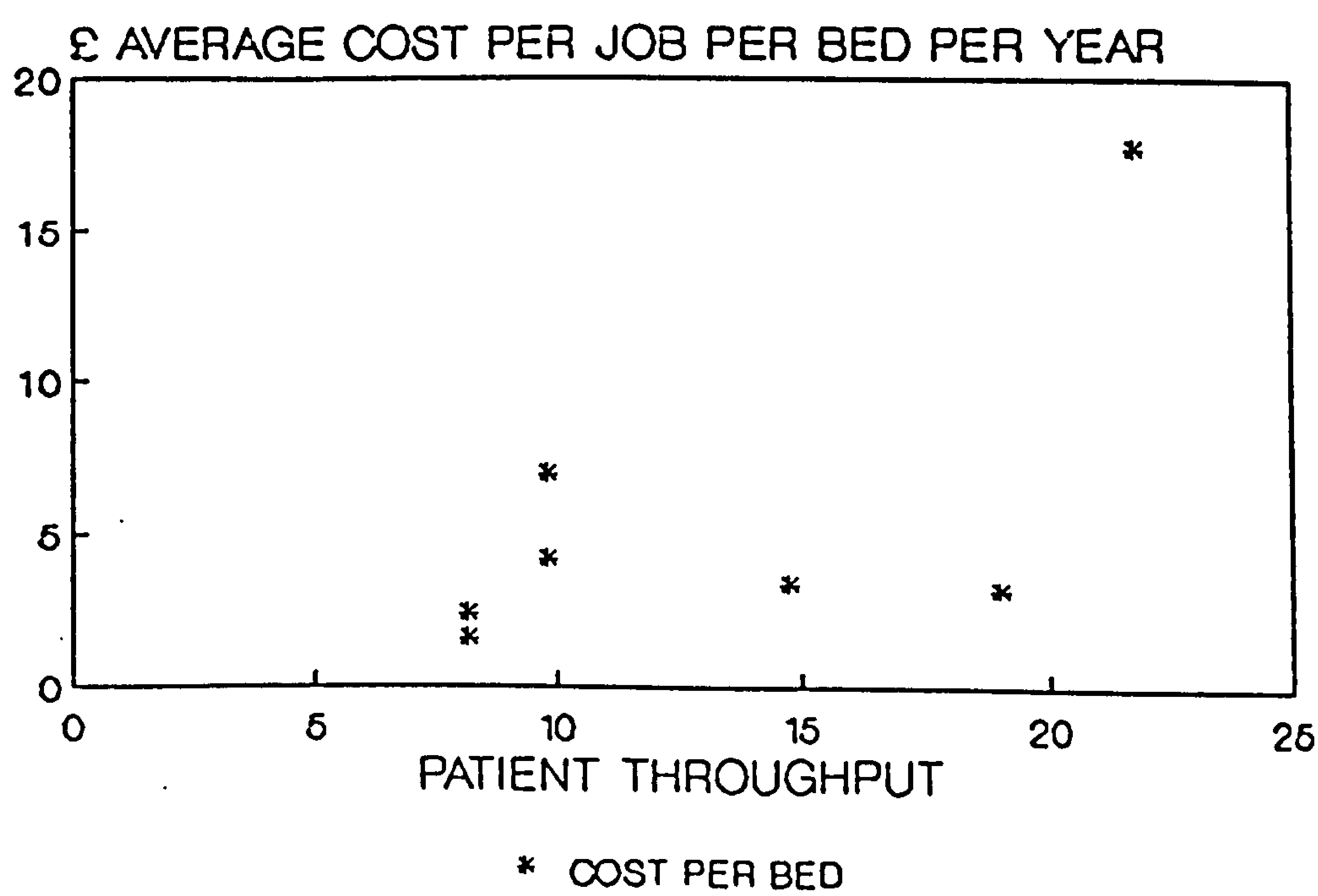
Figure 3.3: (a): Average number of annual engineering jobs per bed versus the age of building. (b): Average annual cost per engineering job per bed versus the age of building.

(a)



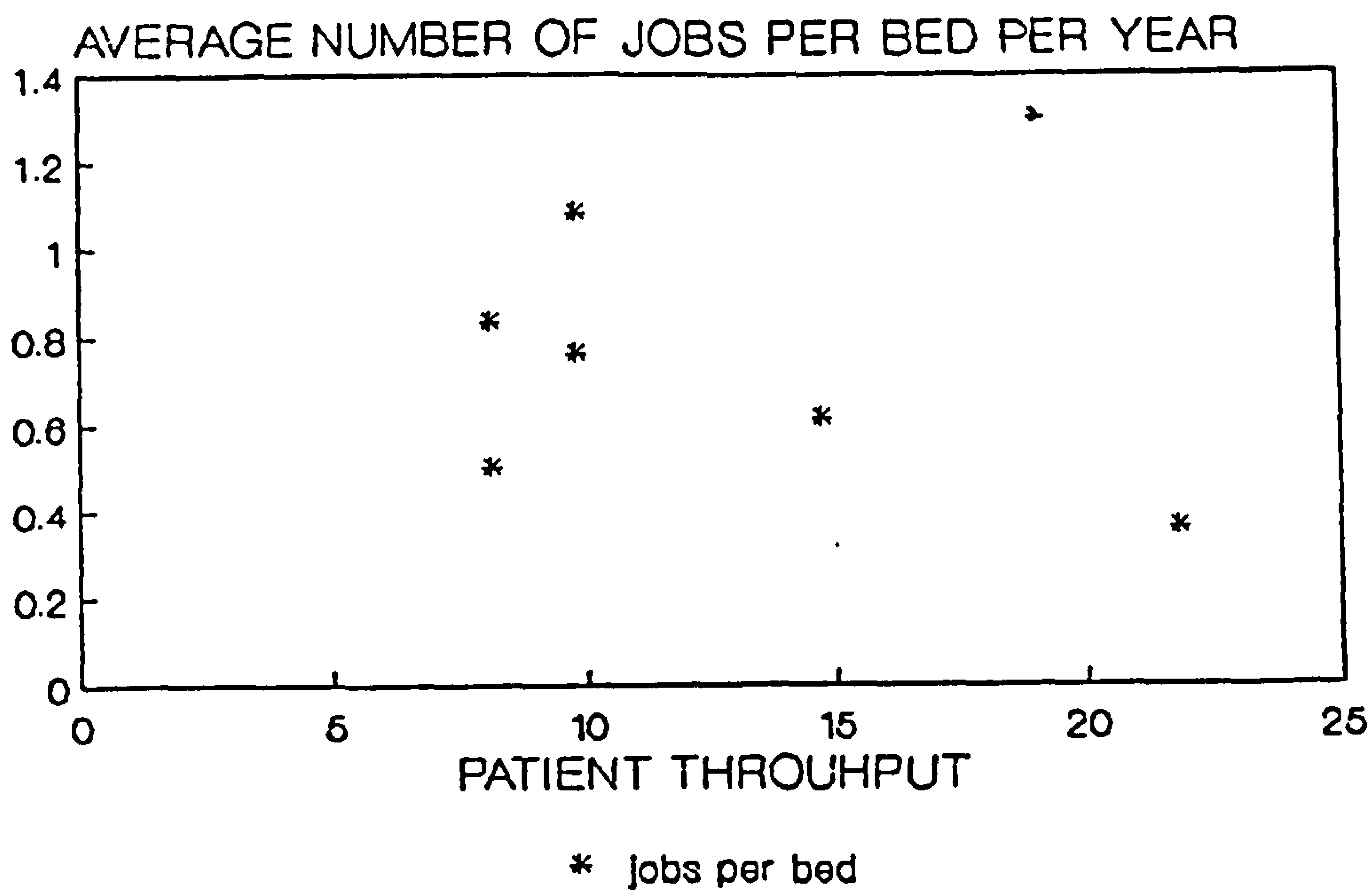
r = 0.542 < 0.7545 NOT SIGNIFICANT

(b)

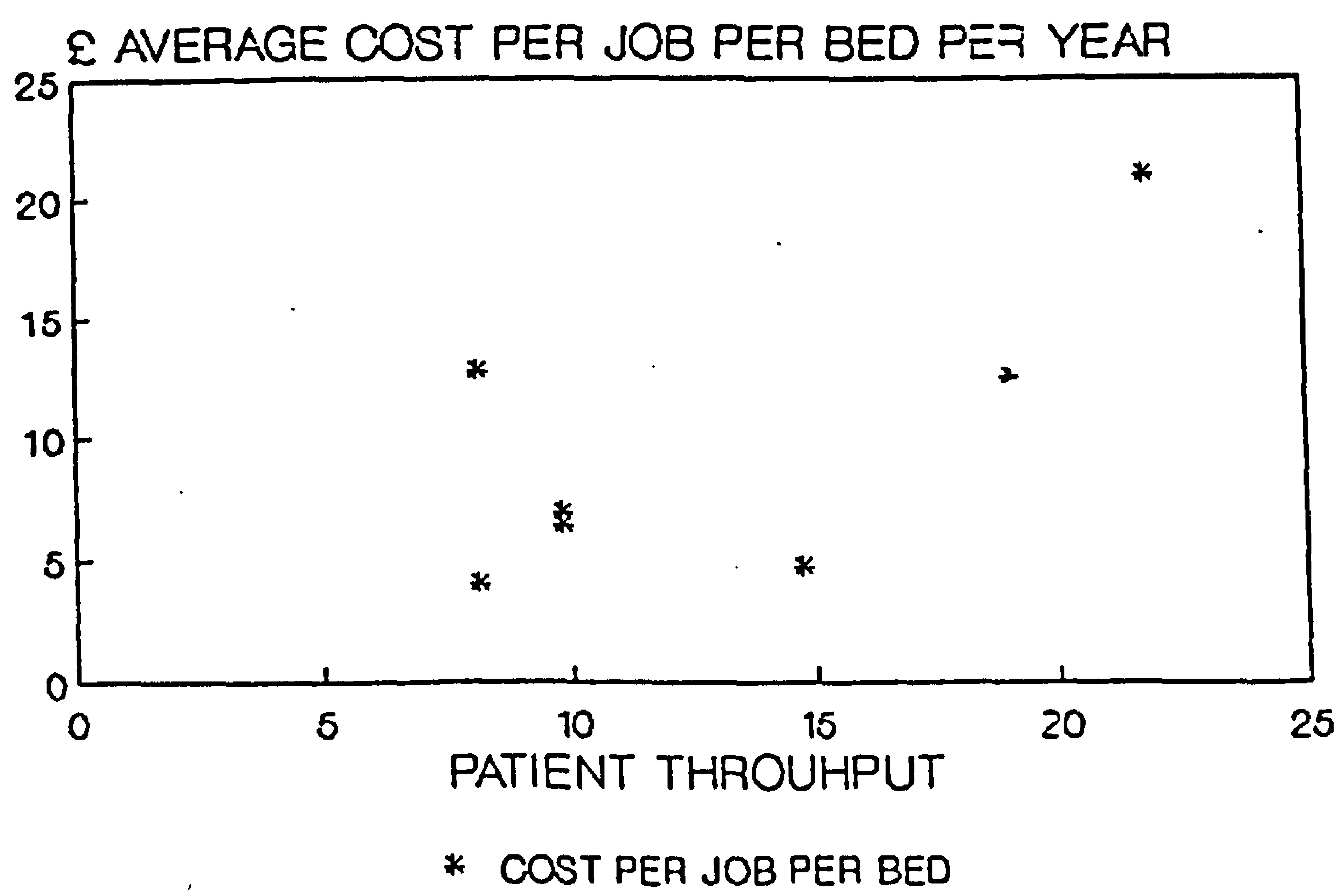


r = 0.663 < 0.7545 NOT SIGNIFICANT

Figure 3.4: (a): Average number of annual building jobs per bed versus the patient throughput. (b): Average annual cost per building job per bed versus the patient throughput.



r = -0.056 < 0.7545 NOT SIGNIFICANT



r=0.669<0.7545 NOT SIGNIFICANT

Figure 3.5: (a): Average number of annual engineering jobs per bed versus the patient throughput. (b): Average annual cost per engineering job per bed versus the patient throughput.

engineering maintenance activities. The probability does, of course, remain that the demand in terms of cost or number of jobs depend upon several measures, that is:

$$\text{demand (or cost) } d = \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4$$

where $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are constants,

A = age of building,

B = number of beds,

C = patient throughput.

To explore whether or not the demand for maintenance in terms of cost of job per bed or number of jobs per bed over the period studied depend upon several measures such as the age of the buildings, the use of buildings, or the number of beds per building, a multi-regression model has been analysed and the demand for maintenance as measured by the number of jobs per bed (demand) or the cost of job per bed (cost) was not significant in the *building* and *engineering* groups, where 'P' value, which measures the level of significance difference between the averages compared, equals 0.843, 0.873 respectively (i.e. highly not significant);

$$\text{demand } d = 0.0119\ A - 0.0003\ B - 0.0049\ C - 0.31$$

$$\text{cost } d = 0.99\ A - 0.048\ B - 1.72\ C - 47.0$$

It was concluded that the age, number of beds and use of building has no significant statistical influence upon the demand for maintenance. This conclusion might be correct, but the analysis was not very accurate for two reasons; first, the use of unreliable data which was available for the study, and may not have represented the correct volume of maintenance demand;

second, it was thought that the age of building studied, between 75-100 year old, was representing the same age group of buildings with insufficient age difference, such as buildings of age 20-50 years. (This is due to unavailable data about these groups of buildings).

3.4.2. The arrival pattern of day-to-day maintenance tasks

The pattern of maintenance activities, and therefore maintenance expenditure, are made up of a large number of small jobs which are random in time together with a limited number of major jobs such as replacement or renewals of building elements, which usually are planned in advance, and whose timing may not depend entirely upon the physical condition of the element.

Day-to-day jobs detected by the building user during working hours of the week (Monday-Friday), are assumed to be reported to the maintenance department either by post or a telephone calls. Emergency jobs reported during the night-time, weekends, holidays or otherwise outside working hours are dealt with by a duty maintenance operative. All non-emergency jobs are dealt with in a notional first in first out priority. The reliable day-to-day jobs data was analysed in order to see whether the number of jobs arriving in any working day are correlated with those arriving during the next or the previous day (figure 3.6). The correlation coefficients between jobs arriving during working days were calculated and were not significant at 90% confidence level, no obvious relationship has been established between the number of jobs arriving per working day and those arriving on the next or the previous working days other than independence, since none of the observed correlation coefficients were significant.

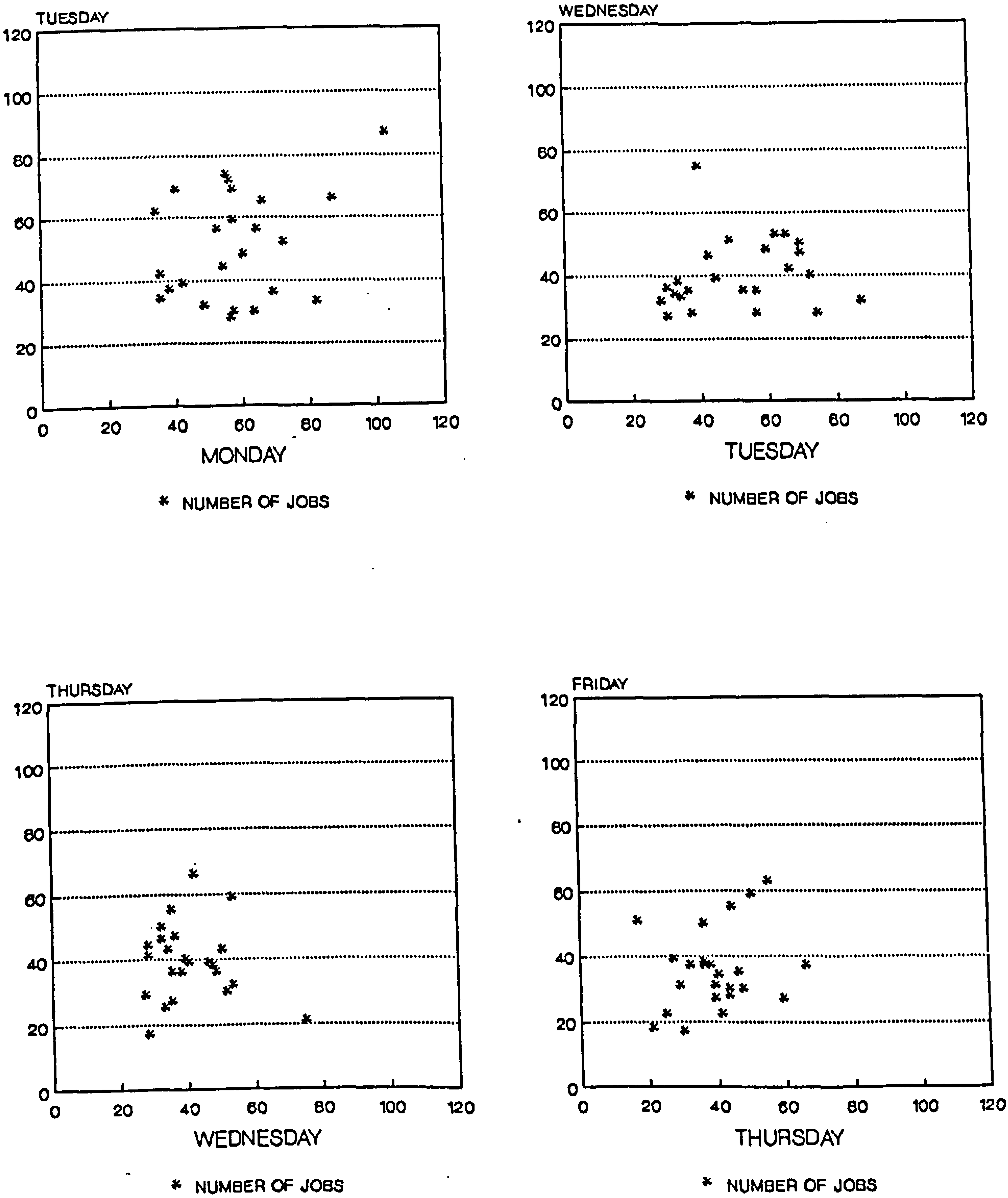


Figure 3.6: The total number of jobs arriving in a working day of the week versus the total number of jobs arriving in the following day of the week.

The same data was analysed in order to see if there is any statistical evidence of a difference in number of jobs arriving per days throughout a week. The analysis has shown that there is strong statistical evidence that the mean number of jobs arriving on Mondays and Tuesdays are different from the mean of those arriving during Wednesdays, Thursdays and Fridays, but there is no significant difference between the mean number of jobs arriving on Mondays and the mean of jobs arriving on Tuesdays. Likewise there was no significant difference between jobs arriving during Wednesdays, Thurdays and Fridays. This result can be explained by the accumulation of non-emergency jobs during weekends which are noted and then reported on Mondays or Tuesdays. Figure 3.7 presents a histogram of the average number of jobs arriving per day of the week along with a table shows the statistical comparison, using analysis of variance and t-test, between the average number of jobs arriving during every two of the working days of the week. First the analysis of variance was used which showed a 'P' value equals to zero, which measures the level of significance difference between the averages compared. It shows that the difference between the average number of jobs arriving during the working days of the week, as evident in figure 3.7, were highly significant, that is the average number of jobs arriving per day of the week are not the same in every day. Further analysis using t-test, to see whether there is any difference between the average number of jobs per day and the next or the previous day, the 'P' values for each of two averages were calculated and shown in the table cells in figure 3.7, a 'P' value equal to or less than 0.05 was taken as significant, and an asterisk (*) is shown with it in the table; a 'P' value equal to or less than 0.01 was taken as highly significant. These significant levels are shown on the table as:

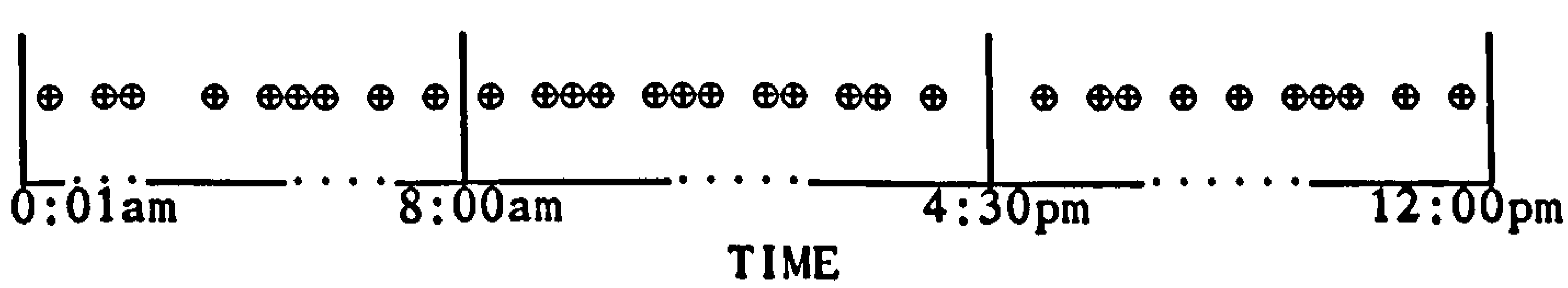
* means $P \leq 0.05$,

** means $P \leq 0.01$,

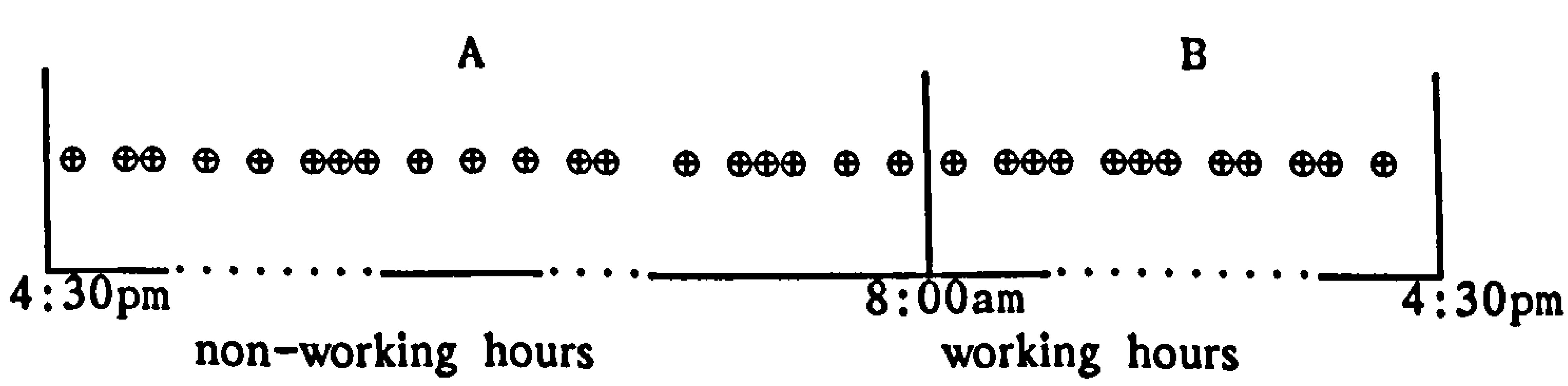
N.S. means Not significant.

Using these results, it is possible to estimate, the steady state of the common maintenance work arrival distribution during Wednesdays, Thursdays, and Fridays. It is assumed that Mondays and Tuesdays have the same underlying distribution as Wednesday-Friday, but with the additional jobs accumulated during weekends. The supervisors (foremen) opinion is that there is no difference between the number of jobs arriving during morning hours from those arriving during the afternoon hours. This suggests that there is no surge of jobs in the morning which have accumulated during the off-working hours, although defects may be noted at a constant rate during a 24 hours period, the reporting of defects to the maintenance department during the working hours is at a constant rate. For the steady state days the jobs arising as in the following hypothetical example:

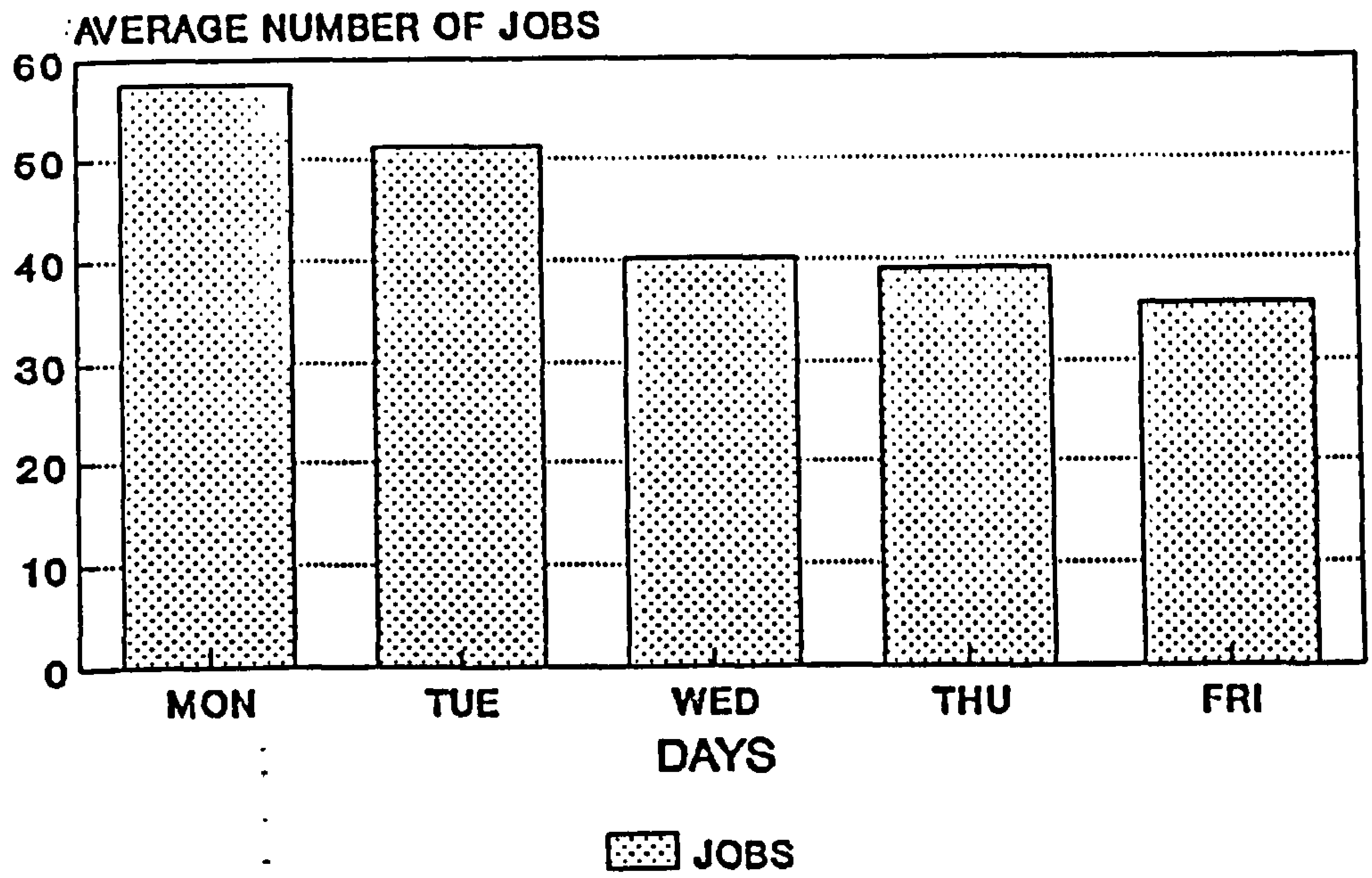
Example:



or the jobs arising can be rearranged in the following example dividing the 24 hours period into maintenance working time and non standard maintenance working time:



⊕ : represent job appearance.



DAYS		MONDAY	TUESDAY	WEDNESDAY	THURSDAY
	MEAN S.D.	57.67 18.26	51.21 17.23	40.12 11.23	39.12 11.58
FRIDAY	35.52 12.57	** 0.0	** 0.0009	N.S.	N.S.
THURSDAY	39.12 11.58	** 0.0002	** 0.0056	N.S.	
WEDNESDAY	40.12 11.23	** 0.0003	* 0.0110		
TUESDAY	51.21 17.23	N.S.			

F = 9.34 P = 0.0
Pooled standard deviasion = 14.38

Figure 3.7: (a) A histogram is showing the average number of jobs arriving to the maintenance department per day of the week;
(b) a table showing the comparison of average number of jobs arriving per working day with the averages of jobs arriving on other working days of the week.

Where

A : is total number of jobs arriving in the interval (4:30pm - 8:00am 'non-working hours');

B : is total number of jobs arriving during the working hours (8:00am - 4:30pm).

Therefore in the steady state days, the total number of jobs arriving during working hours = A + B

3.4.3. The expected day-to-day job arrivals

Let us assume that jobs occur randomly during 24 hours period as shown in the previous example and are subject to the following assumptions:

i. All jobs appear during working hours (8:00am - 4:30pm) weekdays are assumed to be reported to the maintenance department on the same day;

ii. Non-emergency jobs or defects which appear during the interval 4:30pm till 8:00am are assumed to be reported after 8:00am in the following working days;

iii. There are λ maintenance jobs on average arriving in a unit time t, with an average number of jobs, λt, during a time interval t, but the actual number of jobs arrived in one particular time interval is a non-negative integer.

iv. The expected number of jobs reported to the maintenance department during the eight hours working day 24λ.

v. In very small interval of length Δt, let us suppose that the probability of observing one job is given $\lambda\Delta t$ and the chance of reporting more than one job is negligible. In addition let us suppose that the number of jobs reported in two different time intervals are independent of one another.

let $P(r,t)$= probability of reporting exactly r jobs in any time interval of length t, then the probability of reporting no job in very small time interval of length Δt is:

$$P(0,\Delta t) = 1 - \lambda\Delta t \quad \text{(from assumption (iii))}$$

and

$$P(0,t+\Delta t) = P(0,t)P(0,\Delta t) \quad \text{(by the assumption of independence)}$$

$$= P(0,t)(1-\lambda\Delta t)$$

$$= P(0,t) - \lambda\Delta t\, P(0,t)$$

Rearranging this equation we obtain

$$\frac{P(0,t+\Delta t) - P(0,t)}{\Delta t} = -\lambda\, P(0,t)$$

In the limit as $\Delta t \to 0$, the above expression gives us

$$\frac{dP(0,t)}{dt} = -\lambda\, P(0,t)$$

$P(0,t) = e^{-\lambda t}$, *since* $P(0,0)=1$. This is the probability of observing no job in a given time t.

Consider the random variable T, which is the time elapses after any time-instant until the next reported job. This will be greater than a particular value t provided that no job reported up to this point, we have

$$\text{probability } (T > t) = e^{-\lambda t},$$

and,

$$\text{probability } (T \leq t) = 1 - e^{-\lambda t}.$$

This is the cumulative distribution function of random variable T and is recognised as the exponential distribution. Thus under the above assumptions times between jobs being reported (arriving to maintenance department) are distributed exponentially.

Day-to-day jobs data were analysed and the average number of maintenance jobs per day for each key trade on steady state days Wednesday-Friday was calculated as shown in table 3.10. The expected time between job arrivals during working hours may be calculated assuming the constant rate of λ_i jobs arriving on average per day per trade, where i= E for electrical trade, M for mechanical trade, J for joinery trade and P for plumbing trade, i.e. the time between job arrivals is exponentially distributed.

For the key trades of electrical, mechanical, joinery and plumbing, the percentages of jobs arriving, the expected number of jobs per day, and expected time between jobs arriving per trade on a steady state days Wednesdays-Fridays, in minutes, are shown in the table 3.10.

Figure 3.7 shows that there is no significant difference between average number of jobs arriving on Mondays and Tuesdays, or between the number arriving on steady state days Wednesdays-Fridays. However, there is strong statistical evidence of a difference between these two groups. The average number of jobs arriving on Mondays and Tuesdays are, 52% & 37%, more than the average of those arriving on steady state day respectively, we assume here that the expected number of jobs during Mondays and Tuesdays are the same as those on steady state days, but jobs arriving during Mondays and Tuesdays are augmented by jobs accumulated over the weekend.

The average of extra workload of reported jobs on Mondays and Tuesdays is representing 89% of the average workload during a steady state day. This suggests that the pattern of jobs noted at weekend and reported during the week are different to those noted and reported at midweek.

The expected number of jobs arriving on Mondays & Tuesdays, and the expected time, in minutes, between jobs arriving in the key trades, are shown in table 3.11. These information, in tables 3.10 and 3.11 are used as an input to the maintenance management models (simulation models).

Trade	% of jobs arriving	Expected number of jobs per day	Expected time between jobs arriving
Plumbing	34.60%	13.06	36.75
Electrical	25.16%	9.50	50.52
Joinery	24.29%	9.17	52.34
Mechanical	8.02%	3.03	158.41
Others	12%		

Table 3.10: The expected number of jobs per day per trade, and the expected time, in minutes, between job arrivals on steady state days, Wednesday-Friday.

Trade	Expected number of jobs arriving		Expected time between jobs arriving(minutes)	
	Monday	Tuesday	Monday	Tuesday
Plumbing	19.95	17.72	24.06	27.09
Electrical	14.51	12.88	33.08	37.26
Joinery	14.01	12.44	34.26	38.58
Mechanical	4.61	4.09	104.12	117.35

Table 3.11: The expected number of jobs arriving on Mondays and Tuesdays, and the expected time, in minutes, between jobs arriving in the four key trades.

Chapter 4

DATA / INFORMATION SYSTEMS AND DEMAND REDUCTION STUDY

4.1. Introduction

There is growing interest in means to reduce the demand for reactive maintenance, such as planned preventive maintenance, replacement and inspections. These maintenance methods are as applicable to buildings and their contents as they are in the more established context of industrial maintenance. In recent years, a substantial literature has grown around specific topics of industrial maintenance which may be termed collectively as maintenance processes. The development and application of reliability theory (Ascher & Feingold 1984, Bain & Engelhardt 1991, Billinton & Allan 1992), together with models of equipment overhaul (Christer and Doherty 1977, Jardine 1973) and replacement (Jardine 1973, Sussams & Edward 1983), delay-time concept & inspection modelling (Christer & Waller 1984), and condition monitoring (Christer & Wang 1992, Christer 1992) are cases in point concerned in the main with the latter part of a solution process in that it is assumed the existence of a problem has been recognised and its nature defined. As yet, there are few authors, such as (Christer & Whitelaw 1983 and Gits 1984), have addressed the task of problem recognition, or the broader question of how management within an organisation could evaluate and improve upon the overall effectiveness of current maintenance practice (Spedding & Smith 1987). In practice the most common approach to building maintenance is to wait until a defect is reported to the maintenance department by the building user. Often, a better approach might be to adopt a policy of periodic inspection of selective elements or facilities of the property with subsequent rectification of observed defects. Observing and rectifying a defect at an early stage is likely to reduce the severity of the defect and therefore the consequences and the repair cost. There are other gains possibly associated with inspection, in many large building complexes the majority of maintenance repairs are single trade repairs, as shown in chapter 3 table 3.1, such as plumbing and electrical work. Through inspection, a proportion of the maintenance work which is identified and reported to the maintenance department is thereby grouped at a discrete points in time. That enables the maintenance department to allocate its resources and rectify the defects in more efficient manner, which leads to a reduction of non-productive time e.g. travelling time (Christer 1981).

The objective of this chapter is to assess the possibility of applying a number of modelling techniques to building maintenance, which have been successful in the industrial maintenance, by collecting the necessary data for modelling using snap-shot modelling survey, which is based largely upon subjective data. This can facilitate the recognition and identification of the maintenance problem in terms of it's size, nature, location, and possible preventive measures. A necessary requirement of such a model is that it should be capable of indicating both the potential for improvement and the direction of change required to realize the improvement.

4.2. The maintenance problem

The task of maintenance management is to ensure as far as possible that the hospital facilities are kept in an acceptable condition of safety and efficiency at an affordable cost level. Clearly the acceptable condition would be related to safety and efficiency, and the work needs to be done must cause no unnecessarily distruption to services, or inconvenience to staff and patients. The schedule of work is constrained by the available resources set aside for maintenance within the National Health Service, NHS. The facilities in a hospital could be influenced to some extent by external factors outwith the control of management such as, weather (e.g. sun, rain, moisture, frost, wind), pollution (e.g. smoke, detergents), location (e.g. steam in kitchen, proximity to lift, door), medical speciality (e.g. psychiatry wards, X-Ray rooms), quality of design, quality of material, accidents and vandalism (e.g. broken glazing). There are customary decision variables which are used as means by which to control and maintain the hospital facilities in an acceptable condition. Typical amongst these are manpower; level and method of deployment; mix of trades; schedules for service; procedures for replacement and inspection of building facilities; standard of technical training; spares inventory policy. A common assumption implicit in this approach is that by setting appropriate values for the decision variables, hospital facilities can be maintained in an acceptable condition; or equivalently, if hospital facilities are not in an acceptable condition, there is a maintenance problem. Such an assumption may not be invalid. For example if a high breakdown rate has arisen as a consequence of human error or misuse, the problem is one of training, and no amount of maintenance will provide a solution (Christer & Whitelaw 1983).

Improvement in maintenance can be achieved through minimising the number of emergency and day-to-day jobs and thereby improve the safety and availability of hospital facilities. The development of such improvements in maintenance has to rely to a large extent on the quality and quantity of back up data and records available. A survey by Willmott (1988) of 393 companies, sites and directors shows that 52% of companies monitored actual costs of individual machines. A pilot study undertaken at four hospitals by the Salford Centre for Operational Research and Applied Statistics (1990), of the economic life cycle of five representative medical equipment advanced three conclusions concerning the observed maintenance information system. First, there is considerable variability in the quality and sophistication of medical equipment data and information recording systems within hospitals. Some of systems observed compare favourably with the best to be found in industry whilst others are so rudimentary as to virtually not exist. Second, where information and data systems have been established, the potential for using them to provide quantified guidance to assist management in managing equipment operations and replacement decisions is not being realised. Hospital equipment systems tend to be operated rather than managed. This again is an observation one could make to comparable sized orgnisations in industry. Third, an awareness and concern has been observed amongst some hospital managers with responsibility for equipment that greater use should be made of data, but they are unclear what should be collected, how it should be used, and what it can and cannot be expected to do. There appears to be a recognised need for guidance.

A survey by Christer & Whitelaw (1983) of 15 established companies and organisation with maintenance procedures varying from rudimentary to the sophisticated drew attention to a fundamental problem common to virtually all organisations studied, regardless of size and nature. It would appear that maintenance management has to cope with an information system in which there is a mis-match between the data collected and that which is necessary for effective maintenance control which requires data that is capable of defining the nature of the problem and not simply its size. Two reasons advanced by Christer & Whitelaw (1983) to explain this phenomenon. First, in a large number of cases the information system has been designed primarily for another use, such as financial control, monitoring and reporting, and relatively little attention has been given to the requirements of maintenance management. Secondly, maintenance personnel in general remain relatively inexperienced in the analysis and utilization of data as a management tool. Consequently, even in some cases where proper consultation has been made, a lack of well defined criteria concerning the requirements and envisaged use of a maintenance information system invariably resulted in a system which was of limited practical use, other than as an aid to budgetary control and as a source of basic trend statistics.

4.3. Maintenance information system

A management information system has been defined by The Institute of Cost and Works Accountants (1967) as

> *"a system in which defined data are collected, processed and communicated to assist those responsible for the use of resources".*

However, the collection of data is not an end in itself and is only of value if the information obtained is applied to control actions towards the achievement of specific aims prescribed by policy consideration. Even then, it can only be justified if the gain covers the cost of developing and maintaining the system. In the absence of modelling, such justification is not possible. It is important, therefore, that the basic aims should be clearly identified and procedures and techniques developed for processing the relevant data and transforming it to useful information. Robertson (1973) has stated that the information and information flows are justified by their relevance to decision-making and the actions which have to be initiated. It is necessary to examine the need of the maintenance management of the data, the nature of the data that is required, the source from which it may obtained, and the mode of representation which will facilitate its use in the decision-making process.

The Department of Health and Social Security, in conjunction with the National Health Service, has developed a suite of information system, 'Works Information and Management System' (WIMS), to assist in estate management tasks. The development of the WIMS software was started in 1979 which covered the majority of estate management application. There were 230 users registered in 1986 using WIMS, which has 13 modules to assist the maintenance management. These modul are: (1) asset management; (2) stock control; (3) energy monitoring; (4) redecoration; (5) budget monitoring; (6) maintenance contracts (i.e. asset management - budget monitoring link); (7) property appraisal (includes condition appraisal); (8) property management; (9) annual maintenance plan; (10) residential property; (11) contract management (capital projects - part issued); (12) electro-medical management; (13) vehicle management.

Blanchard (1987) has found that the most widely used modules to date are probably asset management, property management and budget monitoring with the property appraisal module coming into wide use as a current NHS estate rationalization policy is implemented. The asset management module is mostly used at hospital level which has facilities to create a register of assets (i.e. building components, plants/equipments), to record details of planned work, to schedule the work and to record details of work done in order to create financial/technical history of the asset. The property management is used at district and regional level, and budget monitoring at all levels. Property appraisal is a district based activity.

The type of data typically available to the hospital maintenance management operating a breakdown system and collected on a routine basis is date of failure, element identification, brief description of fault, and the standard labour cost. Such data is not particularly suited to the task of predicting the consequences of implementing some changes to existing procedures (Christer & Whitelaw 1983). At a breakdown, a considerable amount of data is potentially available. This data split naturally into three main areas, namely cause of fault, consequences of fault and means of prevention (Christer & Whitlaw 1983):

4.3.1. Cause of fault

What has failed is usually self-evident and recorded, but less obvious and just as important is the reason of the fault which is the key factor if past errors are to be avoided. Clearly the causes are many and varied and may fall into one of the following categories:

(1) Normal wear and tear: it is normally acceptable that for a particular type of building, facilities or equipment, depending upon exposure conditions and user activities, defects in the building and services will

arise because of wear and tear.

(2) Other faults arising may be due to the followings reasons:

(a) Design fault: this may be in respect of unsuitable constructional details or materials which are used without taking into account the environment or the user activities.

(b) Exceptional weather conditions for which it would not have been reasonable to make provision in the design.

(c) Improper use: where the possibility of rough usage could have been forseen by the designer, failure to guard against it would amount to a design fault. but wilful damage or gross carelessness should be separately recorded so that where possible maintenance action can be sought or steps taken to avoid a reoccurrence.

(d) Inappropriate maintenance: there is little doubt that the wrong diagnosis of the cause of failure can not only fail to effect a cure, but can result in a worsening of the condition of the building.

(e) Neglect: a work made necessary through overdue delay in carrying out maintenance at the proper time.

Usually there are higher costs resulting from improper delay (see table 4.1–4.4) which show the cost of delay in the maintenance action. The loss is the difference between cost of the work done and the cost which would have been incurred had the work been done at the right time.

Jobs	Percentage frequency	£cost per day
Repair bed	21.0%	350.0
Leaking and blockage	2.1%	1000.0*
Replace site glass	1.1%	5.5
Fire hose leaking	1.1%	1000.0*

* if delayed over three months

Table 4.1: Estimated cost of delaying mechanical jobs per day, subjectively estimated by the maintenance manager.

Jobs	Percentage frequency	£cost per day
Change lamps and bulbs	42.5%	11
Repair bed	2.4%	350
Clinimatic faulty	0.5%	13

Table 4.2: Estimated cost of delaying electrical job per day, subjectively estimated by the maintenance manager.

Jobs	Percentage frequency	£cost per day
Fix hasp, staple & padlock	1.8%	3000
Fit lock to TV.	1.0%	300

Table 4.3: Estimated cost of delaying joinery job per day, subjectively estimated by the maintenance manager.

Jobs	Percentage frequency	£cost per day
Clinimatic faulty	44.8%	13
Sink leaking	6.6%	500*
U bend or pipe leaking	2.9%	500*
Repair overflow broken	1.0%	400*
Grease tap spindle	1.0%	40
Leak in store room ceiling	1.0%	100*
Seal round patient shower	1.0%	100*
Radiator leaking	1.0%	1000*
Overhaul draw tap	1.0%	1000*
Rewasher draw off tap	1.0%	1000*
Replace geyser ball tap	1.0%	1000*
Replace hoses	1.0%	1000*

* if delayed over three months

Table 4.4: Estimated cost of delaying plumbing jobs per day, subjectively estimated by the maintenance manager.

4.3.2. Consequences of fault

Because of a fault, the health care may suffer some inconvenience or penalty. It is proposed that data relating to this penalty be collected at the time or after the breakdown. This may be measured by the downtime which could be recorded on the time spent waiting for tradesmen, diagnosing the fault, collecting spares, gaining access to location, performing the repair, and the total downtime to the facility. Such data provides a quantified measure of the constituent factors of downtime which makes it possible to consider the consequences of policy changes to reduce the consequences of defects: For instance, increasing or decreasing the number of operatives, their engineering expertise and diagnostic ability, their method of deployment, the mix of trades, or perhaps a change in the inventory control system.

4.3.3. Means of prevention

At each breakdown, consideration can be given to possible means of preventing or delaying repetition of the fault. This does not imply that such prevention action is desirable or even viable, but simply that it is possible via a recognized means. Such procedures could be some form of modification, preventive maintenance or servicing, redesigning, user training, or perhaps periodically inspecting or replacing a component.

4.4. Designing-out maintenance

Breakdowns and failures in buildings and their contents in a hospital can be hazardous and involve serious penalties. The cost of damage resulting from neglect can be very high. There is a possiblity of eliminating maintenance by designing-out maintenance. This lies at the heart of the terotechnology (resource management) concept (Husband 1976). The maintenance/design relationship is crucial to effectiveness. One of the common complaints from maintenance engineers is that they could have predicted the worst problem associated with new equipment if they had been consulted at the design stage. There are probably few equipments that could not be improved by some 'designing-out' maintenance (Husband 1976). Designing-out maintenance tend to work best when information is fed back to the designer from the maintenance manager, engineers, user, contractor, or researchers who are involved with or likely to benefit from design feedback.

Fagg (1987) defined the information feedback as *"knowledge acquired from experience during construction in addition to that arising from problems encountered during building maintenance and observations of the building in use"*.

So that it is vital for the design process to include a better utilisation of feedback information to assess the performance of structure, components, facilities and finishes. The ability to create satisfactory and workable design, and therefore to minimise maintenance, derives from knowledge and experience which can be fedback to decision making and the intention to keep learning.

Works and defects do not only result from design problems and wear and tear, but also derives from the interventions during maintenance or services by mechanical, electrical or plumbing operatives. In some cases the defects found in buildings may be caused by work resulting from mis-directed interventions or misuse by building users, and no purely maintenance effort can eliminate these defects since there is a training problem to be addressed, not maintenance.

Briffett (1987) introduced the design feedback diagram (Figure 4.1) to show the communication systems between the designers, contactors, maintainers, users and researchers.

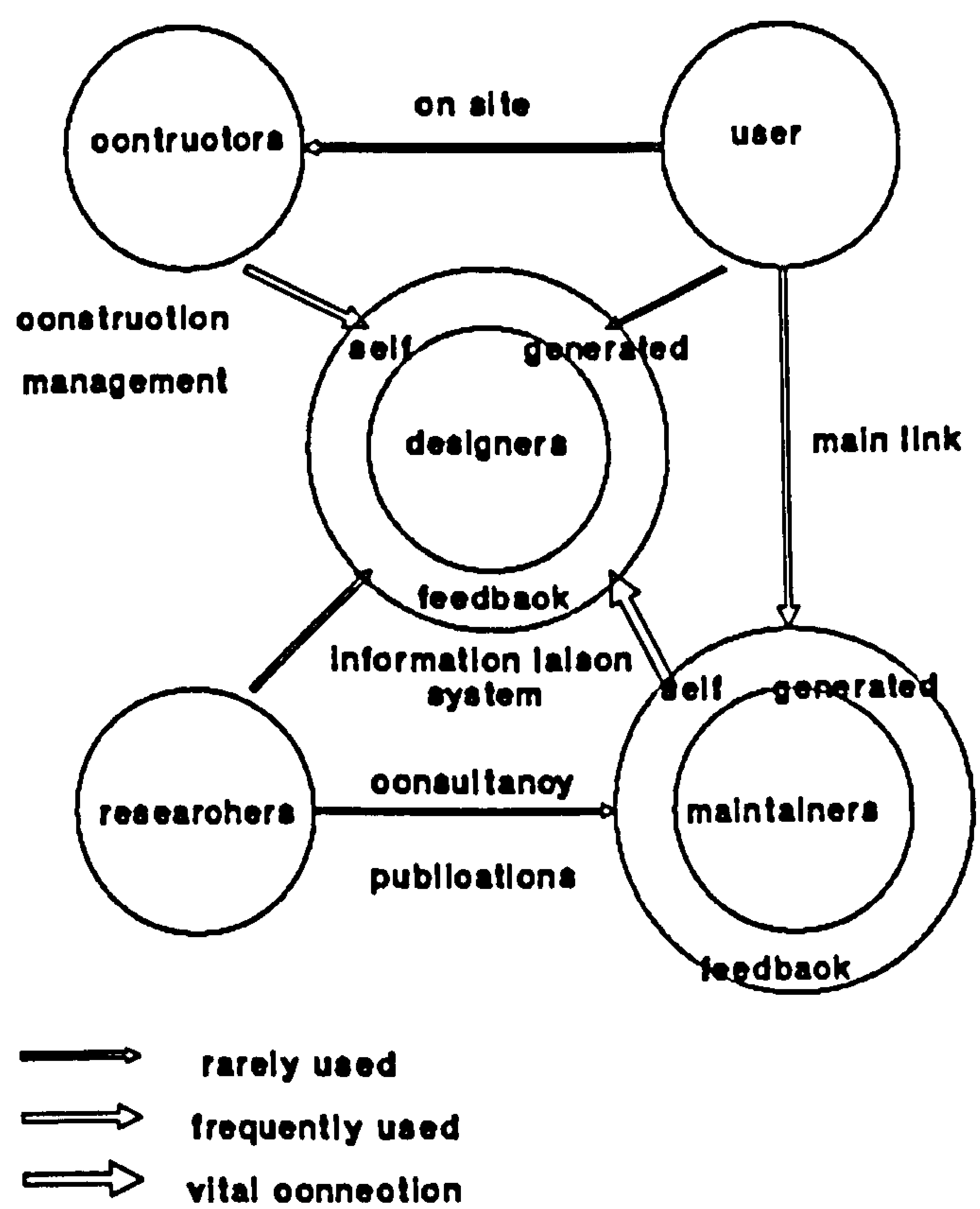


Figure 4.1: Linkage diagram shows design feedback communication system.

The diagram shows the traditional direct link from researchers, through consultancy or publications, and maintainers to designers as the only vital option. Other means of feedback can also be effective and in some circumstances may be more appropriate. In the designer group there is an opportunity for self generated feedback for the purpose of upgrading design which is useful in avoiding the problems of communications between different groups. Engineers in the service industry are probably the most effective self learners of design feedback, because they have general design skills and involved directly in running and maintaining services. On the other hand the architects are considered as the worst because standard practice dictate that they sign off once a building is commissioned and rarely step inside the structure again (Briffett 1987).

Much can be learnt from users on the origin and symptoms of problems and future design should be able to meet their needs. In a practical sense, users cannot directly contribute effectively to design feedback but do provide useful information for maintainers and researchers.

The main responsibility for initiating design feedback lies within the maintainers group who may include the maintenance manager, maintenance engineers, supervisors, and the tradesmen. There must be an incentive and an expertise available to ensure that design feedback is relevant and comprehensive. This cannot be done without reliable data which can be easily accessed by an interested analyst. The problem here lies mainly in the techniques used to identify the source and cause of the defect, and the appropriate analysis to determine the effective maintenance policy to eliminate the number of defects. As we have seen, not all cases have to be fedback to the designer for appropriate solution. Some of the causes may be related to the user practice (i.e. user training is needed), human error (operative training is needed) or to adopt an effective maintenance policy to reduce the number of breakdowns, such as, overhaul, replacement, inspection, planned preventive maintenance, and condition monitoring. There is, therefore, also a self generated feedback within the maintainers group.

The researchers task in the feedback processes of design is important in that they have to present research material which is accurate, easily understood and above all applicable to practice. A considerable amount of potential feedback has simply been filed away serving only the self fulfilment needs of the researcher, and never reaches or makes any impact on designers (Briffett 1987), therefore, the researcher link is not necessarily as strong as depicted in figure 4.1. Allen (1986) quoted a case in point where sulphate problems in brickwork were fully researched, explained and published in the 1950's but this did very little to prevent reoccurence of the defect which is still going on today.

4.5. Data collection snap-shot survey

Data collection is of great importance to maintenance management, but without a proper data collection and analysis, the maintenance of hospital equipments and facilities tend to be operated rather than managed. With modern technology, it is possible to collect vast amounts of generated data. Too much data can overload systems, require additional resources, and obscure important factors. Too little data can fail to provide pointers which can lead to good maintenance management. The adequate analysis of suitable data will highlight the areas in which management can have the greatest impact with regards to improving the service provided. It is important to identify essential features related to data collected (Hall 1987):

(1) Identifying the nature of the organisation: there is a need to establish the source of data and determine the format of existing data which is related to the various members of the management team in the organisation, and reflecting their responsibility. The various parties must be convinced that the supplying of data will allow the maintenance team to be an effective contributor to the orgnisation's overall objectives and will assist each section in achieving individual targets. This organisation identification will determine the final format of data which when recirculated will indicate relevant performance levels of orgnisation and assets being maintained.

(2) Nature and location of data: there is a need to analyse the assets to be maintained through the assets register, this allows the management to assess what data is available and the way it is collected. Analysing the present methods of collection and the data provided determines whether new methods are required to ensure the availability of suitable data for the appropriate application of maintenance management and modelling.

(3) Reasons for collecting data: it is essential that reasons for collecting data are established at the begining of the process and what criteria are to be applied. It is necessary to collect data which can be applied to allow objectives to be met effectively.

Snap-shot modelling survey can meet the above requirements by collecting data of more relevant nature to the objectives of the maintenance modelling exercise. This data can be used to examine the potential for improvement and the possible options available to the maintenance management, as well as allowing the management to take valid decisions regarding possible changes in the current or the proposed policy.

4.5.1. The survey form

The data required for this study was proposed to be collected by means of snap-shot survey questionaires to be completed by the operative who performs the maintenance work. The survey form was designed, first, to simplify the task of completion of the questionaire, by requesting the questions be answered by ticking the box which contains the appropriate answer to the question (this form is shown in Figure 4.2). Secondly, it was designed specially to meet the needs of the maintenance management and the intended modelling study. In particular, the survey was to collect the data necessary to estimate the delay times of faults to be recorded in order to investigate the possibility of applying delay-time modelling, Christer & Waller (1984), in establishing the optimum inspection interval which minimise the occurrence of breakdowns and then to eventually reduce the total cost. It was proposed to fill in the survey form for *every job* received by the maintenance department over six months period. This approach was necessary because of the fragmented and inconsistent history data which was collected by the maintenance department and stored in WIMS system mentioned in chapter (3). Snap-shoting was used in order to find out which components develop faults most frequently, i.e. to identify the major fault areas, the cause of faults, and the possible means of prevention of these faults with a view to identify any major category of faults which may be eliminated by being designing-out or by implementing extra inspection or prevention measures. The causes of faults would also be investigated within the survey.

CONFIDENTIAL

UNIVERSITY OF SALFORD/CENTRE FOR OR & APPLIED STATISTICS
WORKS DEPARTMENT - WITHINGTON HOSPITAL
Building and Engineering Service Questionnaire

(FOR OFFICE USE ONLY)

REQUISITION DATE ____________ ASSET NUMBER ____________

AND TIME ____________

BRIEF DESCRIPTION OF FAULT OR (JOB):

THE REPAIR

1. JOB EXECUTION DATE ____________ AND TIME OF START ____________

IS THE ABOVE DESCRIPTION OF FAULT RIGHT? YES | NO

IF NO, PLEASE DESCRIBE FAULT

2. JOB TYPE (Please tick)

REPAIR OR BREAKDOWN	MODIFICATION OR NEW JOB	PPM	OTHERS

TRADES INVOLVED (Please tick)

PLUMBING	FITTERS	OTHER PLEASE SPECIFY
JOINERY	ELECTRICAL	

3 HOW MUCH TIME WAS REQUIRED TO CARRY OUT THE FOLLOWING STEPS?

	MINUTES					HOURS				DAYS			MORE PLEASE SPECIFY
	0	5	10	20	30	1	2	4	8	1	2	4	
1. INITIAL TRAVEL TO LOCATION													
2. DIAGNOSE FAULT													
3. ACTUAL REPAIR TIME													

4. • WERE ANY SPARES OR MATERIALS REQUIRED? YES | NO

• IF YES, WERE APPROPRIATE SPARES ISSUED INITIALLY? YES | NO

• IF NO, HOW MANY EXTRA TRIPS TO STORE TO COLLECT/RETURN SPARES? [ ]

• WERE NECESSARY SPARES IN STOCK? YES | NO

• PLEASE GIVE A BRIEF DESCRIPTION OF SPARES AND MATERIALS USED.

THE DEFECT

5. WHAT IN YOUR OPINION, CAUSED THIS FAULT TO OCCUR? (Please tick)

WEAR	MISUSE	ACCIDENT	OTHERS - PLEASE SPECIFY

6. • COULD RECURRENCE OF THIS FAULT BE PREVENTED? YES | NO

• IF YES, HOW COULD RECURRENCE OF THIS FAULT BE PREVENTED? (Please tick)

MODIFICATION	USER TRAINING	PREVENTIVE MAINTENANCE OF SOME FORM	PREVENTIVE REPLACEMENT OF A COMPONENT	OTHERS - PLEASE SPECIFY

• IN YOUR OPINION, HOW LONG AGO COULD THE DEFECT HAVE FIRST BEEN NOTICED BY AN INSPECTION?

NOT AT ALL	HOURS				DAYS			WEEKS			MONTHS				MORE - PLEASE SPECIFY
	1	2	4	8	1	2	4	1	2	3	1	2	4	8	

• WOULD YOU HAVE EXPECTED THIS DEFECT TO HAVE BEEN NOTICED AT LAST PPM OR INSPECTION? YES | NO

7. CONSEQUENCES OF DEFECTS

• WAS THE WARD OR THEATRE CLOSED BECAUSE OF THE REPAIR? YES | NO

• DOES THE REPAIR HAVE TO BE DONE NOW? YES | NO

• IF NO, HOW MUCH LONGER COULD THE REPAIR BE DELAYED?

UNABLE TO SAY	HOURS				DAYS			WEEKS			MONTHS			MORE - PLEASE SPECIFY
	1	2	4	8	1	2	4	1	2	3	1	2	4	

SIGNATURE OF TRADESMAN ____________ DATE ____________

Figure 4.2: Survey form

The exercise was planned to take six month of collecting the required data by means of a questionaire. The snap-shot survey (questionaire) form is split into three parts; the first part is, *for office use only*, to be filled by the front end person who receives requests for repair (secretary or supervisor), records the date and time of the request, the asset number, which identifies the element, and records it's location, along with a brief description of the fault or job as reported by the user. The second and third parts of the survey were to be filled by the operative who executes the job.

The second part, questions 1-4, is concerned with *the repair* data. Question 1 is important in establishing the service time i.e. the time since the arrival of the job until the time of finishing the execution, which may be viewed as representing the downtime. The following questions establish whether the job description given by the building user was correct or not. This information can be considered as a parameter in modelling the possibility of relying on the previous experience of the supervisors in allocating the required resources to execute the job in the absence of an inspection before the repair. If the given description is considered to be not correct, there is a request to properly describe the fault.

Question 2 is concerned with identifying the proportion of work done because of a defect or breakdown, compared with modifications or planned maintenance, and with estimating the proportion of work per trade.

Question 3 relates to the time required to carry out the initial travel to location, diagnose the fault, and the actual repair time. These measures are important parameters in evaluating changes in maintenance policy. The initial travel time to location is not trade dependent, whereas the diagnosing and repairing time are trade related. The diagnosing time of plumbing jobs, for instance, will typically take a small proportion of the diagnosing time of electrical or mechanical defects.

Question 4 addresses spares provisioning. Were appropriate spares issued initially?, and were necessary spares in stock? These questions could help in establishing the most frequently used spares, and to improve the way that spares and materials are issued to jobs.

The third part of the survey questionaire is concerned with data required to recognise *the defect*, the cause and the consequences. Identifying the causes and their consequences are vital in choosing the effective maintenance procedures to eliminate the penalties and the consequences of defects studied. This section is also concerned with identifying the possibility of preventing the reoccurrence of the defect, estimating the time since the occurrence of the defect, and the possibility of noticing the defect in the last inspection. These and other questions are designed to enable estimating of the delay time of faults to be made.

4.5.2. Problems associated with data collection

The questions in the questionaire form were established and reviewed with the maintenance management at Withington hospital until a final version of the form has been produced.

The application of the data collection exercise faced a lot of difficulties and reluctance from the trade unions despite the considerable effort by the Works office/maintenance management at Withington hospital and the Centre of Operational Research and Applied Statistics at the University of Salford to address their fears and convince the tradesmen to cooperate with the study. A series of seminars arranged to the tradesmen by the maintenance management at Withington hospital failed to win adequate support for a study to investigate and model maintenance. The trade unions did not assist or co-operate with the collecting of necessary data. At the end the tradesmen decided on a policy of no cooperation with the project. This response was seen to be for a variety of reasons. To understand the situation, it is necessary to review some literatures concerning with the policies and objectives of the trades union and the management towards any sort of management reform or introduction of new technology such as the micro-electronics, the so called third industrial revolution.

Large unions are generally less likely to oppose technological change as policy than are individuals or particular groups of workers who fear that their own position in the labour process will be adversely affected, (Salamon 1992). It is important therefore to distinguish between the position of individuals or groups and that of the unions as collective orgnisations. Rathkey (1983) said in this context,

> *" almost the entire post-war generation of trade uinion leaders in both Britain and West Germany have viewed technological advancement not only as necessary but as fundamental to both the short and long-term interests of their members".*

It is easier for a union leader to adopt such a view, in contrast with a worker or workgroup which is liable to be directly displaced by a particular change. In the negotiation, union leaders aim to influence how technological change is introduced. They do not want to stop it, but rather control it, whether unilaterally, bilaterally or trilaterally (Bamber 1989). Another view by Neal (1989) who said that;

> *" .. decisions of a strategic planning and economic nature properly belong to the sphere of management decision-making, and it is*

> *the role of trade unions to react to, and seek to modify for their own benefit, proposals formulated by management. This reactive, essentially negative, view of trade unionism is open to criticism. One view is that a consequence of continued adherence to such a narrow view of potential trade union functions and influnce in U.K. will be to sacrifice still further opportunities for reform in the direction of effective trade unionism at the already decaying altar of trade union 'autonomy' and illusory 'independence'".*

One way of explaining the union policies towards reforms and new technology is to construct 'ideal type' union policy which includes a series of procedural and substantive objectives (Bamber 1989). A summary of these objectives are as follows: The procedural objective are consultation, union expertise, data protection and joint reviews. And the substantive objectives are job security, redundancy, working hours, pay, job design, retraining and reskilling, health and safety, and equal opportunties. It is important to distinguish between union policies and union responses. In practice worker may be willing to tolerate a repetitive job design or unsafe working condition in exchange for higher level of pay. Union responses can be classified into five categories (Bamber 1989) (1) participative involvement; (2) negotiated trade-offs; (3) unconditional acceptance; (4) reluctant acquiescence; and (5) complete resistance. Participative involvement occurs where unions positively welcome technological change and have a real input into the fundamental decisions about choices and design at the formative stage. Such behaviour seem to follow if the ideal type policy were fully implemented by all concerned in the change; managers, union representative and individual employees. This rarely happened (Bamber 1989). In practice there is little or no union or workgroup involvement in making the formative decisions, which

are made more or less by the engineers and management. In contrast to that is the complete resistance which may occur if the union leaders and members believe that the change will have serious consequences for them and that these can not be sufficiently solved by negotiating or consulting with management. This position also implies that the union can exert some power in relation to the employers.
Here we associate the perception by employees of new technology as indistinguishable from new management techniques (modelling) with the objective of increasing output and improving efficiency and cost effectiveness.

The problems of data collection are considered to be associated with three reasons;

(1) Problems associated with the morale in the NHS and the timing of the data collection exercise. In many organisations, the maintenance department suffers from any cut in the organisation budget as the maintenance activities are considered as unnecessary overhead. In the NHS there were growing feelings amongst the staff that the U.K. Government's review of the health service, "Working for Patients" published in (1989) concerning the Health Service reform, is going to reduce the spending in the NHS and consequently some losses of jobs would be unavoidable. This created a tense feeling amongst the NHS staff including the maintenance staff who were in a state of very low morale during the period of the data collection exersice. Mistrust was evident and rumours were rampant.

(2) The maintenance management at Withington hospital has asked and expected the tradesmen to co-operate with the data collection exercise. According to their assessment the relationship between the tradesmen and the management were considered as reasonably good. Close research

involvement with the maintenance management at the highest level at a time of increasing rumour about the state of the NHS had increased the suspicion of the tradesmen about the true objectives of the research exercise. The fear that it was connected directly with what was happening in the NHS as a whole could not be appeased. This was evident during a number of seminars organized to explain the benefits of the data collection exercise to the maintenance management and to the tradesmen in particular.

(3) Problem associated with the questionaire form. The questionaire form was designed to simplify the process of answering the questions and it was expected that once practiced, filling a questionaire form would take 1 minute in average. The trade union representatives claimed that it would take too long a time to fill in the form as an execuse for not co-operating. But there aspects of the form which may have caused further reluctance among the tradesmen. These are:

(a) At the end of the form, there is a request to sign and date the form by the tradesman who performs the job. Since there is some information concerning the performance of the individual operative, this may cause some sensitivity towards filling the form in case of any criticism to the performance of individuals.

(b) The form was headed "confidential", and joint co-operation between the Works Office at Withington hospital and the Centre for Operational Research and Applied Statistics at the University of Salford.

Again, this made it look an official document, which may have caused some suspicion amongst some tradesmen that the project is part of the White Paper concerning the NHS reform, and not an academic research project.

These reasons may explain the failure to convince the main source of input to the data collection exercise, i.e. the tradesmen, to co-operate with the study. Their concerns proved difficult to combat. Eventually a vote to adopt a non co-operation policy towards the project as a whole was passed. Because of the vote, some of the objectives and programme of the original research project were no longer possible. Revised objectives were required.

To proceed, it was now necessary to rely upon the limited data available to the maintenance management at Withington hospital augmented with subjective opinions which could be obtained, and use these as a basis to assess the scope and effectiveness of quantitative modelling. In particular, we wish to predict the outcome of alternative management actions (policies) for the management of building complexes at Withington hospital.

Policies to be investigated are:

(1) Inspecting a defect before repair to identify the required spares and resources, 'previewing policy'. This policy is recommended by South Manchester District Health Authority, but only partially operated at the time of the study.

(2) Operate without prior inspection of the defect, 'not previewing policy'. Here the policy is one of depending upon the supervisor's knowledge in identifying the required resources correctly.

(3) Issuing a batch of jobs to a tradesman instead of one job at a time.

(4) Delaying non-urgent jobs to grouping them in time.

(5) No sickness policy.

(6) Employing an extra part-time tradesman during busy days (Mondays & Tuesdays).

(7) Working 7 days a week instead of 5 days a week.

(8) Multi-skilled tradesmen policy.

These policies were identified in discussion with the maintenance management as being possibly viable options of interest. The objective of the research is now to develop models of these policies, using a discrete event simulation approach. This should be capable of indicating to management the gains and consequences, in terms of measures of interest to them, of changing operating customs and practice; that is, the consequences of adjusting decision variables. To have any prospect of influencing management, models need to be understood, believable, and convincing. It should be noted that building maintenance management are not generally known for their familiarity with modelling concepts or analysis techniques.

Chapter 5

INPUT DATA OF THE HOSPITAL MAINTENANCE MANAGEMENT MODELS

5.1. Introduction

By its nature, building maintenance requires an ability to respond to a demand that is random in type, random in nature and random in location. This in turn creates complex operational and logistical problems for management, specially if the property complex is large, such as a hospital complex. Management has to ensure that the correct materials are in the appropriate location along with the required tradesmen at the correct time, and to achieve this in a cost-effective fashion, with maximum availability and safety (Christer 1990).

The objective of the maintenance management is to keep the hospital operating in an acceptable manner. This means setting appropriate values to decision variables, such as, manpower requirements, method of deployment, mix of trades, and schedules for cyclic work, component replacement or inspection.

In practice when the maintenance management model is complex in nature, involving many variables of probabilistic nature, simulation techniques can be applied to help to identify the important variables in the system and the outcome of alternative maintenance management policies. Simulation model formulation consists of building a model describing the system behaviour. This model, as illustrated in Figure 5.1., transforms a set of input random variables X_i into a set of output random variables Y_j, also known as the response variables; where i=1,2,..,n; j=1,2,..,m.

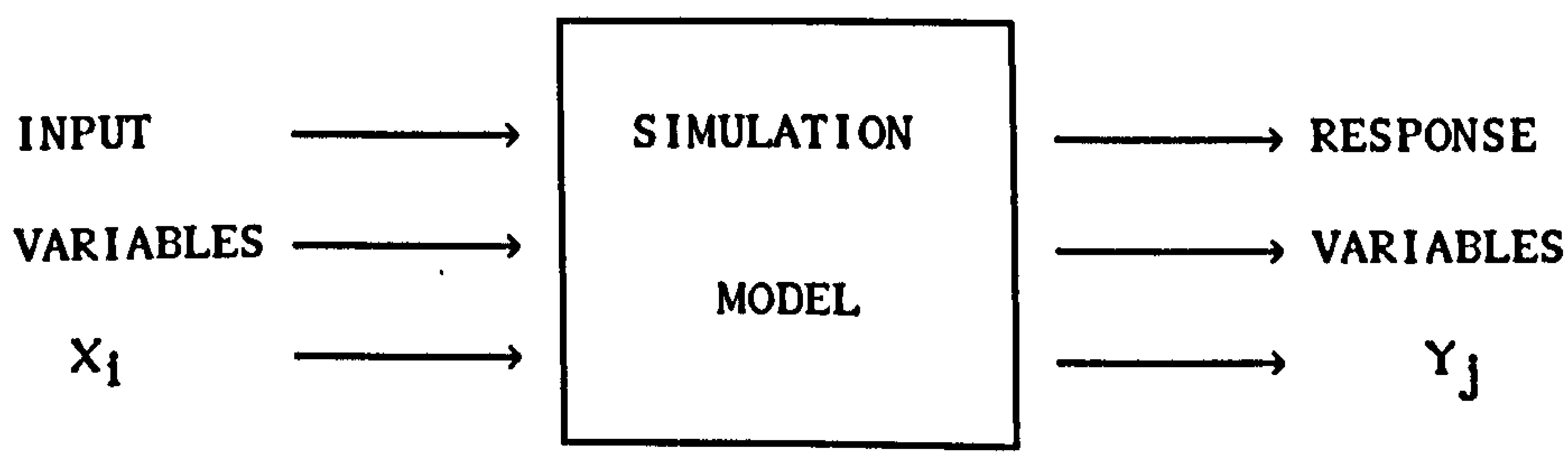


Figure 5.1: A diagram shows a basic idea of a simulation model.

In order to build a maintenance management simulation model, it is necessary to collect and analyse the input data which provide the driving force for the simulation model. Determining appropriate distributions for input data is a major task in simulation from the stand point of time and resources (Banks & Carson 1984). Additionally faulty assumption on input will lead to outputs whose interpretation may give rise to misleading recommendations.

Banks & Carson (1984) advanced four steps in the development of valid input data which have been adopted in this research. The first step, the collection of raw data, is often a major time consumer in the real-world simulation. The second step, the identification of the underlying statistical distribution, begins by developing a frequency distribution, or a histogram of the data. From the frequency distribution a distributional assumption is made. In the third step, estimates are made of the parameters that characterise the distribution. Finally in the fourth step, the distributional assumption and the associated parameter estimates are tested for goodness of fit. The Chi-square and the Kolmogrov-Smirnov tests are frequently used (Lyonnet 1991). If the null hypothesis that data follow the distributional assumption fails, other models for the data, i.e. different frequency distribution forms or histograms, should be considered and tested. If all fail then the empirical or the cumulative form of the histogram may be used.

This chapter is concened with the collection and analysis of simulation model input data; Chapter six deals with the maintenance management simulation models and proposed methods of deployment (maintenance management policies); and Chapter seven discusses and analyses the simulation models output.

5.2. Assumptions and collection of the simulation input data

The reported jobs to the maintenance department are considered to belong to one of the four key trades, Electrical, Mechanical, Plumbing, and Joinery; repairs are conducted on a first come first served basis, for each priority class, and only one tradesman can repair a defect at any one time.

The input data to the simulation model were collected from different sources, which were either objective or subjective data. The input data are given below.

5.2.1. Objective input data

5.2.1.1. The distribution of interarrival time between jobs per trade.

The collection and analysis of the job arrivals data were discussed in section 3.4.3. The average number of jobs arriving was not homogeneous during the days of the week, see figure 3.7(a). But the number of jobs arriving on each working day of the week can be assumed to be homogeneous. Therefore, the interarrival time follows the exponential distribution during any of the working days of the week, with different parameters for the four key trades.

5.2.1.2. The distribution of time to diagnose and repair a defect or job per trade.

No repairing or diagnosing time data were collected by the maintenance department as part of the history data mentioned in section 3.3.1. The recorded history data included only the standard labour cost, which was calculated by the planner estimators in the maintenance department according to previous work measurement, Lewis (1983), and Husband (1976). The standard labour cost is based on the standard repair time and the allowance time which represent 26% of the repair time, which allows for travelling and tea breaks. The observed standard repair time, which is used to fit a theoretical distribution or as an input to the simulation model, was calculated back from the standard labour cost taking into account the cost of labour per hour during the time of the data collection, see figures 5.2 - 5.5, which are showing the frequency distribution of standard repair time

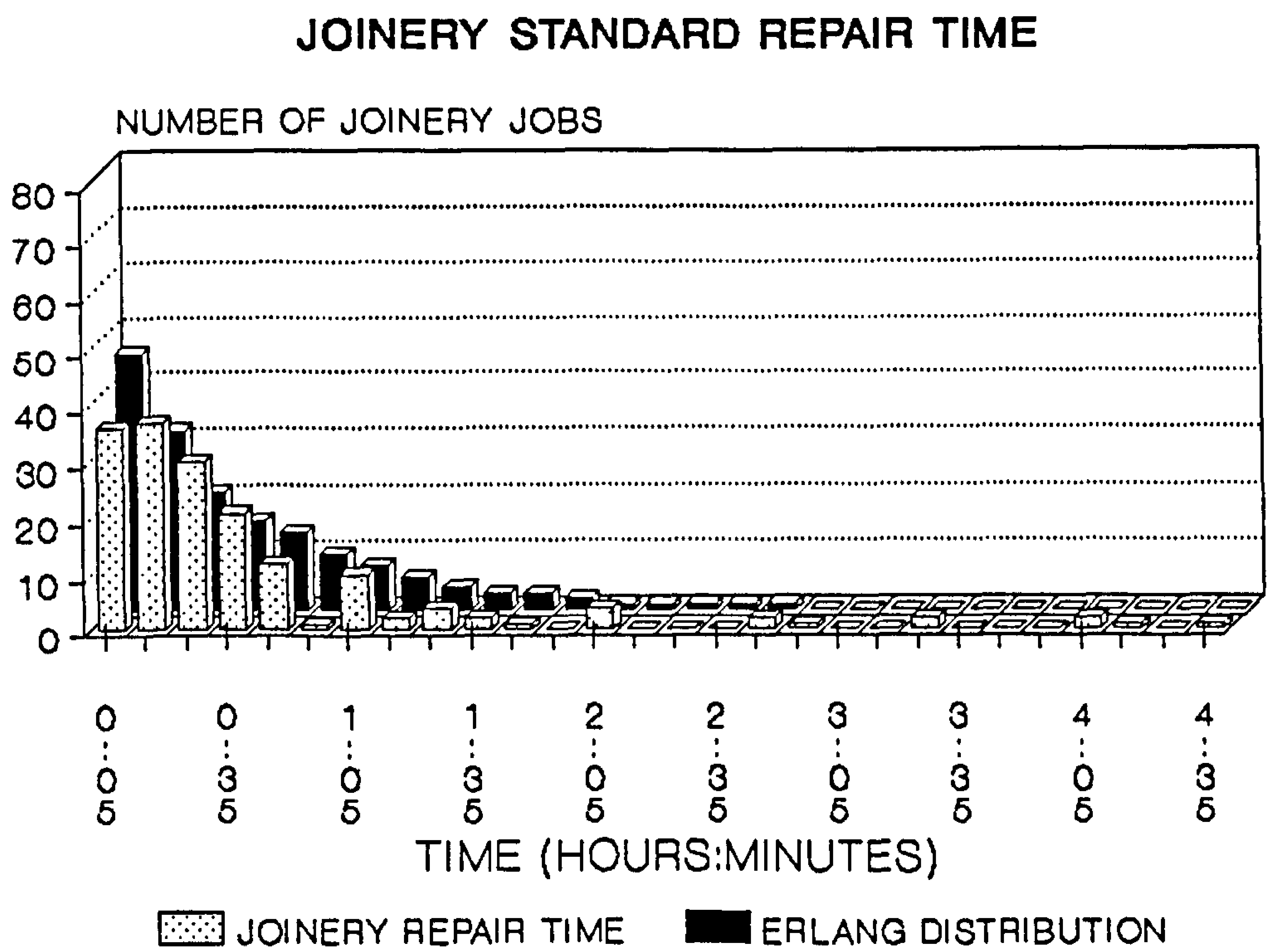


Figure 5.2: Observed and fitted Erlang distribution to the standard repair time of joinery jobs.

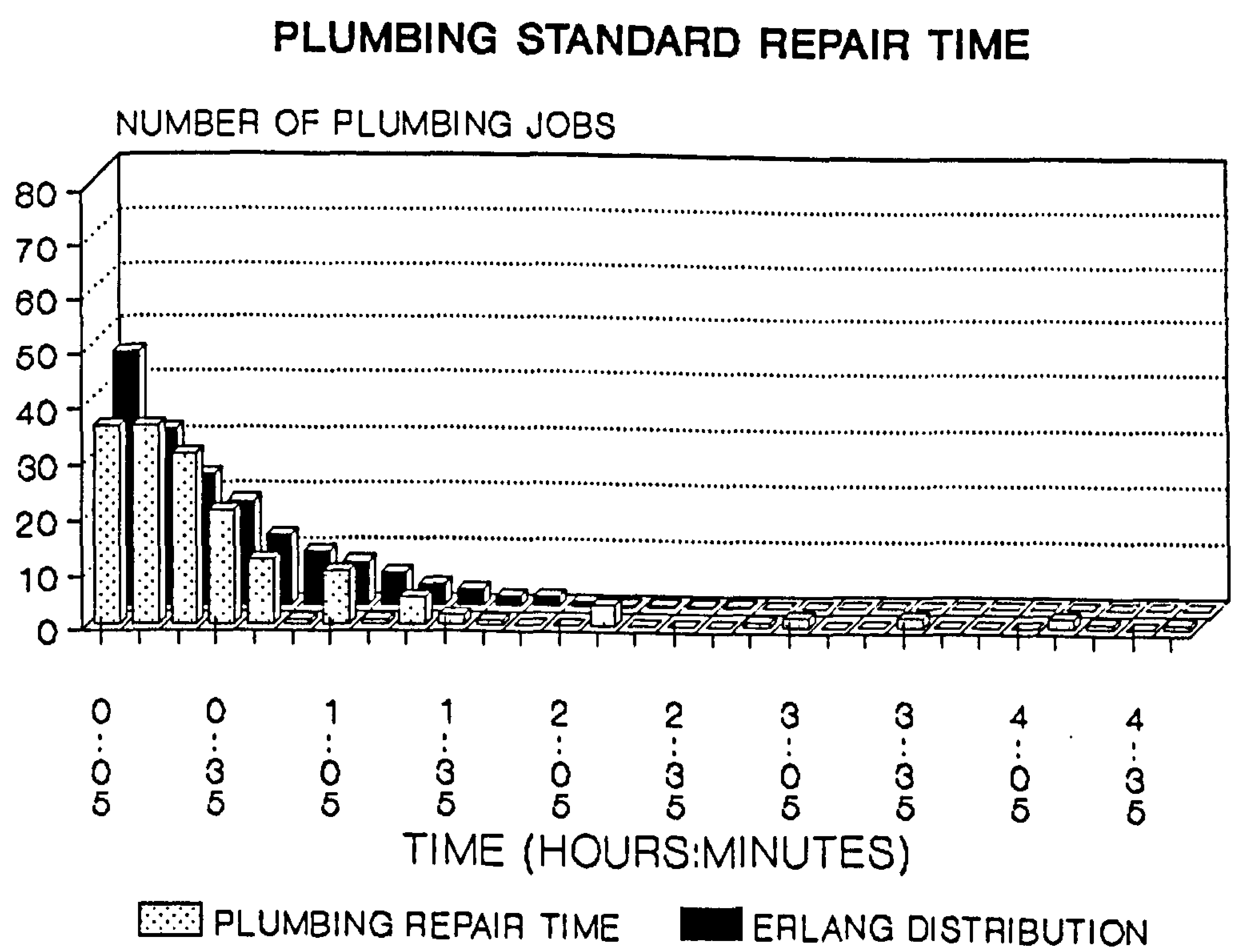


Figure 5.3: Observed and fitted Erlang distribution to the standard repair time of plumbing jobs.

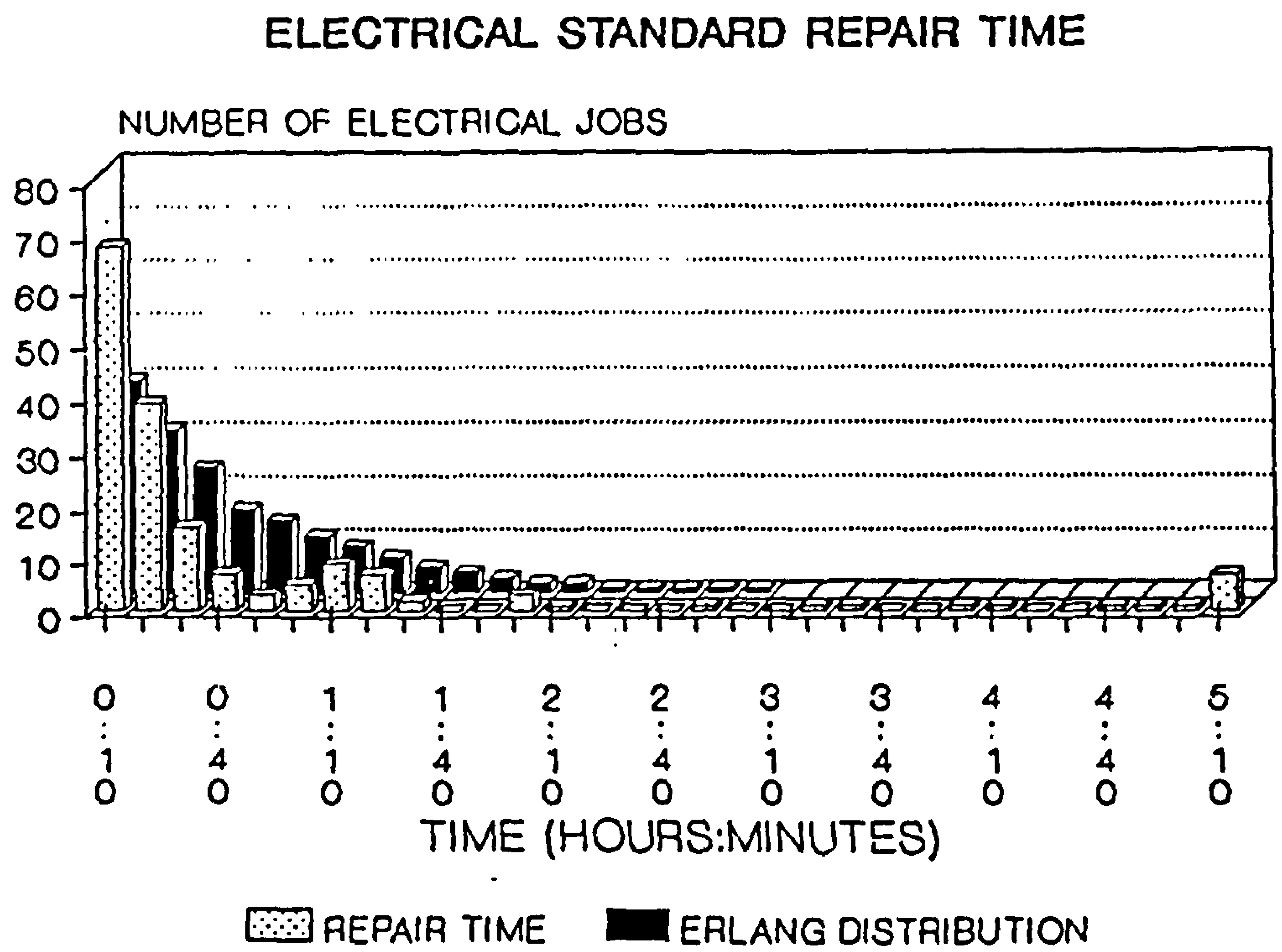


Figure 5.4: Observed and fitted Erlang distribution to the standard repair time of electrical jobs.

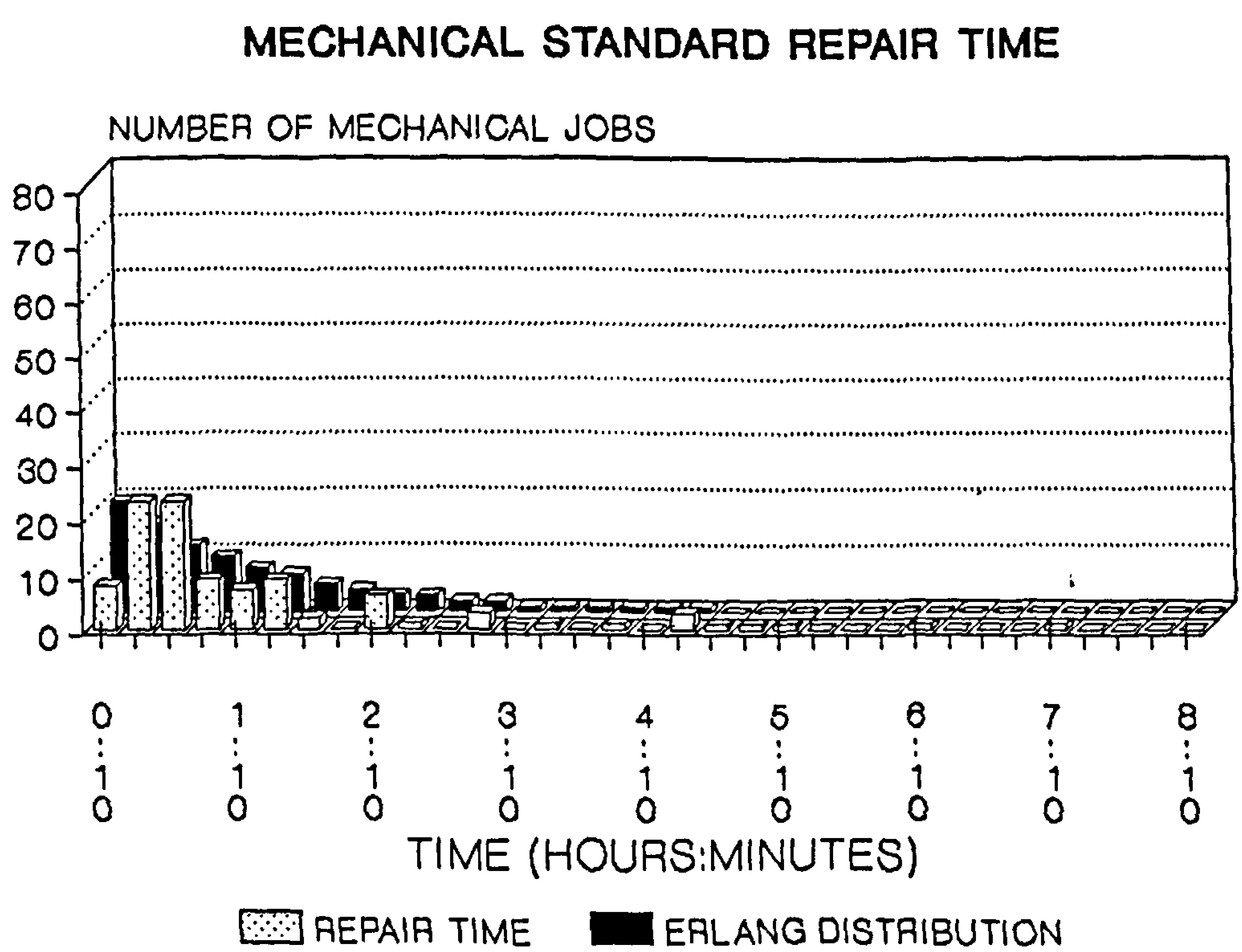


Figure 5.5: Observed and fitted Erlang distribution to the standard repair time of mechanical jobs.

for the four key trades, electrical, mechanical, plumbing and joinery.

The diagnosing time data was not available and has been subjectively estimated, as proportion of the repair time, through the experience of the maintenance management, see table 5.1.

Trades	% Diagnosing time	% Repair time
Electrical	50%	50%
Mechanical	30%	70%
Plumbing	20%	80%
Joinery	20%	80%

Table 5.1: Percentages of diagnosing and repairing time per trades, subjectively estimated by the maintenance manager.

Using the 'FIT' command which is available in ECSL software, Clementson (1990), the distribution of standard repair time, in the four key trades, has been fitted to a number of theoretical distributions available in the software library. The Erlang distribution was the only theoretical distribution considered likely to fit the repair time distribution by the ECSL software. The distribution of the standard repair time did not agree well with the theoretical distribution according to the Chi-square goodness of fit test. But according to Kolmogrov-Smirnov test, the joinery, plumbing and mechanical standard repair time did agree with the theoretical Erlang distribution, see table 5.2 for detailed test values.

Standard Repair Time	Joinery	Plumbing	Electrical	Mechanical
Observed				
Mean	40.56	40.0	48.87	78.17
Stdev	48.78	52.50	74.46	99.88
Fitted Erlang Distribution				
Mean	40.56	40.00	48.87	78.17
Stdev	53.59	52.51	74.68	82.88
Scale b>0	70.80	68.93	114.12	87.87
Shape c>0	0.572	0.580	0.428	0.889
Kolmogorov-Smirnov				
Value test	10.0	9.0	36.0	12.0
5% level	17.7	17.7	18.01	13.0
Hypothesis	not rejected	not rejected	rejected	not rejected
χ^2 goodness of fit				
Observed	18.62	19.55	61.19	24.30
Table value	14.07	14.07	15.51	14.07
	7 d.o.f.	7 d.o.f.	8 d.o.f.	7 d.o.f.
Hypothesis	rejected	rejected	rejected	rejected

Table 5.2: Fitting the Erlang distribution to the observed standard repair time per trade statistics, and testing the hypothesis of no difference between observed and fitted distributions per trade using Kolmogorov-Smirnov and Chi-square goodness of fit tests.

At this point we recall that the analysis of the recorded history data in section 3.3.1, had shown that there were inaccuracies in the recording of jobs, and the observed standard repair time is not the actual observed repair time but it is the estimated standard repair time. Further, in order to get a reliable Chi-square goodness of fit test for a continuous distribution, Kendall & Stuart (1979) have recommended that class intervals that are equal in probability rather than in width of interval should be used. This means that the Chi-square test as used here is less accurate than it should be for the continuous distributions. Therefore, it is not unreasonable to assume here that the Erlang distribution is representing the joinery plumbing and mechanical repair time, see figures 5.2 - 5.5. The Erlang distribution has the following probability density function:

$$f(x) = \frac{(x/b)^{c-1} \exp(-x/b)}{b[(c-1)!]}, \qquad 0 < x < +\infty ,$$

where $b>0$ is the scale parameter, and the shape parameter $c>0$ is an integer, the mean equals 'bc' and the variance equals 'b^2c', Hastings & Peacock (1975).

The standard electrical repair time, figure 5.4, does not agree with the fitted Erlang distribution in either goodness of fit tests. Therefore, the empirical distribution of the standard repair time has been used in the simulation. Table 5.4 shows the goodness of fit tests using Chi-square goodness of fit test and Kolmogorov-Smirnov test.

5.2.1.3. The distributions of sickness and holiday.

Data on sickness and holiday per tradesman, covering one year period from the 1st of March 1990 until the end of February 1991 has been collected. This data is not sufficient for studying the seasonal effects of the holidays and sickness during the months of the year which, it is felt, needs at least three years data to conduct a seasonality study.

In discussion with the management about the monthly holidays and sickness observations, the management's opinion was, after some data revision, that the data is reprsentative of the real life system and can be used to model these events in the simulation program.

(1) Holidays:

Rules of holidays:

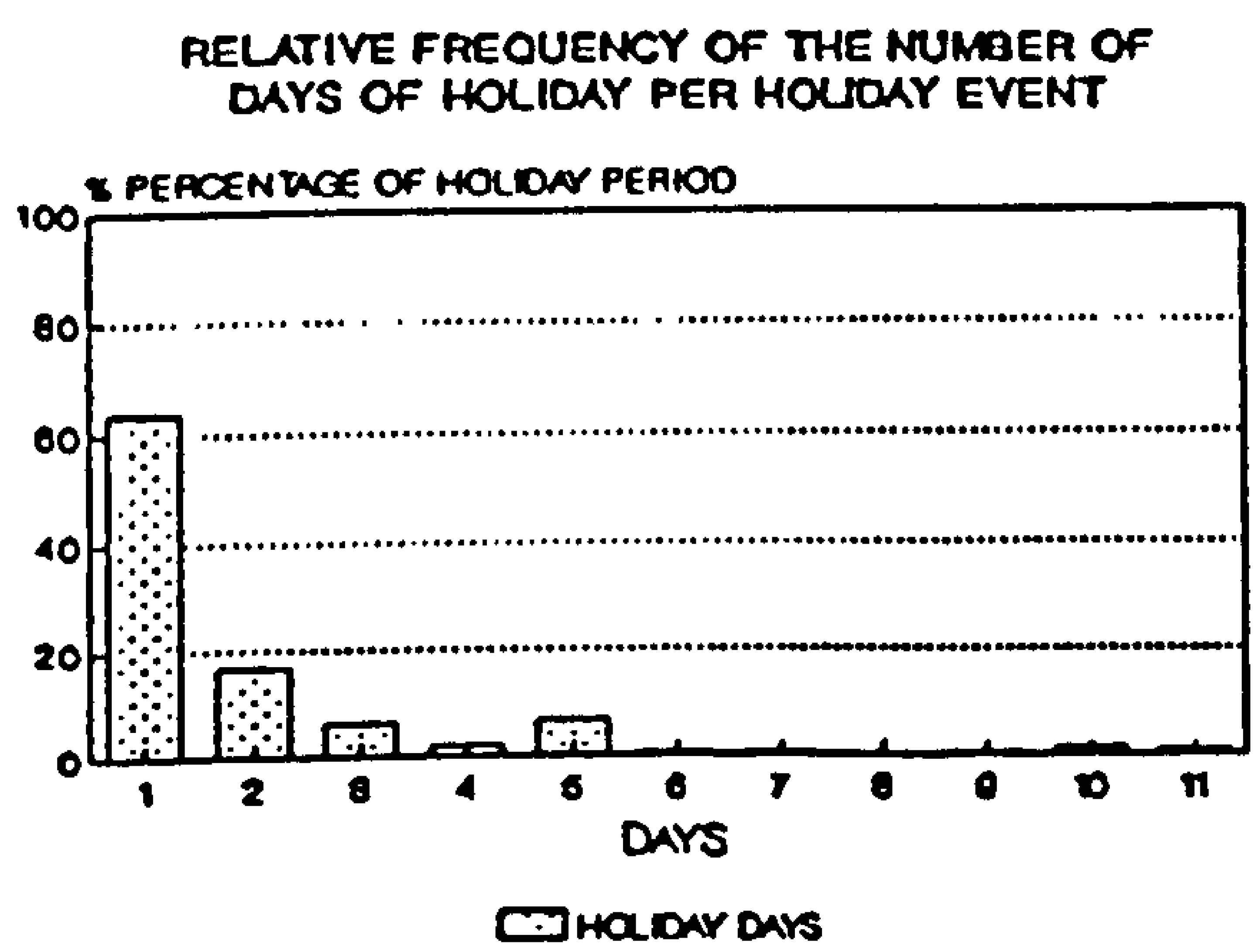
A. Each tradesman can get up to 23 days of holidays per year starting on the first of April, the begining of the financial year.

B. No more than half the holiday entitlement can be taken in the first half of the year.

C. Any remaining days of the worker's entitlement may be lost in the end of March, i.e. the end of the financial year.

The following are some of the observed notes about the holiday data of 31 tradesmen, supervisors, and tradesmen responsible for maintaining the laundry and the plant room planned preventive maintenance in the four key trades. The pooled average number of days of holiday per tradesman per month is shown in figure 5.6A, the relative frequency distribution of the number of days of holiday per holiday figure 5.6B:

-B-



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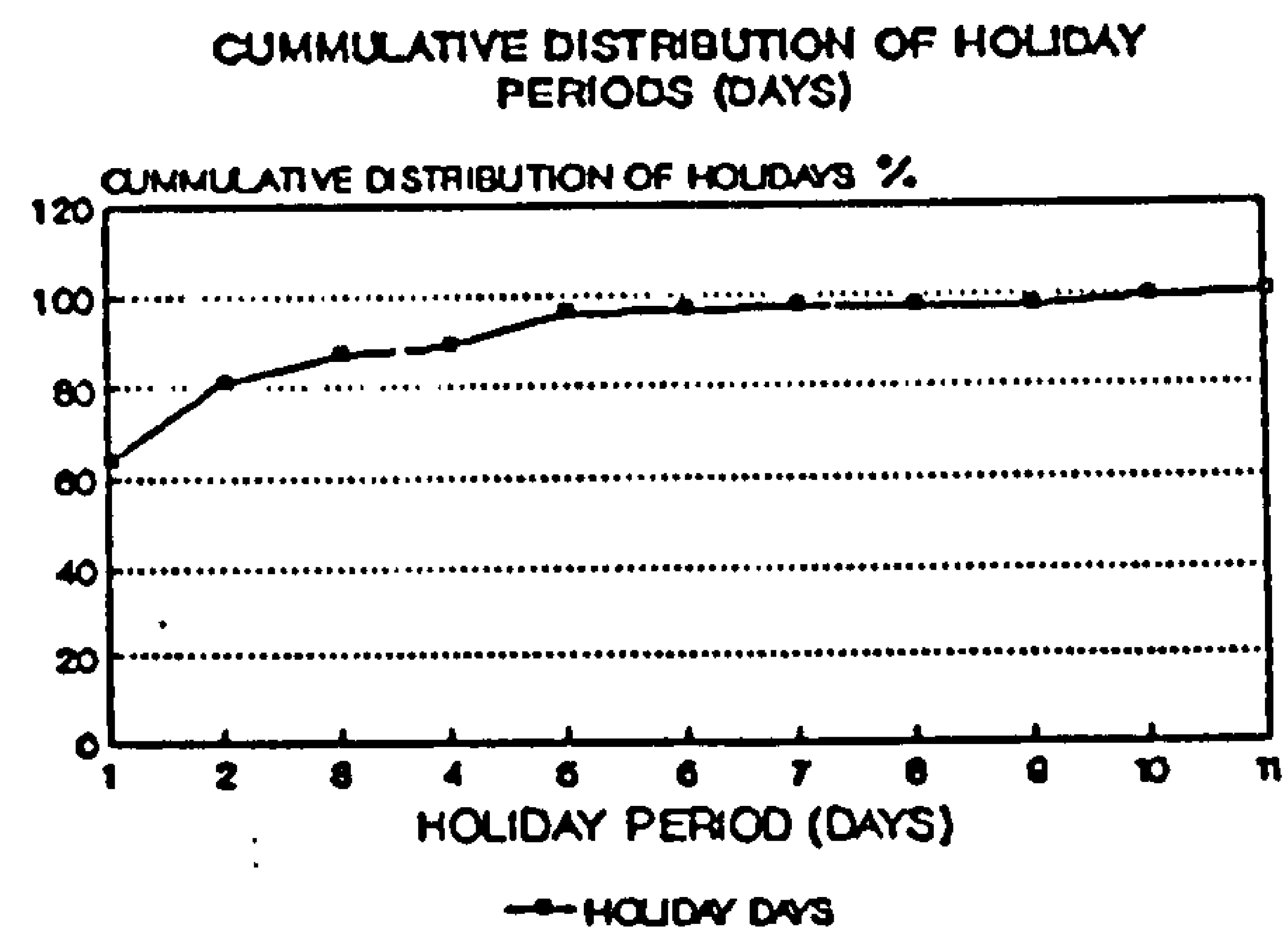

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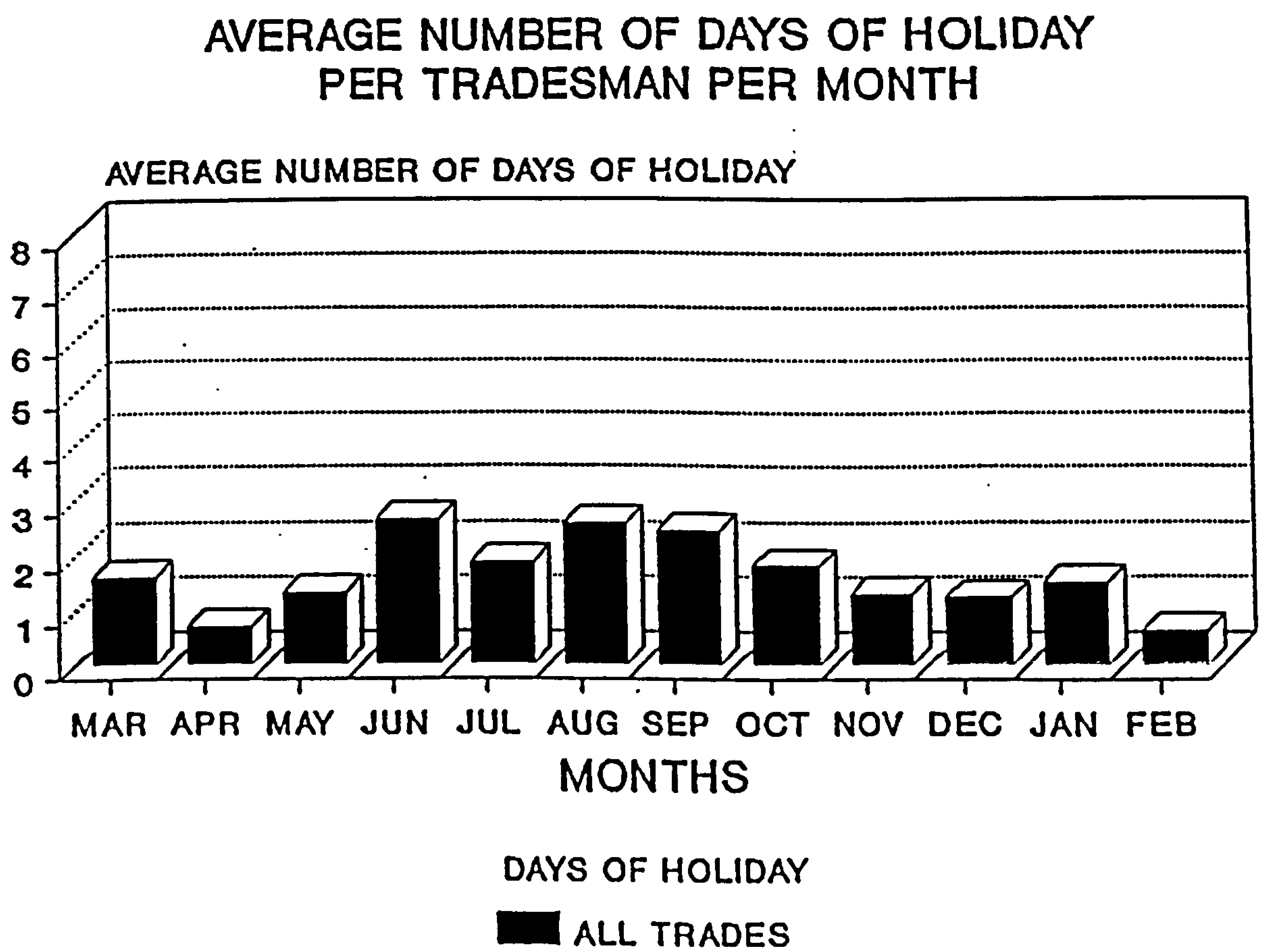


Figure 5.6: A: Average number of days of holidays per tradesman per month.
B: Relative frequencies of the number of days of holiday per holiday event per month.
C: Cumulative distribution of the relative frequencies of the number of days of holiday per event per month.

(a) Holidays are not trade related during the months of the year. Therefore, holidays of all trades are pooled into one histogram figure 5.6A, to get a better estimate to the average number of days of holidays per month.

(b) There is a jump in the average number of days of holiday during March, 1.9 days per tradesman, see figure 5.6A, compared to February and April. This is because March represents the last month of the financial year and any holiday entitlement can be lost in the following month, so that there is a tendency to get all the days of holidays that a tradesman is entitled to.

(c) The lowest level of holidays are during the months of February and April which is about 0.7 of a day per tradesman per month, figure 5.6A.

(d) The Summer and Autumn months June–October show higher holidays than the rest of the year which is about 2.14 days in average per person per month.

(c) There was no significant difference in the number of days of holiday during the months of the year. This is because most of the holidays were of a short period even during the Summer and Autumn months, namely, one or two days per holiday, with just fewer occasions that a tradesman takes longer holiday during the Summer season.

Therefore the cumulative distribution of the pooled frequency distribution of the holiday periods is used to represent the number of days of holiday.

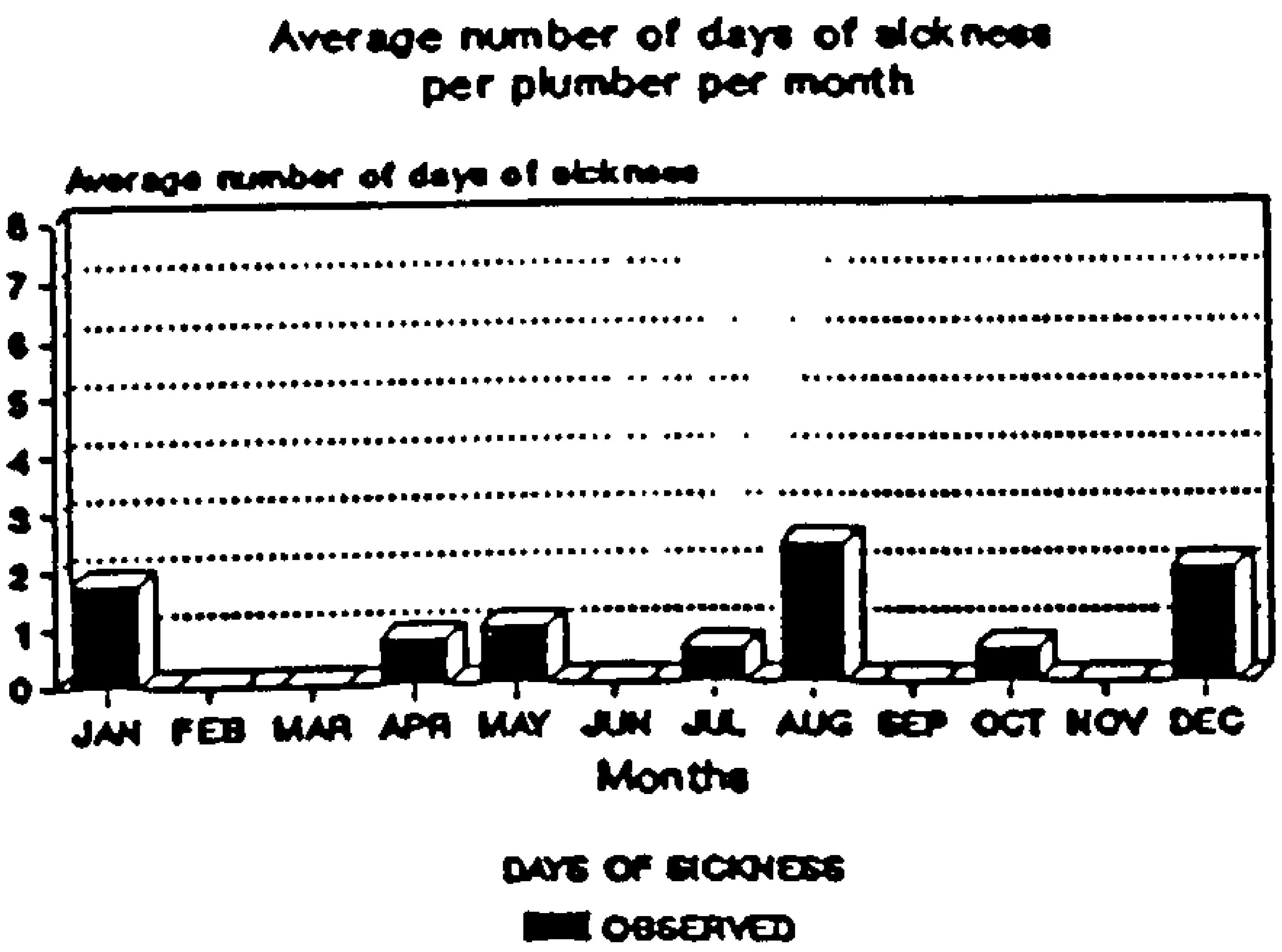
(2) Sickness

First, the analysis of the work or trade related injuries and of sickness data has shown that there was just one simple injury caused at work during the one year period from 1st of March 1990 until the end of february 1991, the rest of absences were considered health related problems, see figures 5.7 for the four key trades. But the average number of days of sickness observed per plumber or joiner, 0.76 and 0.89 day per tradesman per month respectively see figures 5.7A - 5.7B, was considerably less than in the average number of observed days of sickness per electrician and fitter, 2 and 2.5 days per tradesman per month respectively see figures 5.7C - 5.7D.

Further analysis the sickness data per electrician and fitter have shown that three tradesmen suffering from long term illness have caused a rise in the average number of days of sickness, specially during the months March - September for electricians, figure 5.7C, and July to January for the fitters, figure 5.7D. This matter has been discussed with the maintenance management, who suggested that a revised distribution of the average number of days of sickness per tradesman per month, which excludes the tradesmen with permanent illness may reasonably represent the real system, since the three ill tradesmen are retiring very soon during 1991.

Therefore, a pooled average number of days of sickness per month has been used as an input to the simulation model, figure 5.8A, since all the illness cases are not trade related and long term illness is excluded. The cumulative frequency distribution of the days of sickness, figure 5.8C, has been used to model the number of days of sickness leave per sickness event per tradesman per month.

-A-



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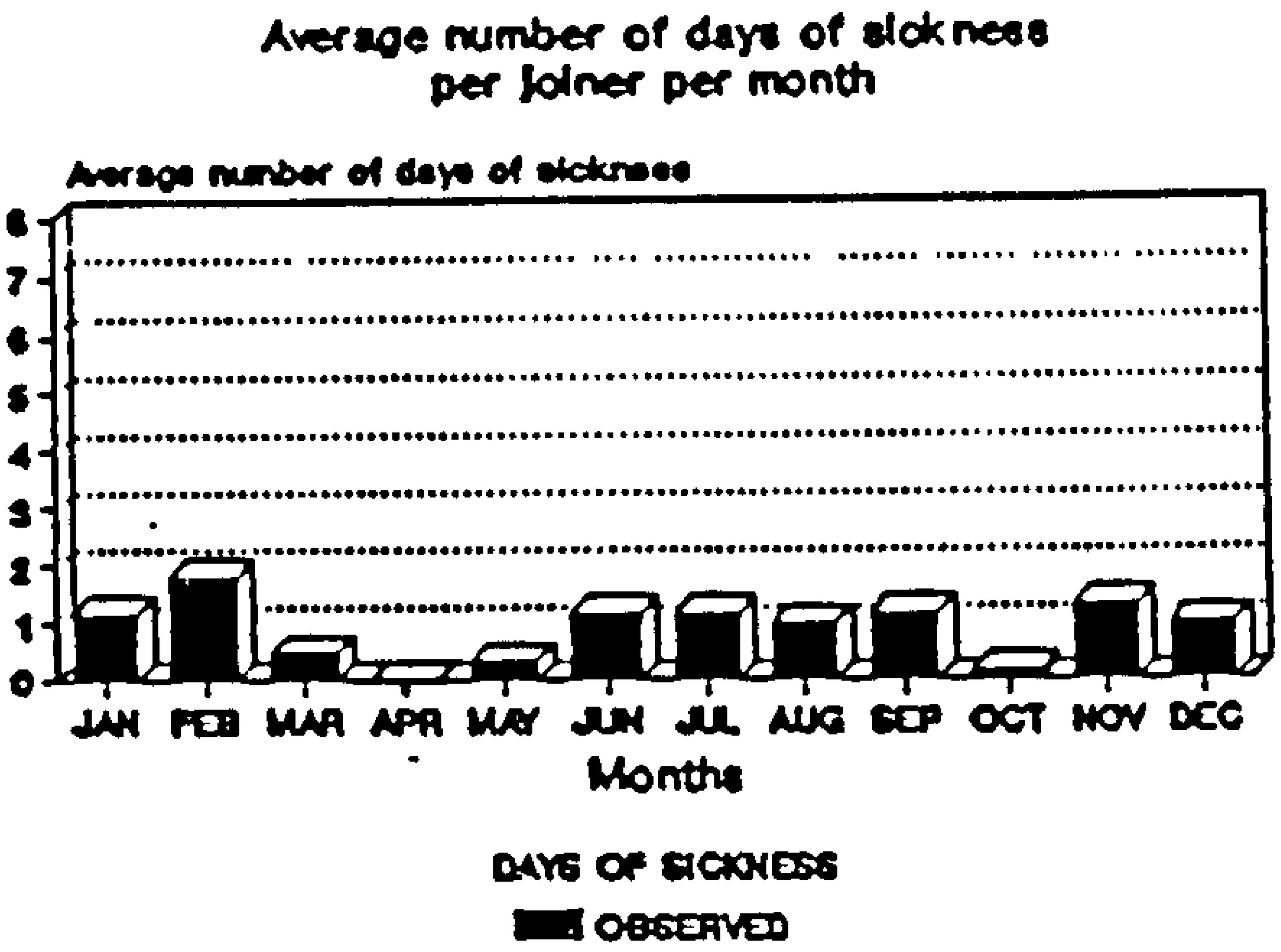

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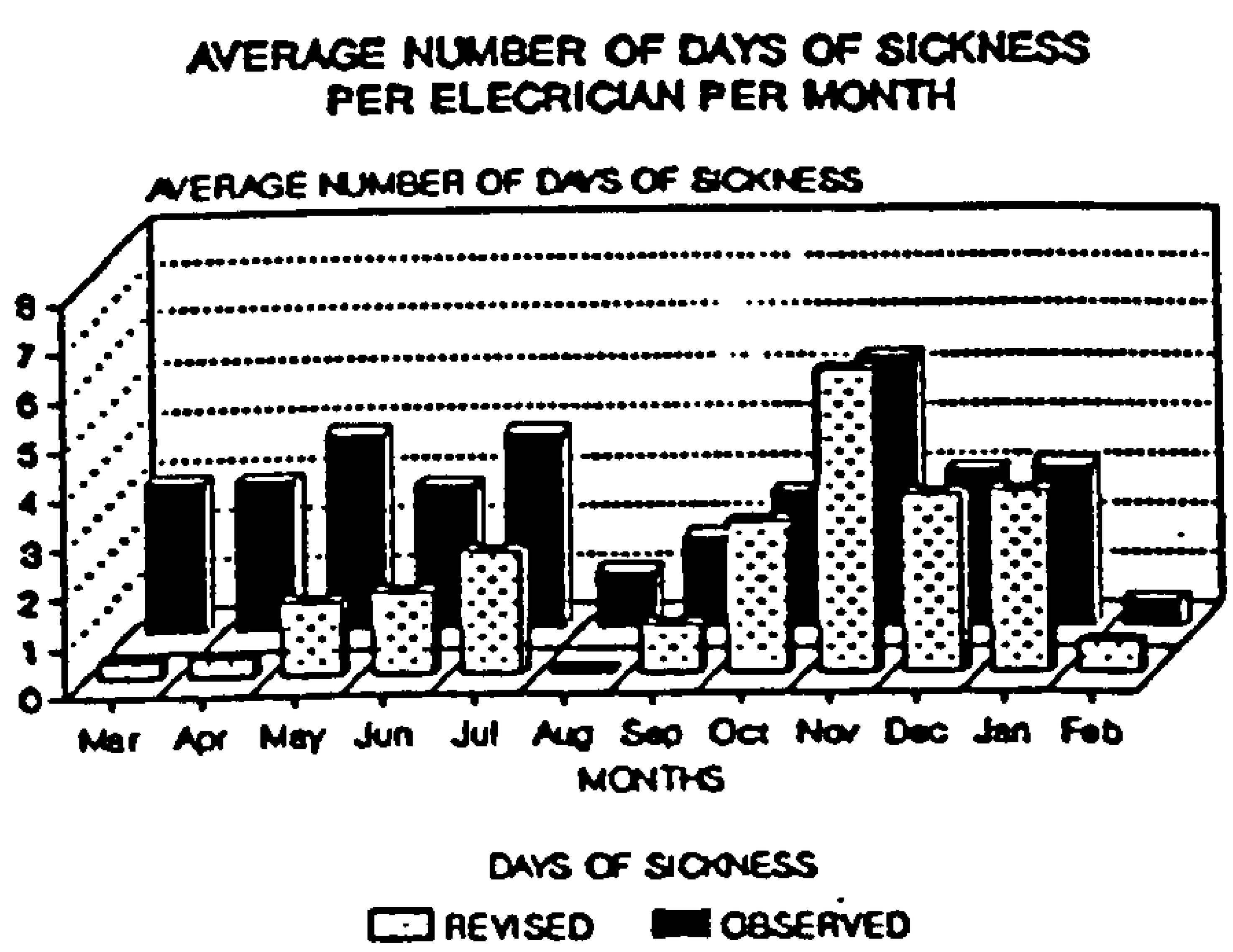

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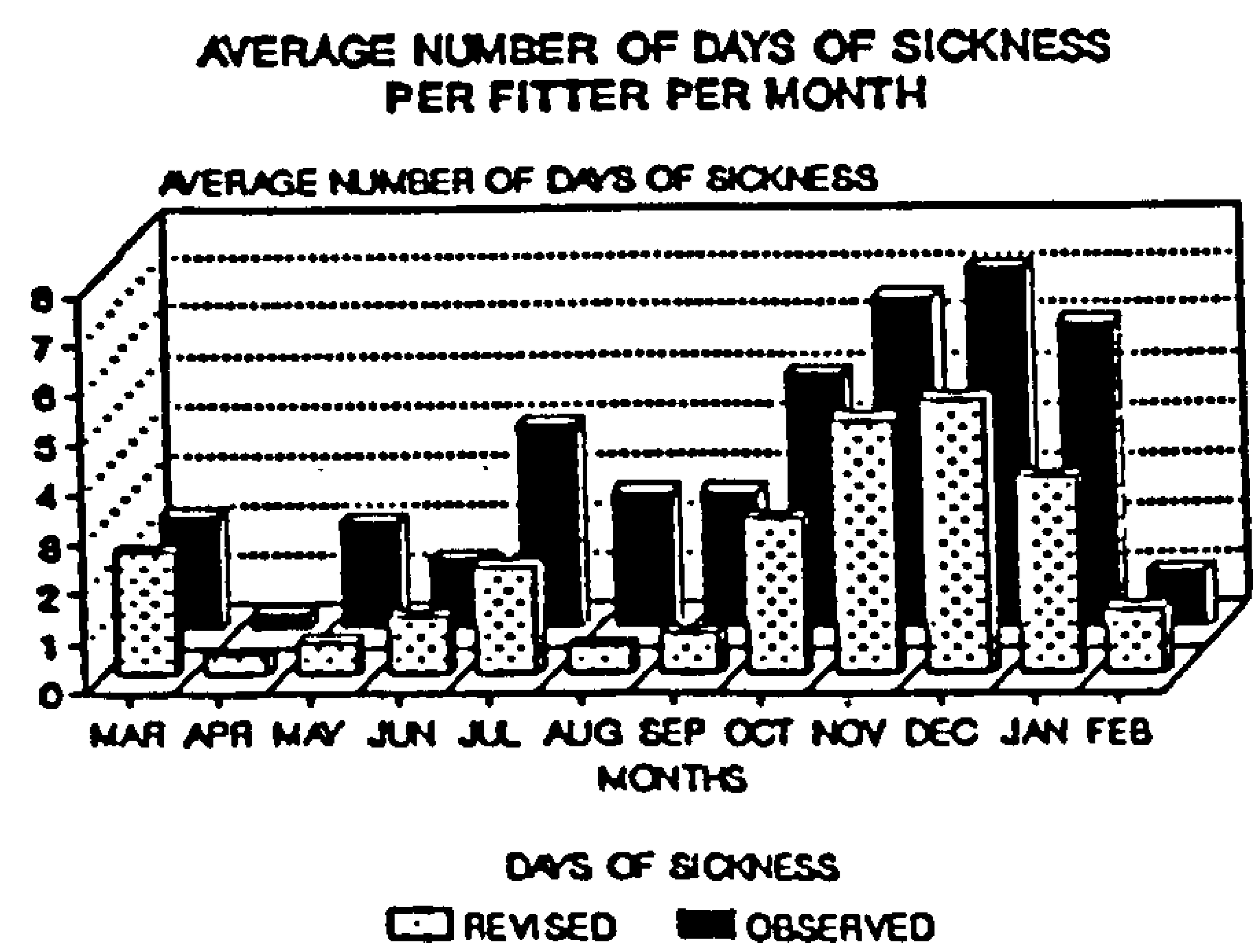


Figure 5.7: The observed average number of days of sickness per month per: A: Plumber. B: Joiner.
And the observed and the revised average number of days of sickness per month per: C: Electrician. D: Fitter.

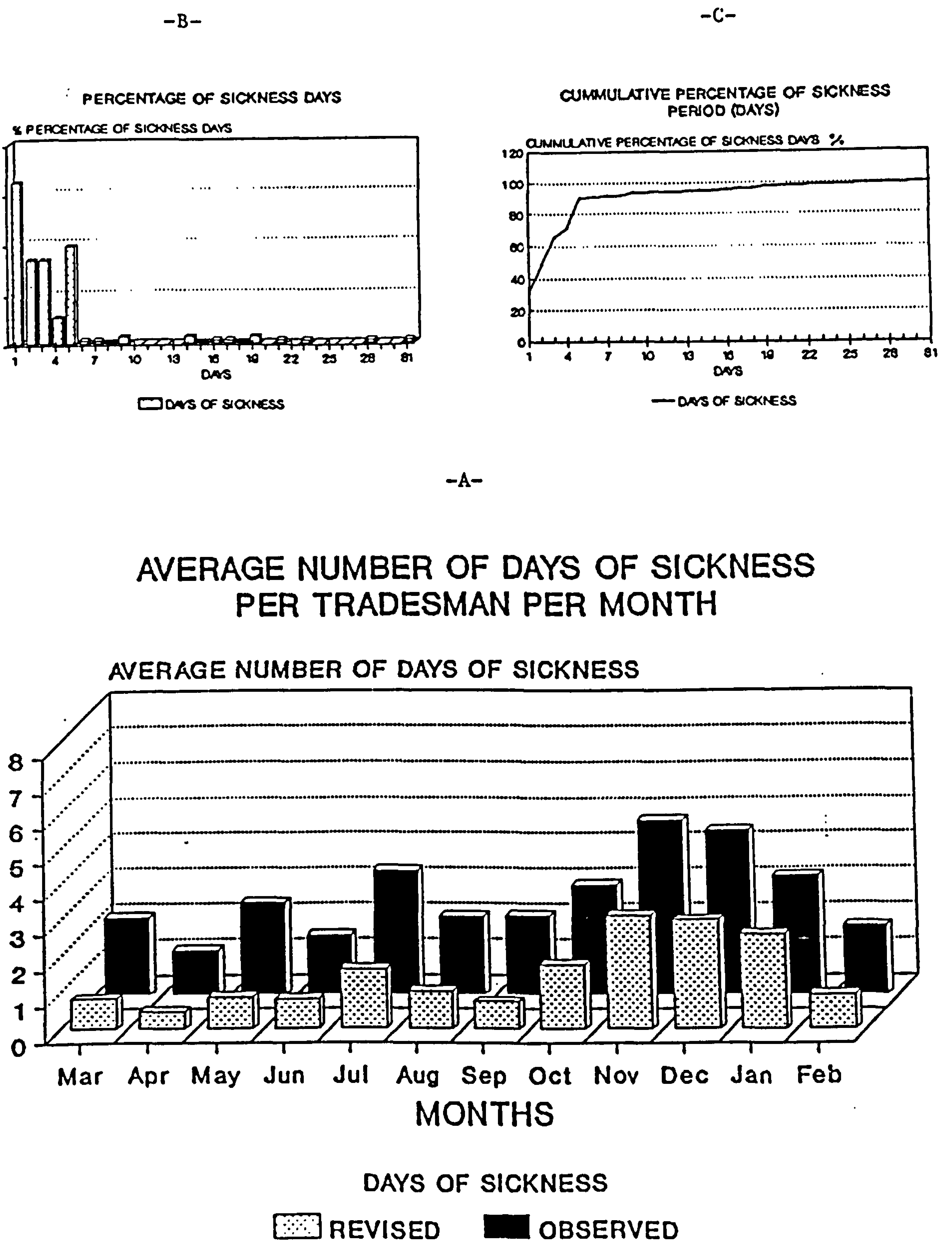


Figure 5.8: A: The pooled observed and revised average number of days of sickness per tradesman per month.
B: Relative frequencies of the number of days of sickness per event during one year period from 1st of March 1990 until the end of of February 1991.
C: The cumulative distribution of the relative frequencies of the number of days of sickness per event.

Another observation is that the average number of days of sickness rises, unusually, during the month of July, about 1.6 days per tradesman per month see figure 5.8A. The maintenance manager explains this observation due to a tendency of some tradesmen to expand their holiday by reporting a sickness leave after their holiday during the month of July.

To allow the simulation model to represent sickness and holiday as in real life, sickness and holiday are sampled in the simulation program on daily basis, in two stages:
First, sampling for the events of sickness and holidays taking into account the probability of sickness and holiday during the current simulated month of the year and the available number of tradesmen on the simulated day 'n'. The events were sampled from the Binomial distribution with the parameters, 'PS_i', the probability of sickness per day during the month i. These probabilities were estimated from the revised sickness events per tradesman per month i. 'PHi', the probability of holiday per day during the month i, are estimated from the number of event of holidays per tradesman per month i, where i=1,2,..,12. 'n' is the number of tradesmen available for work during the current simulated day. The probability function of the Binomial distribution is

$$P(x) = \binom{n}{x} p^x (1-p)^{n-x}, \quad 0 < x < n,$$

where $\binom{n}{x}$ is the binomial coefficient $n!/x!(n-x)!$

and p is either PSi or PHi.

The second stage is to sample the number of days of sickness or holiday for events sampled in the first stage. The sampling method was adopted the empirical distribution of the average number of days of sickness, figure 5.8C, and the empirical distribution of the average number of holiday, figures 5.6C.

5.2.2. Subjective input data

5.2.2.1. The distribution of travelling time between the maintenance department and job location.

The history data, discussed in section 3.3.1, has not included any data about the time spent in travelling between the maintenance department and the job location. This was traditionally calculated as a percentage of the standard repair time estimated by the planner–estimators. This percentage of travelling time was part of the allowance for travel, tea break and cleaning after finishing the job, which represents 26% of the repair time. It was felt that the percentage is unrealistic since there are a lot of jobs with very short standard repair time, i.e. less than 10 minutes such as changing a light bulb, which may, sometimes, need more than 20 minutes for travelling to and from the job location. The same can be considered for big jobs which may need little travelling time relative to the time spent on repair.

Therefore, since we were unable to collect objective data directly, subjective data was needed to estimate the travelling time. This was collected with the help of the supervisor who gave an estimate of the travelling time for each of the observed jobs in the day-to-day jobs data discussed in section 3.3.4, and shown in tables 3.6 –3.9, (Chapter 3).

The total travelling time distribution over the two months period of observation, figure 5.9, was influenced by the location of buildings within the hospital, buildings have different distances from the maintenance department and therefore a different average travelling time to the job locations (i.e. not trade dependent). The average travelling time therefore, is represented as discrete points according to location and distance.

No statistical distribution appears to fit to the travelling time, figure 5.9, and therefore a cumulative distribution of the observed relative frequencies is used for sampling the travelling time.

5.2.2.2. The expected time required to schedule and allocate the necessary resources and the requisition of spares.

Again no observed data was collected to estimate the time required by the supervisor to schedule and allocate the necessary resources for a job and the time required by the tradesman to request and collect spares from the stock. Therefore, a subjective estimate of two minutes has been given to the activity of scheduling and allocating the required resources, and five minutes has been given to the activity of collecting spares. These values have been subjectively estimated by the supervisor and have been used in the simulation of these activities.

5.2.2.3. The expected tradesman's time required to collect a job from the maintenance department.

The time required by a tradesman to collect a job from the planboard has been estimated subjectively, by the supervisor, to be around 2 minutes on

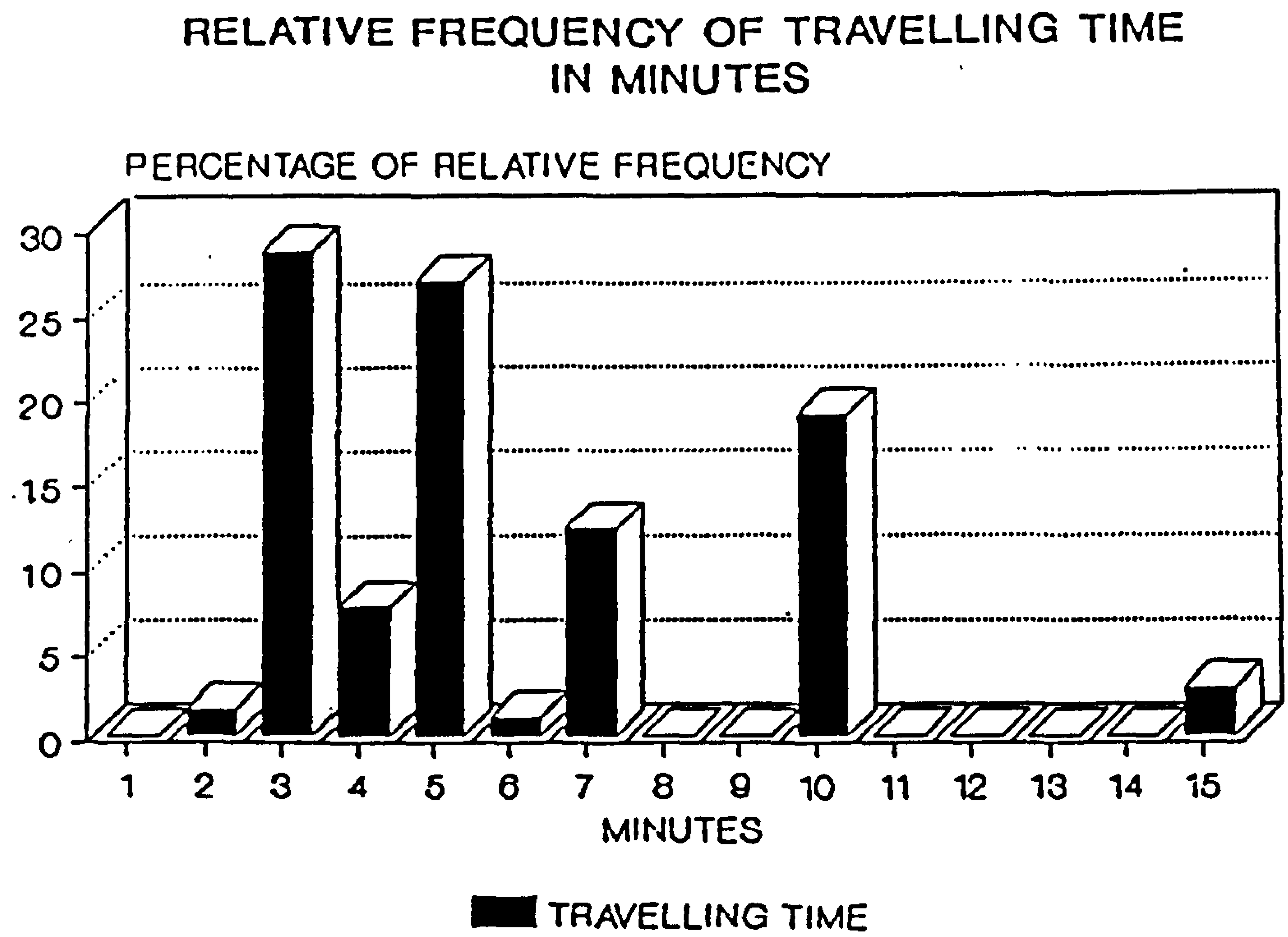


Figure 5.9: Relative frequency distribution of the travelling time from the maintenance department to the job location per job.

average and has been used as an input to the collecting jobs activity in the simulation model.

5.2.2.4. Percentage of emergency, urgent and non-urgent jobs by trades.

The summary of jobs per trade, figure 3.6 - 3.9 in the day-to-day jobs data has been shown to and discussed with the maintenance management and the supervisors as a basis to estimate the number of jobs which are to be considered an emergency, urgent and non-urgent job. The emergency jobs are those which have to be done immediately, urgent jobs which have to be done within 48 hours, and those jobs which can be delayed for more than that are considered to be non-urgent jobs. The percentages of these jobs per trade have been subjectively estimated by the maintenance manager, table 5.3, and used as an input to the simulation model.

	% PRIORITIES		
Trade	Emergency	Urgent	Not urgent
Electrical	5%	10%	85%
Mechanical	5%	10%	85%
Plumbing	8%	10%	82%
Joinery	1%	5%	94%

Table 5.3: Proportions of emergency , urgent, and not urgent jobs per trade, subjectively estimated by the maintenance manager.

Trades	% spares not available in stock	lead time of ordering spares
Electrical	25%	2 weeks
Mechanical	25%	2 weeks
Plumbing	10%	2 weeks
Joinery	15%	3-4 weeks

Table 5.4: Percentages of spares are not available in stock per trades and have to be ordered, and the average lead time, subjectively estimated by the maintenance manager.

5.2.2.5. Expected time spent attempting to gain access to a job location and the percentage of times tradesmen fail to gain access to the job locations has been estimated subjectively, by the maintenance management, to be around 2 minutes on average for each event.

5.2.2.6. Probability that a tradesman collects wrong spares.

In adopting a policy of depending on the opinion of the supervisor in itemising the required spares without previewing the defect before repair, there is a possibility that the wrong or incomplete spares are collected. The probability of a wrong judgement about the required spares was estimated subjectively by the supervisor, to be around 20% of all cases.

5.2.2.7. Probability that the required spares are not available in stock and have to be ordered and the lead time of ordering spare per trade has been subjectively estimated by the maintenance manager, table 5.4.

Chapter 6

HOSPITAL MAINTENANCE MANAGEMENT SIMULATION MODELLING

6.1. Introduction

In a major hospital complex, maintenance managers are confronted by a set of interacting problems associated with the maintenance management processes for which they have responsibility. These problems can be solved by setting appropriate values to decision variables such as, manpower requirement, method of deployment, mix of trades, and schedules for cyclic work.

Simulation modelling may be used to structure the maintenance management system in order to explore the consequences of suggestions and options to improve the maintenance services delivered to the hospital. To do this, maintenance managers need to have a broad-based model covering the set of interacting activities that make up their system; this form of modelling is called structural modelling, Finlay & Wilson (1987). Structural models give a methodology and provides a framework within which the consequences of proposed courses of action or proposed management policies might be analysed.

A modern hospital complex normally consists of a large number of building and engineering elements and equipments, which creates a demand for maintenance. Where these demands for maintenance must be met by a limited number of tradesmen, the downtime waiting for repair is sometimes associated with the safety of, or the inconvenience to, patients and staff. This waiting time might be reduced by increasing the number of tradesmen. The optimum number of tradesmen, necessary to meet the demand for, or the backlog of, maintenance can be found by minimizing a measure of the labour cost and the inconvenience to patients and staff, or by maximizing a measure of the efficiency of the maintenance operations within the overall context of the hospital. Such a measure is not easy to find and is avoided here by presenting consequences of maintenance action to aid management choice. Of chief interest is modelling the gang size problem under different operating circumstances.

Manpower or gang size problems arise in numerous forms. In structure, they often resemble the standard queueing situation in a store where interest is in the performance of various numbers of cash-out locations assuming both stochastic arrivals and service time. It is not surprising, therefore, that simulation tool is used frequently (Christer 1984). Several attempts have been made to develop a realistic model for solving the maintenance manpower requirements or (gang size). Cox (1970), Morse (1965), Vergin (1966) and Carruthers & MacGow & Hackemer (1970) have formulated some mathematical models based on queueing theory, Mann & Bostock (1982) have formulated a model based on the forecasting techniques, but these models are only valid under assumptions, which are seldom fulfiled in practice. Real life problems in this area are normally too complex for using analytical methods. However, many studies, such as, Poulsen (1984), Basker & Husband (1983), and

Duffuaa & Raouf (1992), have shown that the methods of simulating the maintenance work in order to assess the manpower requirements can be applied in much wider range of problems than analytical methods.

The simulation model of the maintenance activities at Withington hospital are based on a rather wide description of the relation between maintenance policies, maintenance activities, and the manpower requirements. Simulation models have been developed using "Extended Control and Simulation Language", ECSLPLUS, Clementson (1990), to model the maintenance activities and proposed maintenance management policies, assessing the manpower requirements, and any changes in operating procedures. The advantage of modelling is that the magnitude and nature of changes can be assessed and contemplated prior to any actual change in operating procedures. This is generally recognised as being most valuable.

The maintenance management policies have been simulated by developing three main simulation programs representing three methods of deployment, namely: "collecting one job at a time", "collecting a batch of jobs at a time", and "delaying non-urgent jobs and grouping them in time".. These simulation programs have a lot of features in common, but they are sufficiently different in the assumptions for the modelling of the maintenance management activities that these differences are stated sepcifically in each program.

Section 6.2 gives general description of the main simulation programs; section 6.3 deals with the first simulation program, "collecting one job at a time"; section 6.4 deals with the second simulation program, "collecting a batch of jobs at a time"; section 6.5. deals with the third simulation program, "delaying non-urgent jobs and grouping them in time".

Each simulation program is capable, through some changes, to simulate the maintenance management policies described in section 6.6, for the four key trades, namely: 'previewing' and 'not previewing' a defect before repair; 'employing part-time tradesmen' during peak days (Mondays and Tuesdays); 'working seven days a week instead of five days a week'; 'no sickness model'; and 'employing a multi-skill tradesmen policy'.

6.1.1. ECSLPLUS simulation software

Extended Control and Simulation Language, ECSLPLUS (Clementson 1990), is a popular British simulation language, was developed by Clementson as an extension to CSL (Buxton and Laski 1962), which was produced by Esso in 1960. Both versions apply the simple activity scan approach. New 'PC eduction version' have been introduced in 1989 by Clementson, refined in 1990, and in 1992. This version is more powerful than the old mainframe version. It is capable of simulating a complex model which consists of up to 100 activities, whereas the old version was capable of simulating a problem consists of up to 33 activities. A 'Computer Aided Programming System' CAPS (Clementson 1990) is also available which automatically generates ECSL code from a basic model specification which the user supplies to the system interrogatively. However, ECSL is slow in execution, because of the use of the interpreter (Pidd 1988). CAPS can, sometimes, produce unexecutable programs due to logic error, and the documentations are not user friendly and not well organized to allow quick and easy access to all that the ECSL language can offer in programming a complex problem.

6.2. General description of the simulation models

Simulation is a technique which involves setting up a model of an existing or new system and conducting experiments on the model rather than on the real system itself. So that the effects of new maintenance policies, decision rules, and variables can be studied before running the risk of operating on the real system. Simulation can involve many types of mathematical and logical models which describe the behaviour, over extended period of real time, of the maintenance management simulation model.

The technique used here is to consider the maintenance activities at Withington hospital over a period of time, known as 'the simulation run length', which is a *working day*, Mondays–Thursdays equivalent to 420 minutes in total of working time excluding lunch and tea breaks, and 360 minutes during Fridays and Satudays; no maintenance activities are considered on Sundays. The model runs, as a batch system, on a daily basis taking into account the job arrivals rates per trade during the days of the week, and the seasonal changes of absenteeism (sickness and holidays) on a monthly basis.
The simulation program runs for a period of one calendar year, employing different number of tradesmen per trade, 1, 2,.., n, in a number of simulation runs, with the exception of Saturdays when just one tradesman per trade is working to deal with emergency jobs. This has been accomplished by feeding rules and information to the simulation program about the number of days per week and per month, and the number of months per calendar year.

6.2.1. The activity cycle diagram

The activity cycle diagrams, figures 6.2, 6.4, 6.6, were popularized by Hills (1971), are used in the formulation phase of the discrete-event simulation modelling. They provide a simple and powerful method of setting down a systematic outline of a simulation model, Clementson (1990). This helps in the formulation and in the attempt to understand the system under study, helps in building a computerised version of the model, and helps in model validation and discussion with management about the system. Therefore the activity cycle diagram is an excellent means of communication between the various people such as, managers, model builder and programmer, and all involved in the simulation project.

In order to build a model suitable to discrete-event simulation, it is necessary to identify the important classes of entities; consider the activities in which the entities engage; and link these activities together, Pidd (1988).
The simulation models of the maintenance activities at Withington hospital are composed of various classes of entities such as, tradesmen, jobs, supervisors, and secretary. These are the elements of the system being simulated and can be individually identified and processed. These entities interact through simulated time.
The activity cycle diagrams are one way of modelling the interactions of the entities and are particularly useful for systems with a strong queueing structure, Pidd (1988). In most cases they cannot include the full complexity of the system being simulated, but they do provide a skeleton which can be enhanced later.

The activity cycle diagram itself, figures 6.2, 6.4, 6.6, is a map which shows the life history of each entity and displays graphically their interactions. Each class of entity is considered to have a life cycle which consists of a series of states. The entities move from state to state as their life proceeds.
An *active state* (activity) usually involves the co-operation of different classes of entity. The duration of an active state can always be determined in advance, usually by taking a sample from an appropriate probability or empirical distribution if the simulation model is stochastic.

On the other hand, ***a dead state*** (queue) involves no co-operation between different classes of entity and is generally a state in which the entity waits for something to happen. Dead states are often thought of as queues, therefore, the length of time that an entity spend in a queue cannot be determined in advance.

Drawing the activity cycle diagram of the maintenance activities at Withington hospital, figures 6.2, 6.4, 6.6, involve listing the states through which each class of entity passes, and normally these are drawn as alternate dead (queue) and active (activity) states. The activities are represented by rectangles, and queues by rounded rectangles, inside which is written an abbreviated name of the active or dead state. The states are connected by arrows to show the valid sequences in which state can occur. Queues and arrows are drawn in different colours for each entity type such as, jobs are red, tradesmen are blue, the supervisor is green, and the secretary is magenta, figures 6.2, 6.4, 6.6. Activities are drawn in a neutral colour usually black. The complete diagram consists of a combination of all the individual life cycles of entities.

6.3. Collecting one job at a time simulation model

The main rule of this method of deployment presented in a simulation program is that the tradesman of any trade collects one job at a time from the plan board and undertakes all the necessay activities to complete the repair of the job. When the tradesman completes the repair, he is considered free, then another job is collected until the end of the simulation run length time of a day is reached. This one day module program is used as a base model in assessing any changes in the method of deployment of jobs to tradesmen such as 'collecting a batch of jobs' instead of 'collecting one job at a time', and 'delaying non-urgent jobs and grouping them in time', in order to estimate the gains and consequences of different procedures.

6.3.1. Characteristics of the simulation models

Kerckhoffs & Vansteenkiste (1986) stated:

> *"translating human knowledge about reality into a simulation model is the facinating attempt to compress an analogous world into a formal system".*

The development of simulation models has shown that discrete-event simulation is a very useful tool for modelling problems of very complex nature in a rather realistic fashion.

The main characteristics of this simulation model are:

(1) The simulation model is representing the maintenance activities on daily basis for one year period, starting from 8.30am until 4.30pm during Mondays-Thursdays, and until 3.30pm during Fridays and Saturdays. A minute represents the unit time of the simulation run. So that the simulation program of one year period is detailed but slow.

(2) The simulation program identifies the day of the week and the month of the year in every day of the simulation runs. This is necessary to enable the simulation program to sample it's input from the appropriate distributions of interarrival time per day, and the monthly distributions of sickness and holiday.

(3) The simulation program allocates the number of tradesmen every day. This has been programmed by calculating the number of tradesmen who

are expected to be available for work in the current simulated day, which equals the total number of tradesmen per trade per day minus those who are previously known to be sick or on holiday leave. The program then samples the number of tradesmen who become sick, and the number of tradesmen starting a holiday for the current simulated day, taking into consideration the holiday rules mentioned in section 5.2.1.3. If these rules permit a holiday event, then a period of holiday is sampled, and the number of days of the holiday period is saved in the program for further calculation in the coming simulated days.

(4) The simulation program has a fresh start in every simulated day, i.e. it is clearing the contents of the counters and queues in the end of every working day and transfers the remaining jobs to the planboard queue, sorts them out for new start in the morning of the next simulated working day. Started but incomplete jobs from the previous day become first priority jobs.

(5) The simulation model samples the job arrivals from infinite source of jobs per trade, assuming one secretary to receive the incoming jobs. It also assumes one engineering supervisor and one building supervisor for scheduling jobs.

(6) The simulation program has imitated the real system behaviour of the emergency jobs. In practice the emergency jobs is transfered immediately by the secretary to the supervisor to take action. The supervisor's first priority is to look for an appropriate and free tradesman to do the emergency job, or looks for appropriate tradesman in the maintenance department busy in collecting jobs, requesting or collecting spares. If all

the tradesmen are engaged in repair activities, then the supervisor will interrupt another, less urgent job in order to repair the emergency job. In the simulation model, the first priority is to find free tradesman to do the emergency job. If all the tradesmen are engaged in other activities then the model will interrupt activities that are performed in the maintenance department such as, collecting jobs from the planboard, and requesting and collecting spares. If the model fails to find a tradesman then the model will interrupt diagnosing and repairing activities, since the job location is known to the supervisor. The last option is to interrupt travelling activities since it is difficult to interrupt a tradesman walking around the corridors of the hospital. When the tradesman finishes repairing the emergency job, he returns back to the interrupted job.

(7) In every stage of the simulation, the program checks the remaining time of the simulation run. If the remaining time is less than 15 minutes and does not allow the job to be finished in the simulated day, then it will be retained to the next simulated working day. If the job is in progress and there is little overtime needed to perform the repair, less than 15 minutes, then the job will be considered finished and the overtime is calculated.

(8) The simulation program can trace every job from it's arrival until its departure, i.e. until completing the repair, in order to calculate the service time, no matter how long ago a job arrival was, i.e. the program memorizes the details of time and date of the job arrivals and completions.

6.3.2. Sections, steps and flow chart of the simulation program

A simulation program written in ECSL normally have five to seven sections, Clementson (1990), Pidd (1988), as shown in figure 6.1. Each section is made up of a large number of different ECSL blocks. Each block has a special meaning and represents several program routines.

These sections are as follows:

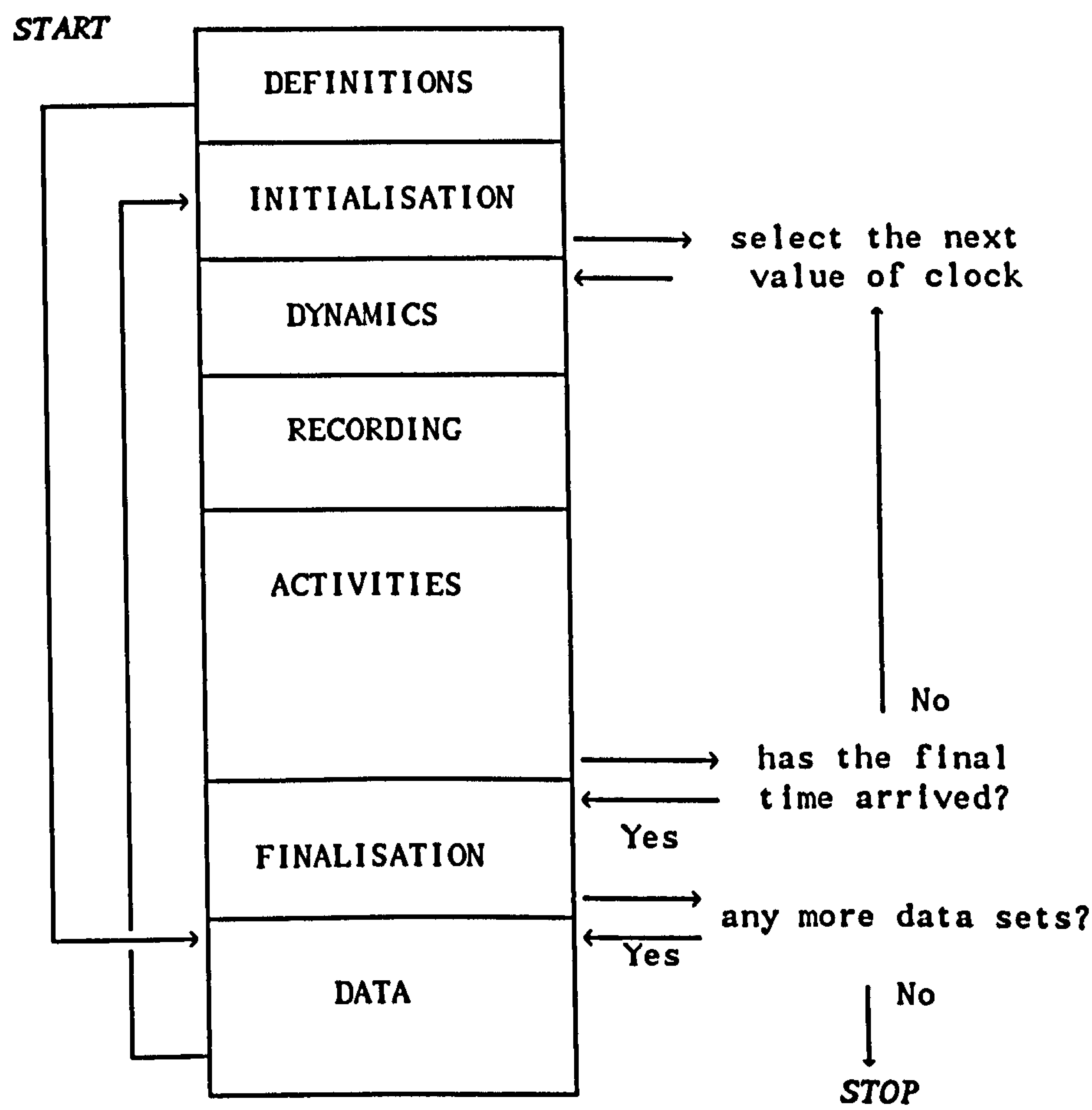


Figure 6.1: The sections of an ECSL program.

(a) *Definitions:* Establishing the entities and the sets (queues) of which each class of entities may be members. The definition section may also be used to establish any histograms or special variables required.

(b) *Initialisation:* Setting up the initial state of the specific entities. These are statements written in normal syntax of ECSL.

(c) *Dynamic and Recording:* The dynamic block is only used if it is necessary to represent some continuous processes; and recording is only used if an intermediate result is required.

(d) *Activities:* This is the main body of the program. Each activity is regarded as a completely independent block of ECSL code. The structure of an ECSL activity consists of a test and an action blocks. If the conditions within the simulation are such that the activity may not take place, control passes to the next activity in schedule; otherwise the action works by keeping the entities engaged in the activity for the (sampled) duration of the activity.

(e) *Finalisation:* Used to produce the final report of the performance of the simulation. Entered only after the simulation "run length time" is complete.

(f) *Data:* Establishes initial values of some of the variables in conjunction with the initialisation section.

The overall structure of the simulation model is shown in the activity cycle diagram produced by ECSLPLUS software, see figures 6.2 for the one job at a time simulation. This diagram is not user friendly, because of the limited number of characters given to the activities and queues names, which

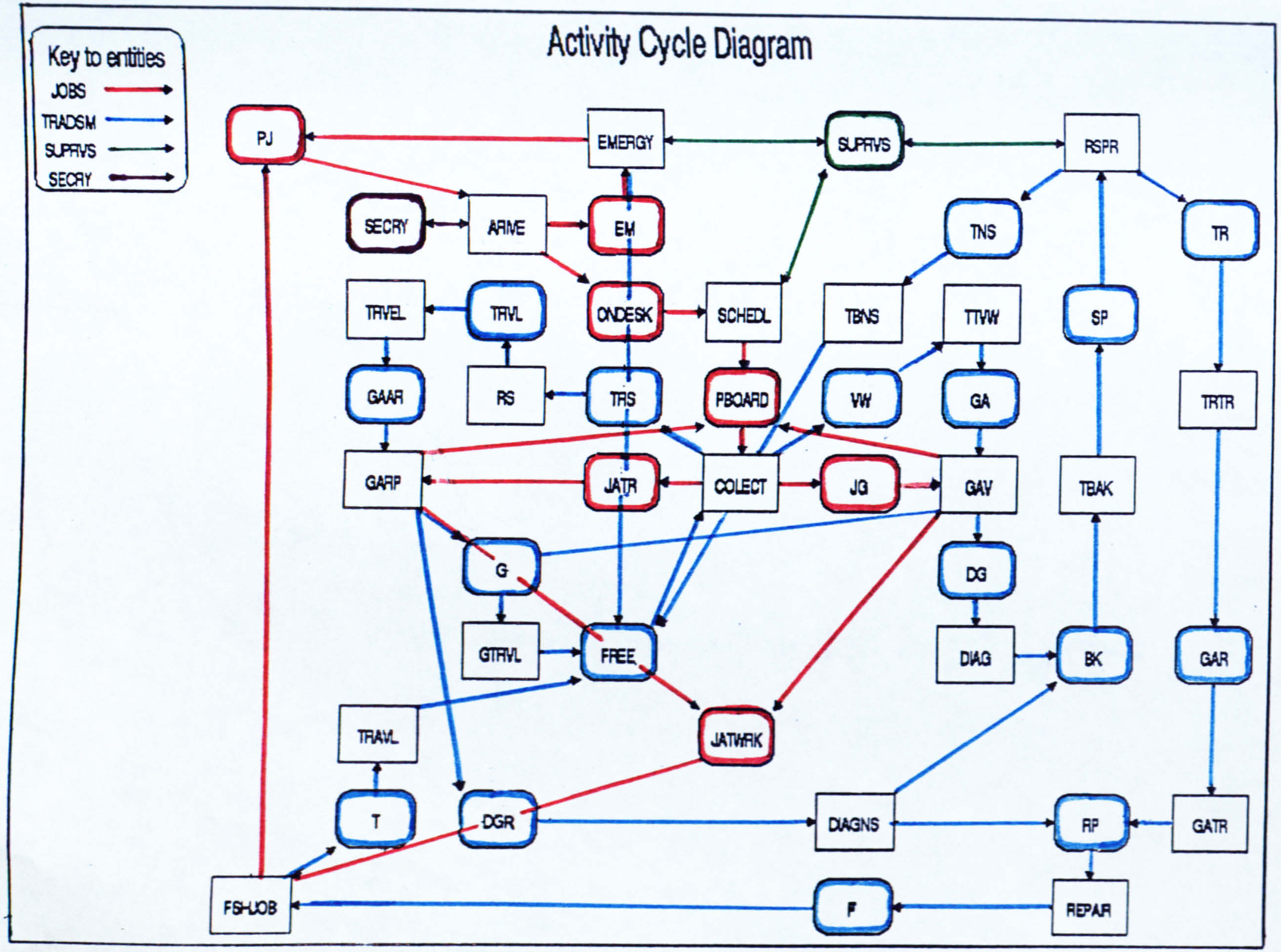


Figure 6.2: Activity cycle diagram for 'collecting one job at a time' simulation model.

necessitates the use of abbreviated names, as well as the fact that branching conditions are not stated on the diagram. Therefore the simulation program is illustrated by a flow chart in figure 6.3.

Sections and steps of the simulation program flow chart, see figure 6.3, are as follows:

a. Definitions:

Step 1: The program starts by defining the following:

Entities: Defines entities and the number of entities involved in the simulation, these are: jobs (JOBS), tradesmen (TRADSM), supervisor (SUPRVS) and secretary (SECRY);

Queues: Defines queues for each of the above entities, a list of queues is given in the list of abbreviations.

Histograms: Defines histograms of the number of days of sickness and of holiday per event; Travelling time histogram; priority levels histogram; and repair time of electrical jobs histogram.

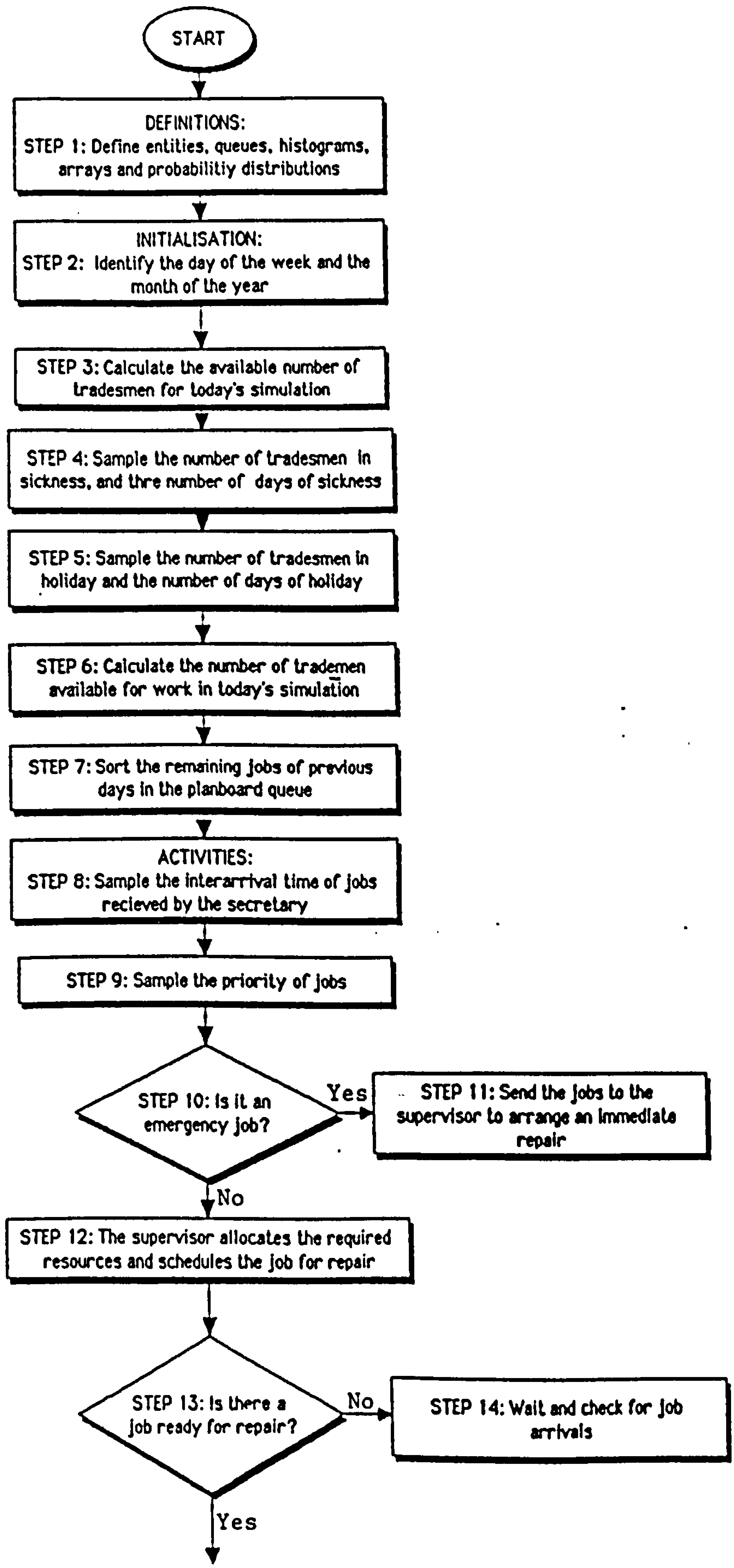
Arrays: Probabilities of sickness and of holiday events per month arrays; Number of days of sickness and of holiday per tradesman arrays.

Probability distributions: Negative exponential distribution; Binomial distibution; and Erlang distribution.

b. Initialisation:

Step 2: The program identifies the current simulated day of the week and the month of the year.

Step 3: The simulation program calculates the number of tradesmen per trade who are expected to be available for work in the begining of each working day.


START
DEFINITIONS:
STEP 1: Define entities, queues, histograms, arrays and probabilitiy distributions
INITIALISATION:
STEP 2: Identify the day of the week and the month of the year
STEP 3: Calculate the available number of tradesmen for today's simulation
STEP 4: Sample the number of tradesmen in sickness, and thre number of days of sickness
STEP 5: Sample the number of tradesmen in holiday and the number of days of holiday
STEP 6: Calculate the number of trademen available for work in today's simulation
STEP 7: Sort the remaining jobs of previous days in the planboard queue
ACTIVITIES:
STEP 8: Sample the interarrival time of jobs recieved by the secretary
STEP 9: Sample the priority of jobs
STEP 10: Is it an emergency job?
Yes
STEP 11: Send the jobs to the supervisor to arrange an immediate repair
No
STEP 12: The supervisor allocates the required resources and schedules the job for repair
STEP 13: Is there a job ready for repair?
No
STEP 14: Wait and check for job arrivals
Yes

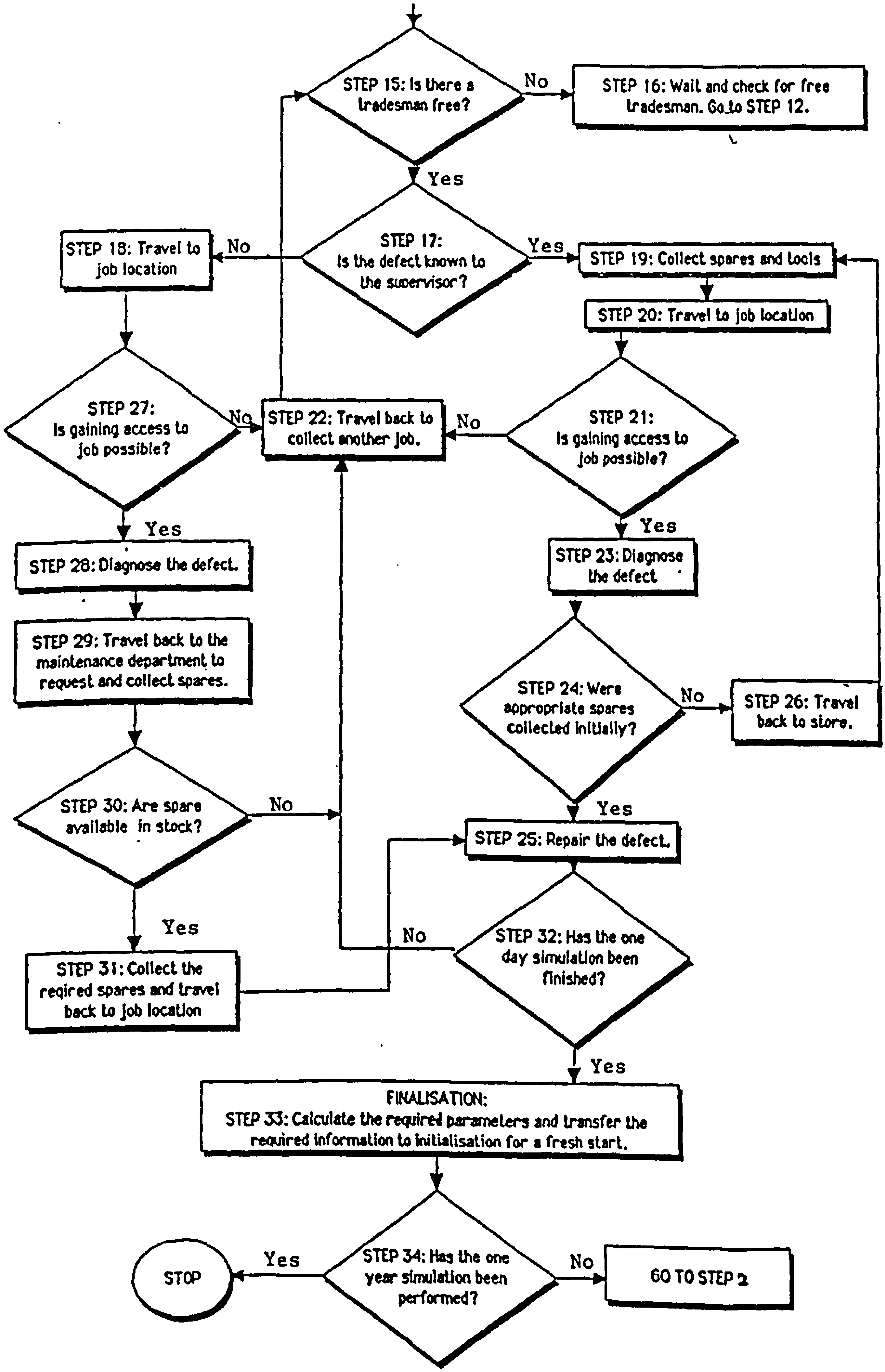


Figure 6.3: Flow chart for 'collecting one job at a time' simulation program.

Step 4: Sample the number of tradesmen who report their sickness in the morning of the simulated day, from a binomial distribution, and sample the period of their sickness from an empirical distribution.

Step 5: Taking steps 3 - 4 into account, sample the number of tradesmen who are enjoying their holiday starting from today, (from a binomial distribution) taking into account the rules of holiday mentioned in section 5.3.1.3, and then sample the number of days of any permitted holiday from an empirical distribution. The number of days of sickness and the number of days of holiday per tradesman are used in calculating the number of tradesmen available on the following days.

Step 6: Calculate the number of tradesmen who are actually available for work on a day by taking into account the previous and current sickness and holidays, i.e. steps 3 - 5.

Step 7: Sort the jobs waiting from previous days according to their priority and sequence which is determined by their arrival time and date, i.e. first in first out for each priority level. Order these jobs to be collected by tradesmen in the planboard queue.

c. *Activities:*

Step 8: Sample the interarrival time of jobs, by using the current simulated day parameters of interarrival distribution, which is an exponential distribution. Jobs are received by the secretary through the telephone or internal mail. Record the time and date of arrival as an attribute to each job.

Step 9: Sample the priority level as an attribute to each job.

Step 10: Is there an emergency job? If yes, then go to step 11, if the answer is no, go to step 12.

Step 11: Send the job to the supervisor to arrange the repair immediately.

Step 12: Put the job on the supervisor's desk waiting for the necessary allocation of resources and schedule the job ready for collection in the planboard queue.

Step 13: Is there a job waiting in the planboard queue? If no, go to step 14 which is waiting for job arrivals. If yes, go to step 15.

Step 15: Is there a tradesman free, in queue, waiting for a job arrival? If no, go to step 16 which is to wait and check for a free tradesman. If yes, go to step 17.

Step 17: Is the defect known to the supervisor and no inspection is necessary before repair? If no, go to step 18 to preview the defect. If yes, go to step 19.

Step 18: Sample the travelling time, from the maintenance department to the job location, and go to step 27.

Step 19: Sample the time required to collect the required spares, materials and tools for the job.

Step 20: Sample the time required to travel from the maintenance department to the job location.

Step 21: Is it possible to gain access to job location? if no, go to step 22. If yes, go to step 23.

Step 22: Return back to the maintenance department to collect another job.

Step 23: Sample the time required to diagnose the defect.

Step 24: Were appropriate spares issued initially? if no, then return back to exchange or collect the necessary spares, step 26. If yes go to step 25.

Step 25: Compute the time required to repair the defect, which is a proportion of the total repair time sampled in the diagnosing activity, step 23. Go to step 32.

Step 26: Travel back to the maintenance department to collect the right spares.

Step 27: This step follows step 18 which is travelling to preview the defect. In this step, the simulation program samples the possibility of gaining access to job location. If gaining access is not possible, then go to step 22. If yes go to step 28.

Step 28: Sample the time required to diagnose the defect.

Step 29: Travel back to the maintenance department to request and collect the necessary spares and tools.

Step 30: Are spares available in the stock? If no, order spares and go to step 22. If yes, go to step 31 which is to collect the required spares and travel back to the job location, and go to step 25.

Step 32: Has the simulation run length time finished, i.e. has the end of the working day arrived? If no, continue the simulation, go to step 22. If yes, go to step 33.

d. Finalisation:

Step 33: Calculate the required statistics and save the required output data into a specified output file. Transfer the remaining jobs into the planboard queue, and clear the contents of the activities counters and queues ready for a fresh start in the next working day.

Step 34: Has the one year simulation been performed? if no, go to step 2. If yes, stop the simulation program.

6.4. Collecting a batch of jobs at a time simulation model

This simulation program is designed to investigate an alternative method of managing maintenance work by letting the tradesman collects a batch of locally clustered jobs, instead of 'collecting one job at a time'. This model can be used in assessing any improvement in efficiency which could be available by reducing the number of visits to the maintenance department, as the batch of jobs size increases.

The main characteristic of this simulation program, in addition to the general characteristics of collecting one job at a time simulation model mentioned in section 6.3.1, is the ability to allocate a variable number of jobs per batch to a tradesman. This has been done by averaging the number of trade jobs waiting in the planboard to the number of tradesmen available to work in the giving simulated day, and allocating a batch of jobs equal to the integer value of the average. If the value of the ratio is less than one then one job at a time is allocated to tradesmen. If the batch of jobs is greater than five, then a maximum of five jobs are allocated to each tradesman. As the number of tradesmen available to work decreases, the batch of jobs size increases, and vice versa.

If any job fails to be completed by the tradesman, because of the possibility of not gaining access to job location, collecting wrong spares, or spares are not available in stock, then that job is dropped from the batch of jobs and is rescheduled for on the plan board. The completed jobs are also dropped from the batch. The simulation program checks the number of jobs left in the batch in each activity. When the number of jobs in the batch reaches zero, the tradesman returns back to the maintenance department to collect more jobs.

6.4.1. Sections, steps and flow chart of the simulation model.

The structure of the simulation program for collecting a batch of jobs at a time is shown in the activity cycle diagram, figure 6.4. Sections, steps and the flow chart of the simulation program, figure 6.5, are as follows:

a. Definitions:

Step 1: as in section 6.3.2.

b. Initialisation:

Steps 2 - 7, as in section 6.3.2.

c. Activities:

Steps 8-12, as in section 6.3.2.

Step 13: The simulation program counts the number of jobs waiting, for free tradesmen, in the plan board to be repaired.

Step 14: Calculate the ratio of jobs waiting in the plan board to the number of tradesmen available for work in the days simulation, (calculated in step 6).

Step 15: The program checks the value of the ratio; If the ratio is less than one, then go to step 16, to let a tradesman collect one job at a time, i.e. batch=1; if ratio greater than 5, then go to step 17, to let the tradesman collect a batch of 5 jobs; and if the ratio is between 1 and 5, then go to step 18, to collect a batch of jobs equals the integer value of the ratio.

Step 19: The program engaged the tradesman to request, collect spares and travel to job location.

Step 20: Is gaining access to job location possible? If no, then go to step 23; If yes, then go to step 21 to diagnose the defect.

Step 22: Were appropriate spares collected initialy? If no go to step 23; if yes go to step 24.

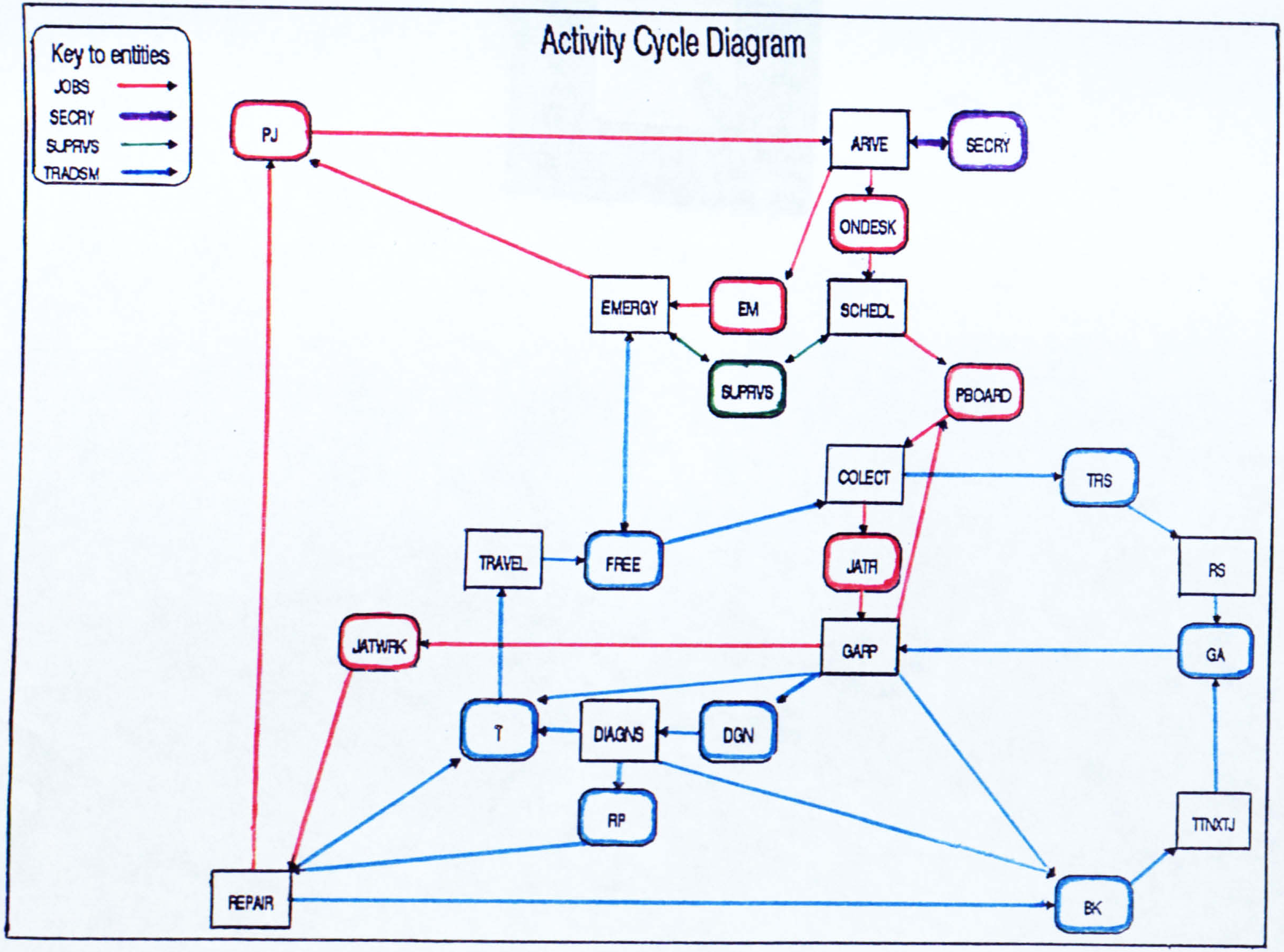
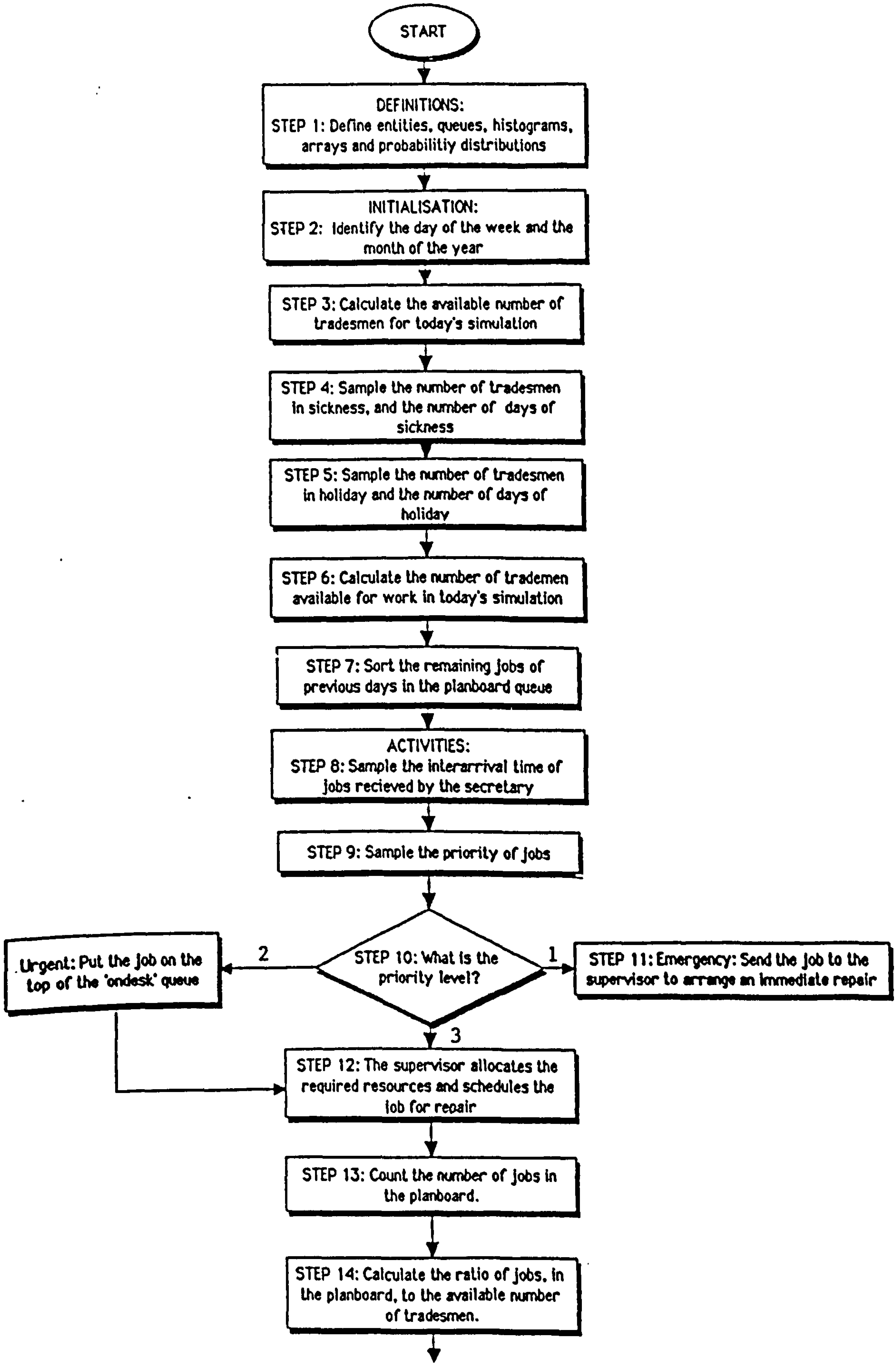


Figure 6.4: Activity cycle diagram for 'collecting a batch of jobs at a time' simulation model.


START
DEFINITIONS:
STEP 1: Define entities, queues, histograms, arrays and probabilitiy distributions
INITIALISATION:
STEP 2: Identify the day of the week and the month of the year
STEP 3: Calculate the available number of tradesmen for today's simulation
STEP 4: Sample the number of tradesmen in sickness, and the number of days of sickness
STEP 5: Sample the number of tradesmen in holiday and the number of days of holiday
STEP 6: Calculate the number of trademen available for work in today's simulation
STEP 7: Sort the remaining jobs of previous days in the planboard queue
ACTIVITIES:
STEP 8: Sample the interarrival time of jobs recieved by the secretary
STEP 9: Sample the priority of jobs
STEP 10: What is the priority level?
2
Urgent: Put the job on the top of the 'ondesk' queue
1
STEP 11: Emergency: Send the job to the supervisor to arrange an immediate repair
3
STEP 12: The supervisor allocates the required resources and schedules the job for repair
STEP 13: Count the number of jobs in the planboard.
STEP 14: Calculate the ratio of jobs, in the planboard, to the available number of tradesmen.

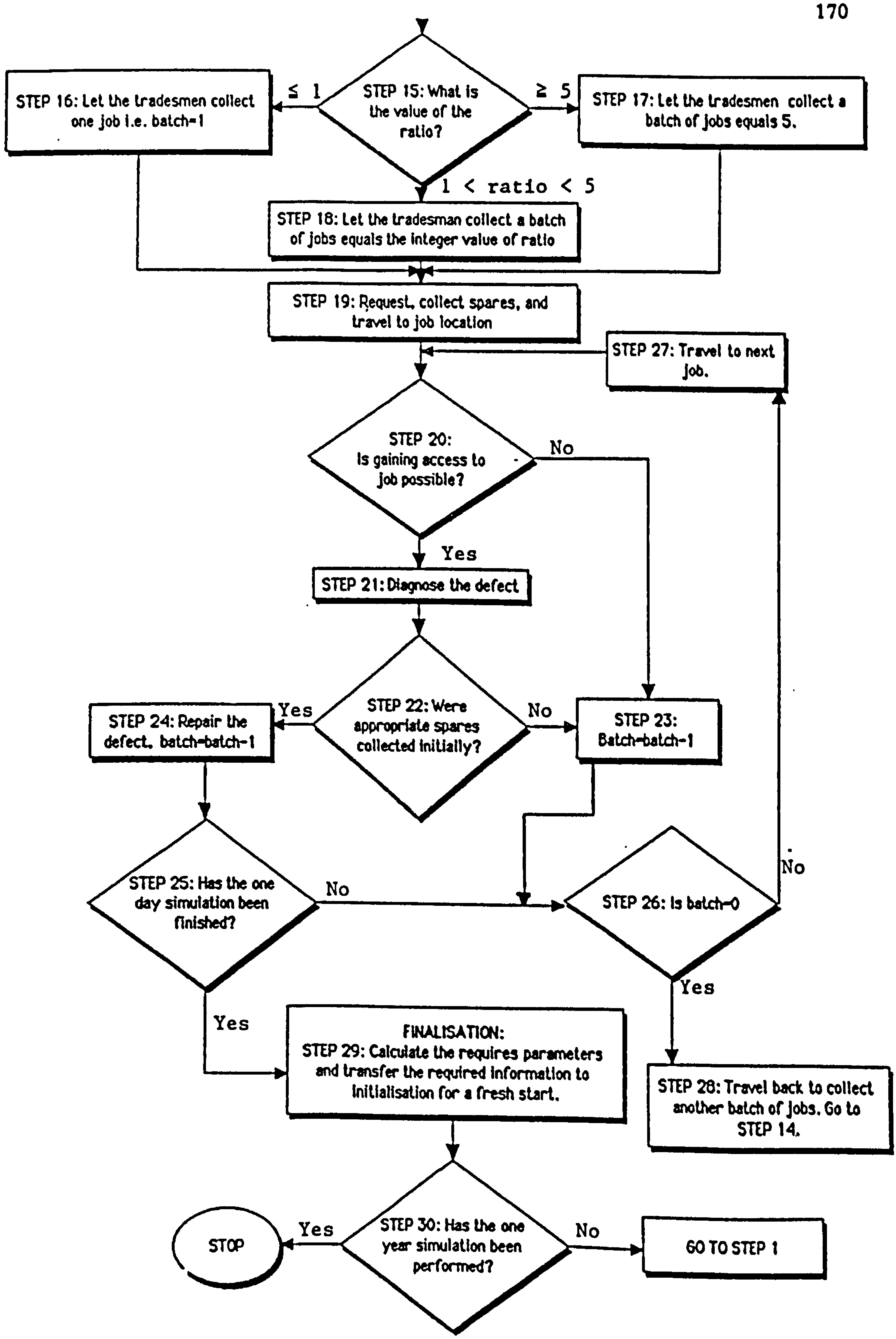


Figure 6.5: Flow chart for 'collecting a batch of jobs at a time' simulation program.

Step 23: Drop one job from the batch of jobs because of lack of access to job location, or because of collecting wrong spares.

Step 24: Repair the defect, the time required to compelete the repair is calculated from the total repair time sampled in step 21. Deduct one job from the batch of jobs to be completed.

Step 25: Has the simulation run length time finished? If no, go to step 26, If yes go to the finalisation in step 29.

Step 26: Is outstanding batch of jobs zero? If yes, go to step 28; if no go to step 27, which is travelling to next job.

Step 28: Travel back to collect another batch of jobs, and go to step 14.

d. Finalisation:

Step 29: Calculate the required parameters and transfer the necessary data for initialisation for a fresh start the next working day, and clear the contents of queues and activities.

Step 30: Has the simulation of one year period been performed? If no, go to initialisation section in step 2; If yes then stop the simulation program.

6.5. Delaying non-urgent jobs model and its characteristics.

A considerable percentage of the four key trades jobs are over a short time scale non-urgent jobs, table 5.2. These jobs can be delayed for a week or even for a month, at either no risk to patients or staff associated with the defect, or at negligible down-time cost.

Instead of attempting to respond daily to requests for repairs, a delay system can be introduced whereby regular weekly visits at a fixed time are made by tradesmen to a pre-planned area. The hospital may be divided into 5 such areas, when a tradesman visits say area 1 on Mondays, area 2 on Tuesdays, ..., and area 5 on Fridays. This method has proven a success in a previous study, Christer (1981), and has given more satisfaction to the medical staff and the maintenance department as evidenced by reducing the number of complaints considerably. Another advantage of this method is to help the maintenance management in organizing their work, and increases their efficiency by reducing the travelling time.

The main characteristic of this simulation model is the ability to allocate a number of tradesmen to do the delayed jobs and another number of tradesmen to do the emergency and the urgent job. This allocation of tradesmen is dependent upon the number of tradesmen available for work in every simulated day.

6.5.1. Section, steps and flow chart of the simulation program.

The structure of the simulation program for, 'delaying non-urgent jobs and grouping them in time', is shown in the activity cycle diagram, figure 6.6. Sections, and steps in flow chart of the simulation program, figure 6.7, are as follows:

a. Definitions:

Step 1, as in section 6.3.2.

b. Initialisation:

Steps 2–6 as in section 6.3.2.

Step 7: Allocate the number of tradesmen to repair emergency and urgent jobs, and the number of tradesmen to visit the pre-planned area and repair the non-urgent jobs.

Steps 8: Sort the remaining jobs from previous days on the plan board.

c. Activities:

Step 9: Sample the interarrival time of jobs recieved by the secretary, from an exponential distribution.

Step 10: Sample the priority of the jobs arriving in the previous step.

Step 11: The program checks the priority level of jobs; If the job is emergency, then go to step 12; If it is not urgent, go to step 13; If the job is urgent, go to step 15.

Step 12: The supervisor arranges for an immediate repair to the emergency job.

Step 13: Sample the area (location) of the non-urgent job to be as an attribute to the job, and let the job join the delayed jobs queue.

Step 14: Send a number of tradesmen to a disclosed area which matched the code of the current simulated day, such as on Mondays send tradesmen to area 1, on Tuesdays send to area 2, ..., and on Friday send to area 5.

Step 15: The supervisor examines the urgent jobs, allocates the necessary resorces and schedules it for repair.

Step 16: The program counts the number of jobs on the plan board in order to calculate the ratio of outstanding jobs to tradesmen.

Steps 17– 33: These steps are the same as steps 14–30 in section 6.4.1.

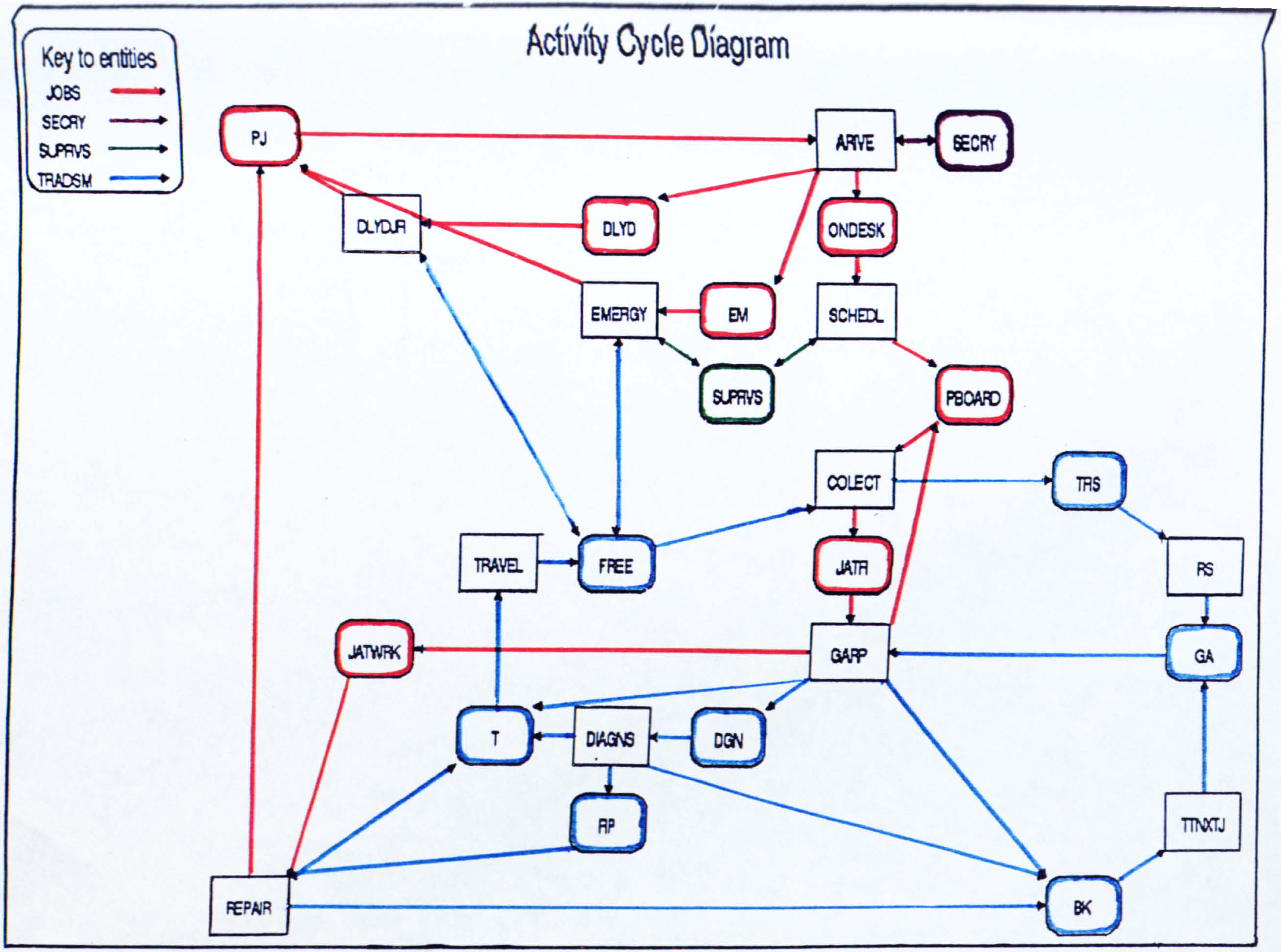
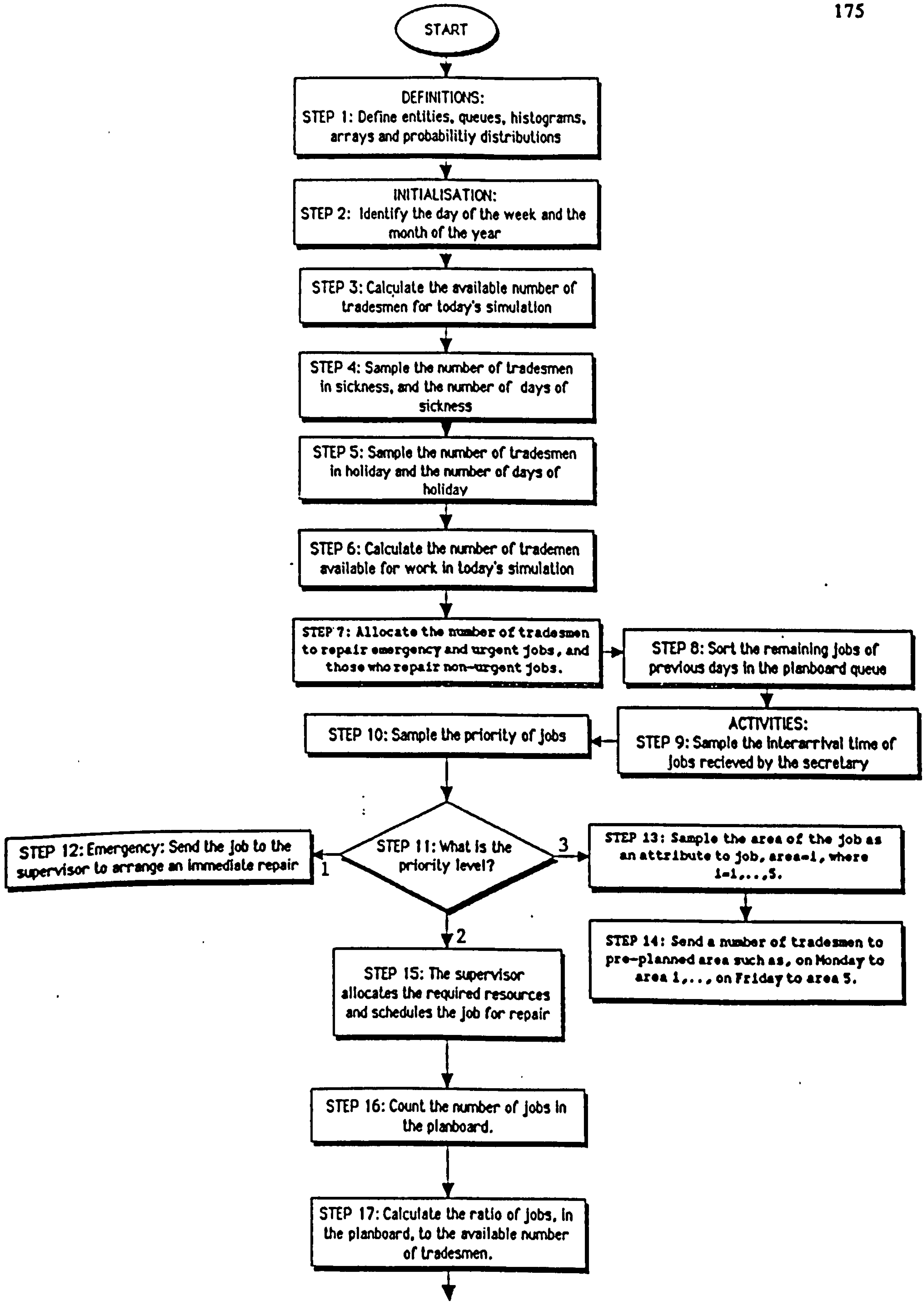


Figure 6.6: Activity cycle diagram for 'delaying non-urgent jobs and group them in time' simulation model.


START
DEFINITIONS:
STEP 1: Define entities, queues, histograms, arrays and probabilitiy distributions
INITIALISATION:
STEP 2: Identify the day of the week and the month of the year
STEP 3: Calculate the available number of tradesmen for today's simulation
STEP 4: Sample the number of tradesmen in sickness, and the number of days of sickness
STEP 5: Sample the number of tradesmen in holiday and the number of days of holiday
STEP 6: Calculate the number of trademen available for work in today's simulation
STEP 7: Allocate the number of tradesmen to repair emergency and urgent jobs, and those who repair non-urgent jobs.
STEP 8: Sort the remaining jobs of previous days in the planboard queue
ACTIVITIES:
STEP 9: Sample the interarrival time of jobs recieved by the secretary
STEP 10: Sample the priority of jobs
STEP 11: What is the priority level?
1
2
3
STEP 12: Emergency: Send the job to the supervisor to arrange an immediate repair
STEP 13: Sample the area of the job as an attribute to job, area=i, where i=1,...,5.
STEP 14: Send a number of tradesmen to pre-planned area such as, on Monday to area 1,..., on Friday to area 5.
STEP 15: The supervisor allocates the required resources and schedules the job for repair
STEP 16: Count the number of jobs in the planboard.
STEP 17: Calculate the ratio of jobs, in the planboard, to the available number of tradesmen.

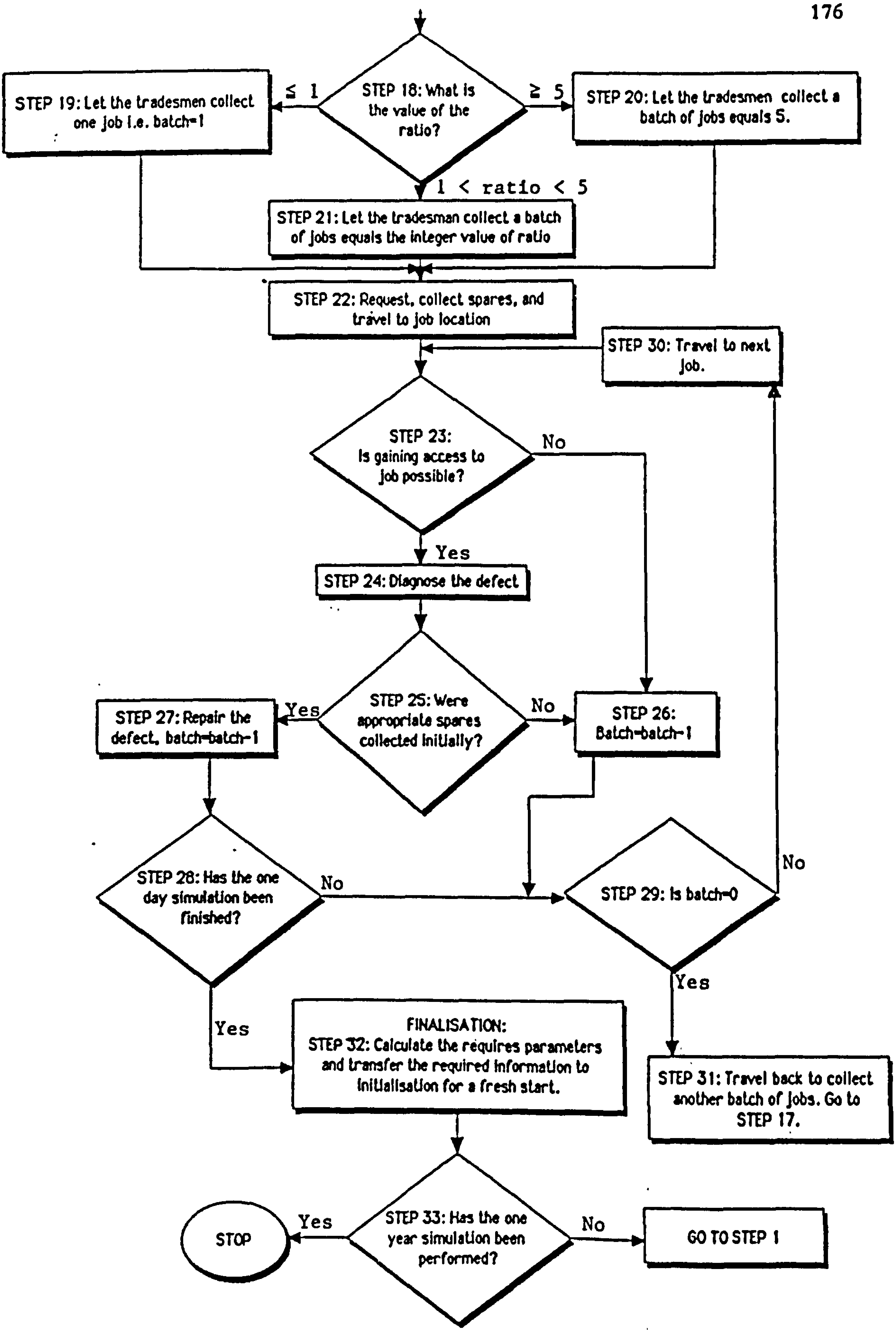


Figure 6.7: Flow chart for 'delaying non-urgent jobs and group them in time' simulation program.

6.6. Maintenance management policies

Simulation is an indispensable tool in formulating complex maintenance management models and policies. These models mimic the detailed operation of the system by means of computer program which effectively steps through each event that would occur in the system. As such, simulation permits controlled experiments on a complex system with no disturbance of the actual system.

A number of maintenance management policies have been proposed with the co-operation of the maintenance management at Withington hospital, these policies, can be investigated with little changes in the previously mentioned simulation programs, are discussed in the following sections.

6.6.1. Previewing jobs before repair

The South Manchester District Health Authority has a proposed standard rule to be followed by the maintenance management at Withington hospital. This is to preview every job in order to assess the priority and the required resources such as, manpower, tool and spare parts. In reality this policy is not in use, but it has been simulated in order to assess alternative maintenance management policies and their efficiency in terms of reducing the travelling time and increasing the available productive time (repair time). This policy can be investigated using the first simulation program 'collecting one job at a time', section 6.3.

6.6.2. Not-previewing jobs before repair policy

In reality, the few jobs which are previewed before repair are usually either emergency jobs or jobs for which very little information is available as to their nature. These previewed jobs represent an estimated 20% of all the arriving jobs. It is assumed that the supervisor's experience is sufficient enough for an estimated 85% of the correct resources to be identified for defects not previewed. Simulating this policy with previewing only 20% of the incoming jobs should show possible increase in efficiency, through the reduction of the travelling time, when it is compared with the total previewing policy. This policy can be simulated in all the three simulation programs mentioned in sections 6.3, 6.4, 6.5, namely, collecting one job at a time simulation model, collecting a batch of jobs at a time simulation model, and delaying non-urgent jobs simulation model.

6.6.3. Employing part-time tradesmen policy.

Currently there are five working days with full work force Monday-Friday, and just one tradesman per trade is working during Saturdays. The current practice has shown that the management faces a backlog of work on Mondays and Tuesdays, this backlog of work accumulated during the weekends. To overcome this problem it was proposed to investigate the possibility of employing part-time tradesmen during Mondays and Tuesdays, in order to cope with the high maintenance demand. This policy can be used to assess the manpower level which can smooth and reduce the backlog of jobs during Mondays and Tuesdays, and the possibility of reducing slack time, i.e. increasing the productivity of the workforce. This policy can be simulated in all the three simulation programs mentioned in section 6.3, 6.4, 6.5.

6.6.4. Working seven days a week policy

In order to overcome the backlog problem of maintenance work during Mondays and Tuesdays, as mentioned earlier, the maintenance management proposed assessing the possibility of working seven days a week insead of five days a week. Their argument is that the health care is the continuous process in the hospital, which needs a continuous support of the maintenance department during the days of the week. This policy can assess the gains and the reduction in the service time when compared with employing part-time tradesmen during the peak days of the week. This policy can be simulated and also run in the three simulation programs mentioned in section 6.3, 6.4, 6.5.

6.6.5. No sickness model

The analysis of sickness, section 5.2.1.3, has revealed that there are considerable losses of man hours because of sickness, and this loss can rise to the range of 3-5 days per tradesman per month. It is proposed to run the previous method of deployment program in the absence of the sickness factor. This can help in assessing the impact of sickness on the productivity of the tradesmen, and open up the potential for, say, a health bouns for those who are not sick.

6.6.6. Multi-skill tradesmen policy.

There is currently growing interest in reducing skill demarcation in maintenance departments. The advantages claimed for multi-skill working include improved maintenance effectiveness, and improved worker morale as a result of greater job satisfaction, (Basker & Husband 1983).

It was assumed to train and to mix the engineering trades, electrical and mechanical, in order to enable tradesmen of these trades to repair jobs of both trades, i.e. to be engineering multi-skilled; and to train and to mix the building trades, plumbing and joinery, in order to enable them to repair jobs of both trades, i.e. to be building multi-skilled. This policy is expected to enhance the effectiveness of the maintenance department considerably by decreasing the slack or idle time, due to increases in the efficiency of the batching of jobs and scheduling of manpower. This policy can be simulated within all the simulation programs mentioned in section 6.3, 6.4, 6.5. This has been done by sampling from pooled distributions, for instance, the pooled distribution of electrical and mechanical repair time, is the distribution of engineering repair time.

6.7. Verification and validation of simulation models

Verification and validation are closely linked, and usually are conducted simultaneously by the modeller. Verification is defined by Banks (1990) as:

> *"Verification refers to the comparison made between a conceptual model and the computer model examined to implement the conception"*;

and defined by Gass (1983) as:

> *"The process of demonstrating that the computer program 'runs as*

intended'".

The verification, therefore, means debugging the computer program. Although verification is simple in concept, debugging a large-scale simulation model can be quite a hard task to accomplish (Law & Kelton 1982).

Validation is defined by Banks (1990) as: *"Validation refers to the techniques employed to ensure that a simulation model represents true system behaviour with sufficient accuracy to allow the simulation model to be used as a substitute for the actual system"*;

and defined by Fishman and Kiviat (1968) as: *" Model validation tests the agreement between the behaviour of the model and the real world system being modelled"*.

Thus the verification would help in establishing the level of confidence of the modeller, whilst validation would establish the level of confidence of the client, Finlay & Wilson (1987).

The maintenance management simulation models developed have been programmed using three important steps in order to simplify the verification process. First, it would be poor programming practice to write the entire program, with all it's complexity, before attempting any debugging. When this large, complex, and untested program is finally run, it almost certainly will not execute, and determining the errors will be exetremely difficult. Therefore, we start with a simple simulation program which is gradually made as complex as needed, by adding and debugging additional subprograms or levels of details successively until a desired model is developed. Second, in order to determine whether a simulation model is operating as intended, the model was run under simplifying assumptions for which the model's true characteristics are known or can be easily computed. Third, the simulation models have been run by displaying the activity cycle diagram and the simulation output on a graphic terminal as the simulation actually progresses. This method is important in diagnosing any error, and, therefore rectifying it.

To verify the simulation models, the output of the simulation programs have been closely examined for reasonablness by examining a large number of the simulation programs runs under a variety of setting of input parameters such as, interarrival time for maintenance jobs, repair time, travelling time, probability of sickness and holidays, and different number of tradesmen and their utilization.

The developed maintenance management simulation models are substitute for actually experimenting with an existing or proposed system. Thus a reasonable goal in validation is to ensure that the model is developed which can actually be used by a decision maker to make the same decision that would be made if it were feasible and cost-effective to experiment with the system itself. Three steps approach to validation have been implemented. First, by developing a model with high face validity, i.e. a model which, on the surface, seams reasonable to people who are knolegeable about the system under study. The maintenance management simulation models developed have been face-validated in close consultation with the maintenance management and supervisors at Withington hospital, and knowledgeable people in the Centre for Operational Research and Applied Statistics at the University of Salford, who helped in the evaluating of the simulation models and identifying the model's deficiencies. This has been done through ensuring that the activity cycle diagrams (the conceptual models), are reasonably representative of the behaviour of the real system, and that the simulation programs represent the logical flow of events in the activity cycle diagrams shown in figure 6.2, 6.4, 6.6. Second, the model assumptions which include the structural assumptions and data assumptions have been validated by ensuring that each simulation program has reasonably represented the structural assumptions of the method of deployments such as, collecting one job at a time, collecting a variable batch size of jobs by a tradesman at a time, and delaying non-urgent jobs and grouping them in time. Data validity and assumptions are discussed in chapter 5. Third, is to determine how representative the simulation output data are. The output has been subject to the scrutiny of the management as well as the modellers. No points of specific concern have arisen and all appears reasonable within the limits of the experience of management.

Chapter 7

ANALYSIS AND INTERPRETATION OF SIMULATION OUTPUT DATA

7.1 Introduction

Philips & Ravindran & Solberg (1976) stated that *"simulation is one of the easiest tools of management science to use, but probably one of the hardest to apply properly and perhaps the most difficult from which to draw accurate conclusions"*.

Simulation modelling requires substantial skills to develop and operate an effective simulation model. The variability of simulation results is a significant problem in itself. Since the simulation model is an input–output transformation, as illustrated in figure 5.1, and since some of the input variables are random variables, such as the interarrival time and the repair time of defects (jobs), it follows that in general the model output variables are random variables. Thus it may require long and complex simulation analysis in order to draw meaningful conclusions from the simulation.

Law & Kelton (1982) define the two types of simulations with regard to analysis of the output, namely, terminating and steady-state simulations. A *teminating simulation* is one for which the desired measures of system performance are defined relative to the interval of simulated time $[0,T_E]$, where T_E is the instant in the simulation when specified event E occures. The event E is specified before the simulation begins. A *steady-state simulation* is one for which the measures of performance are defined as the limits as the run length of the simulation increases beyond bound. When there is no natural event E to terminate the simulation, the length of one simulation run needs to be large enough to get "good" estimates of the quantities of interest. The length itself is usually the result of experimentation.

Most of the simulation literature on the analysis of simulation output data, such as Bulgren (1982), Fishman (1978), and Lewis & Orav (1989), deal with the steady-state case, which may lead one to believe that only steady-state simulations are important. This may be a carryover from mathematical queueing theory, where only a steady-state mathematical analysis is generally possible (Law & Kelton 1982).

Terminating simulations are also important. Law & Kelton (1982) have discovered by talking to a large number of simulation practitioners that a significant proportion of simulations in the real world are actually of the terminating type. Two reasons have been advanced as to why it may be considered that a steady-state mathematical analysis is not appropriate for terminating models. These are: First, the system under consideration is physically terminating. In this case, letting the length of a simulation run be very large and selected at random may make no sense. Second, the input distributions for the system change over time. In this case, steady-state measures of performance will probably not exist.

Perhaps the most important point about a terminating system simulation, is that the performance measure, X_j, resulting from replication or simulation run j, should be representative of what is actually to be estimated. Terminating analysis have the advantage that each replication produces an independent identically distributed IID "observation" and thus the procedures for constructing confidence intervals are relatively simpler than those in steady-state simulations. A survey of statistical methods applicable to terminating simulations is given by Law (1980). Statistical methods for both types of simulations are given in Banks & Carson (1984), Law & Kelton (1982), and Kleijnen & Groenendaal (1992).

The proposed simulation models of the maintenance activities at Withington hospital are considered to be terminating simulations, because there is an event which starts the daily simulation runs, that is 8.30am, and there is another event that stops them, that is the arrival of a specific point of time, namely 4.30pm on Mondays-Thursdays and 3.30pm on Fridays and Saturdays, which stops the daily simulation runs. Another reason for considering the terminating simulation is the input distributions, of the interarrival time of jobs changes over the working days of the week, and the distributions of sickness and holidays change over the months of the year. Therefore steady-state simulations are not appropriate for these terminating models.
On the other hand the daily simulation module for a specific day of the week can be considered as a steady-state simulation, since the input distributions are not changed during the one day simulation run. But if the simulation run consideres several days with different interarrival times, sickness, and holiday distributions, then it is no longer a steady-state simulation.

7.1.1. Output or response variables

The simulation models of the maintenance activities at Withington hospital are considered over a period of time called the simulation run length, which is a *working day*, starting from 8.30am until 4.30pm on Mondays-Thursdays equivalent to 420 minutes, and starting from 8.30am until 3.30pm on Fridays and Saturdays equivalent to 360 minutes. The simulation run length is the total working time in minutes excluding lunch and tea breaks. The simulation models are run for one calendar year period.

The purpose here of the output analysis is to determine the appropriate number of tradesmen required to meet the day-to-day demand for maintenance per trade, to predict the performance of a system, and to compare the performance of two or more alternative maintenance management policies. The purpose of building the simulation model is to get output variables, which can be considered as representative of the performance measures of the simulation models. The response variables which are recorded, and averaged in each simulation run over the number of tradesmen, as applicable, in order to evaluate the maintenance management models. These response variables are as follows:

(a) The active time per tradesman per day. This is the time per tradesman per day spent in collecting jobs and spares, travelling to and between job locations, gaining access to job location, diagnosing and repairing defects, i.e. the complement of the idle or non productive time.

(b) The travelling time spent in travelling to and from the job locations, per tradesman per day.

(c) The time spent gaining access to job location per tradesman per day.

(d) The actual repairing and diagnosing time per tradesman per day per trade.

(e) The number of remaining jobs either incomplete or outstanding at the end of each simulated day per trade.

(f) The service time per job. This time represents the time interval from the job arrival until its completion.

(g) The number of jobs completed per day per trade.

(h) The number of emergency jobs reported and completed per trade per day.

The analysis of output simulation data in this chapter starts in section 7.2 by describing the method of determining the consequences of fixed number of maintenance staff per maintenance management policy per trade, 'previewing plumbing jobs simulation' has been used for demonstration. Section 7.3 discusses the methods used in the comparisons and evaluations of alternative maintenance management policies. The Appendix in the end of this thesis includes a number of tables showing some statistics measures of the simulation output data discussed in this chapter.

To avoid repetition, the plumbing trade only has been considered in detail in the following analysis for demonstration puposes.

7.2. Determining the consequences of maintenance staff levels

Most of the published work concerning determining maintenance staff level such as, Basker & Husband (1983), Poulsen (1984), and Duffuaa & Raouf (1992) are concerned with determining the maintenance staff level in the industrial environment where the downtime cost can be easily measured by considering the loss of production opportunities, wages, and/or loss of materials, see figure (7.1). This figure shows a hypothetical example of the traditional way of determining the maintenance staff level in an industrial which usually estimated by the simulation. The optimum number of maintenance men, in the above hypothetical example, is the number which minimises the total cost, figure 7.1.

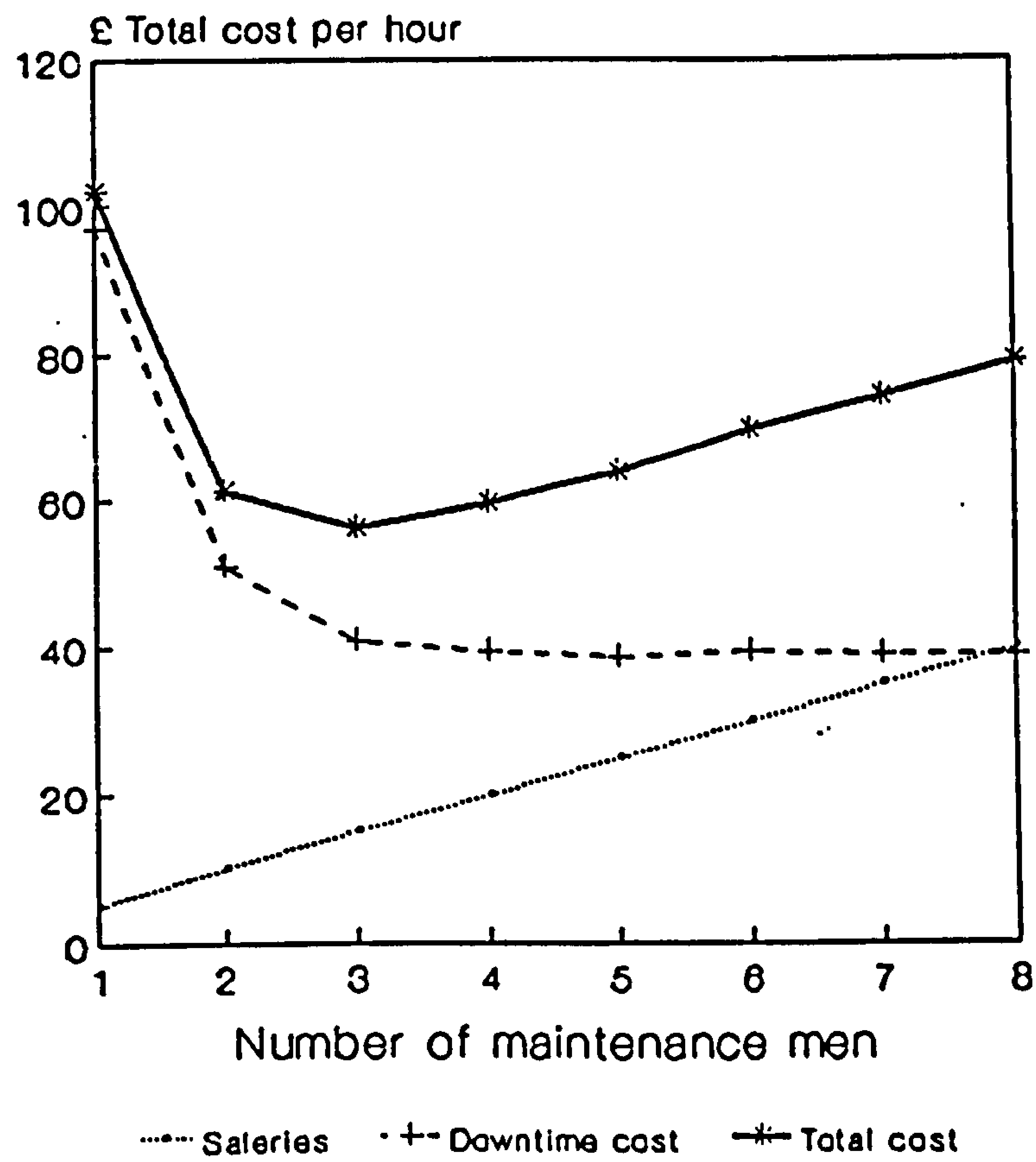


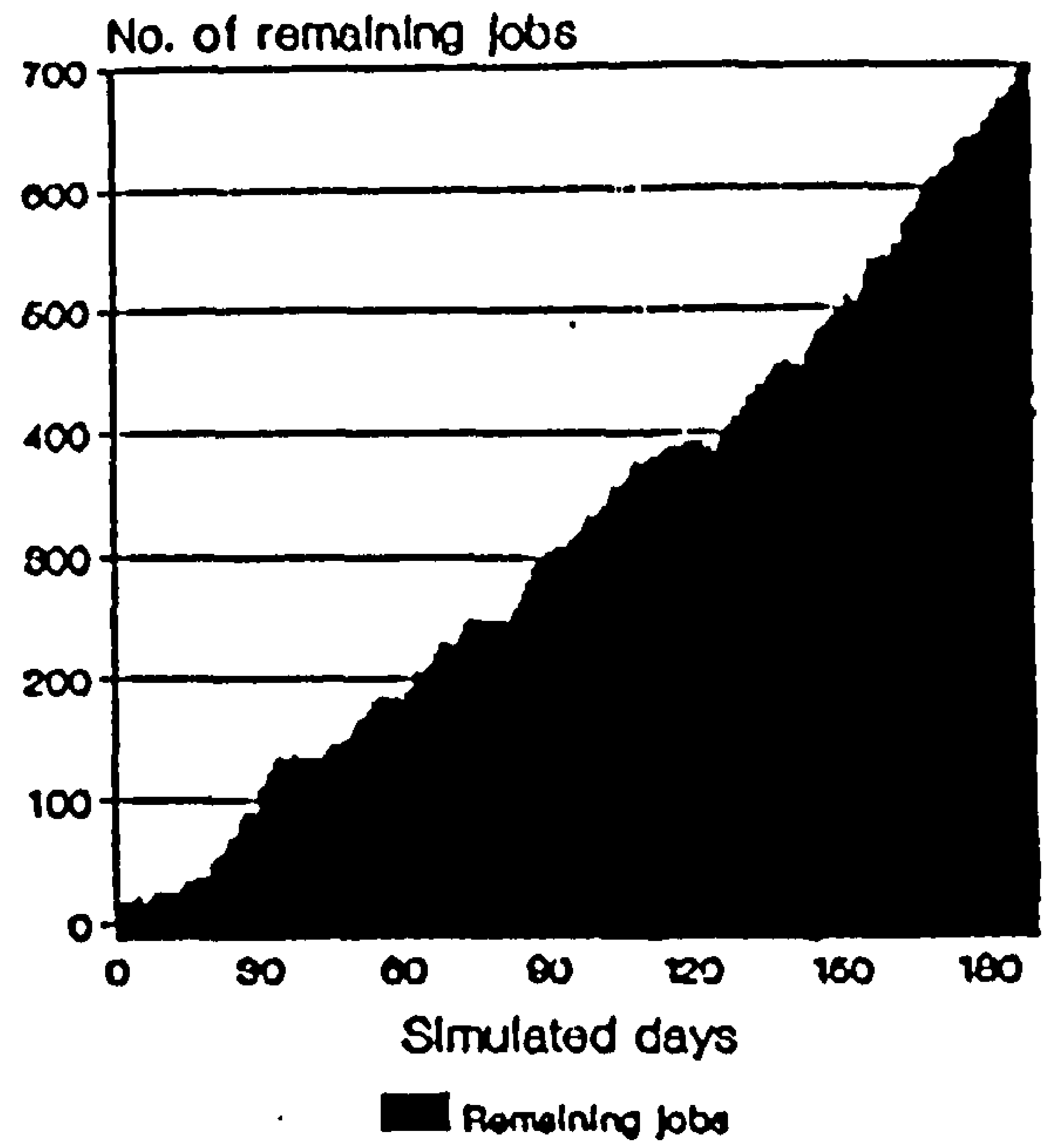
Figure 7.1: Shows a hypothetical example of the traditional way of determining the maintenance staff level in the industrial environment.

In the service and building maintenance environment, it is more difficult to quantify and measure the downtime cost of building defects, or the inconvenience to patients and staff created by a defect in the hospital facilities (Centre for Operational Research and Applied Statistics 1990). For instance, within the health service, the penalty associated with an unavailable bed is estimated around £350 per day which represents the loss of an opportunity of treating a patient. However the true downtime cost per bed is difficult to estimate because of the availability of standby beds or the possibility of borrowing beds from the next ward. The consequences of such a defect is the inconvenience either to patients and/or staff, and delaying such a defect may cause a lot of complaints from the medical staff to the maintenance department. Therefore the downtime cost approach, which has been used in the industrial maintenance, is considered to be not appropriate for hospital maintenance manpower problems.

The average active time per tradesman per day, recorded in every replication or simulation run, is calculated as the ordinary sample average over all replications, and has been considered as a prime measure in determining the consequences of maintenance staff levels, since repairing any defect (job) requires, beside the repairing and diagnosing time, other necessary activities such as, travelling time to and from the job location, collecting jobs, gaining access to job locations, and requesting and collecting spares. Other important measures of performance have also been considered in the analysis.

Results of Simulating the 'previewing policy' when employing only one plumber in the plumbing trade, given all other conditions remain the same, are presented in figure 7.2(a). One plumber can not cope with all the jobs arriving, see figure 7.2(a). Figure 7.2(b) shows the same experimental

(a)
USING 1 PLUMBER (1st EXPERIMENT)



(b)
USING 1 PLUMBER (2nd EXPERIMENT)

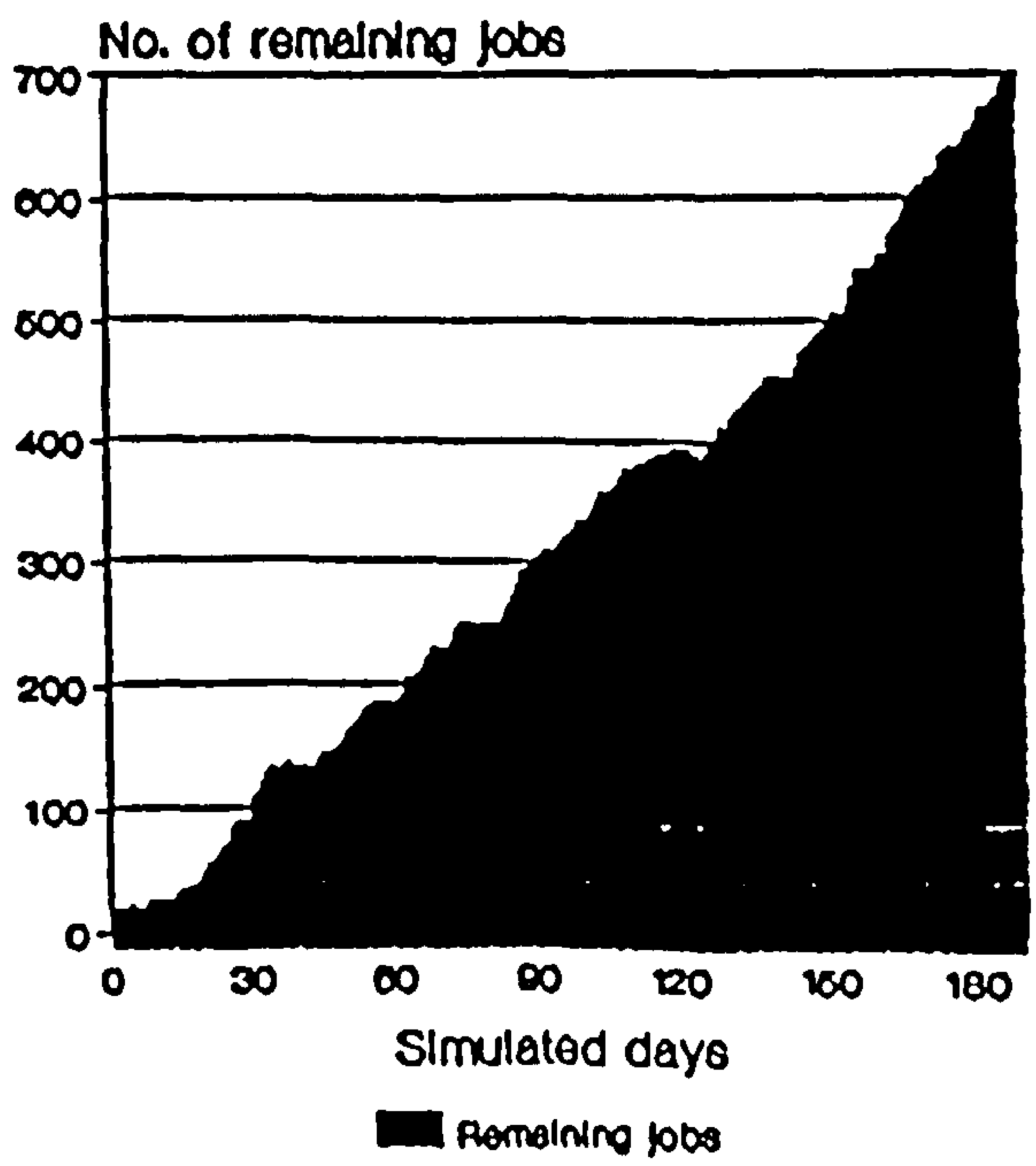


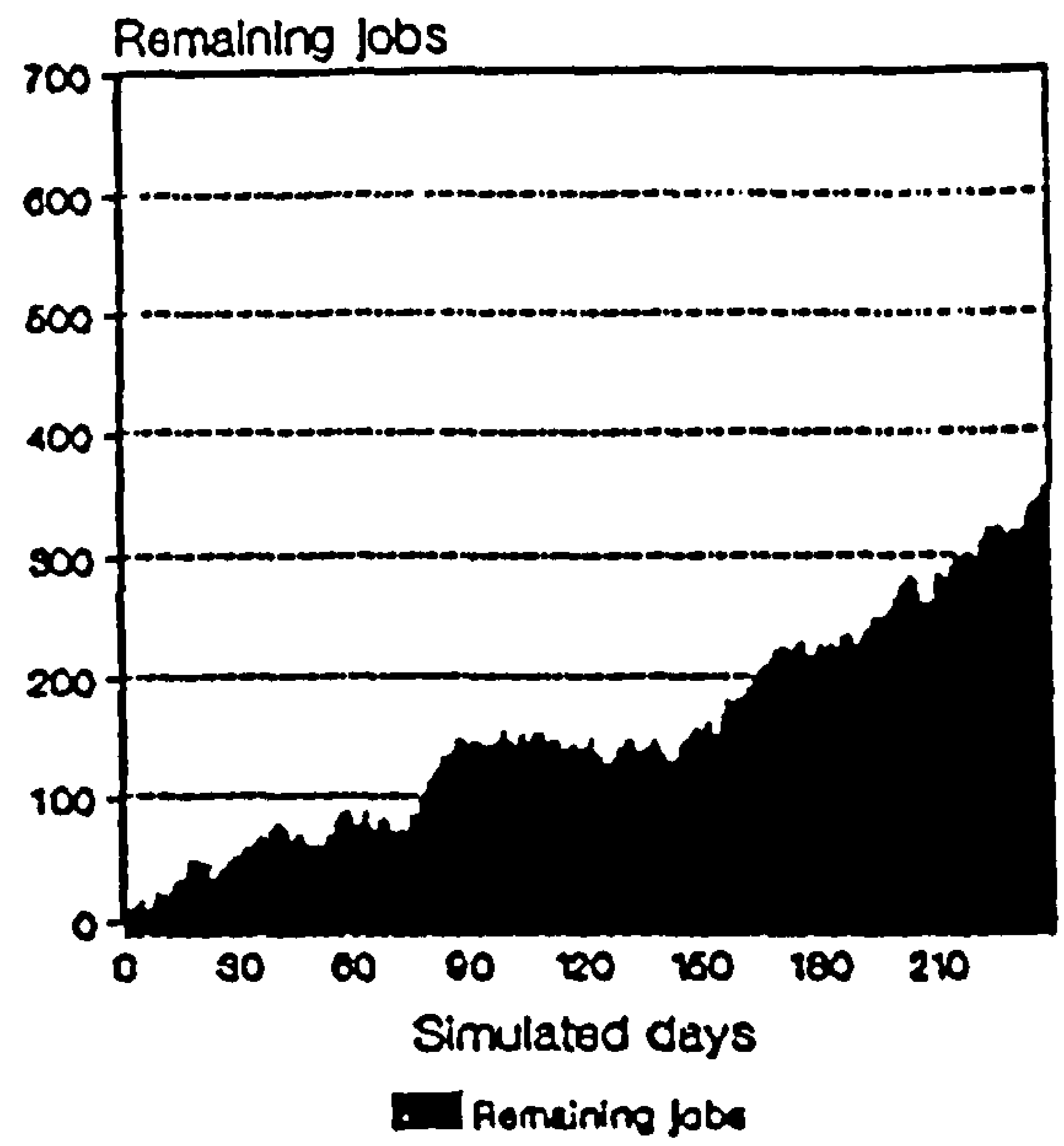
Figure 7.2: Shows the number of remaining jobs per simulated day in two experiments, by using different random numbers seeds in each experiment. One tradesman is employed using previewing policy.

results obtained using different random number seeds. Both figures 7.2(a) and 7.2(b) show that the number of remaining jobs are increasing day after day of simulation, and indicate that the increase in the remaining jobs is not related to the use of random numbers seeds as it can be concluded from the trend in both figures 7.2(a) and 7.2(b). The jobs, when employing just one plumber, are arriving faster than they could be repaired or completed and will, therefore, form a continually growing queue which is called, a "bottleneck" situation. Therefore jobs are stacking and have to wait longer times in order to be repaired. Employing 2, and 3 plumbers in the simulation, jobs are still stacking day after day of a simulation run but in a decreasing rate than before, see figure 7.3-7.5 and note that figure 7.5 magnifies figure 7.4 by changing the Y scale. In these figures, the (a) and (b) refer to different seeds used in the simulation runs.

Employing 4 plumbers would seem to have tasks in control, see figure 7.6, but there are two peak periods when jobs are piling. These periods are thought to be the peak time of sickness and holiday seasons. Employing more than 4 plumbers, see figures 7.7 and 7.8 and please notice the change in Y scale from previous figures, show that the number of plumbers employed is adequate, and they are in control, since there is no increase (piling) in the incompleted or remaining jobs. The utilization of employing only one plumber in the simulation, as measured in terms of the total active time, has been observed in these experiments to be 47.5%, which is considered realistic when we take into account that one hour and a half is lost per day per tradesman for lunch and tea breaks. The rest of the total active time is considered lost to sickness and holiday leave. Therefore, the above utilization can be considered to be at its highest level for this policy, since there is no idle time, i.e. no waiting for the job arrival, has been observed in either experiment.

(a)

USING 2 PLUMBERS (1st EXPERIMENT)



(b)

USING 2 PLUMBER (2nd EXPERIMENT)

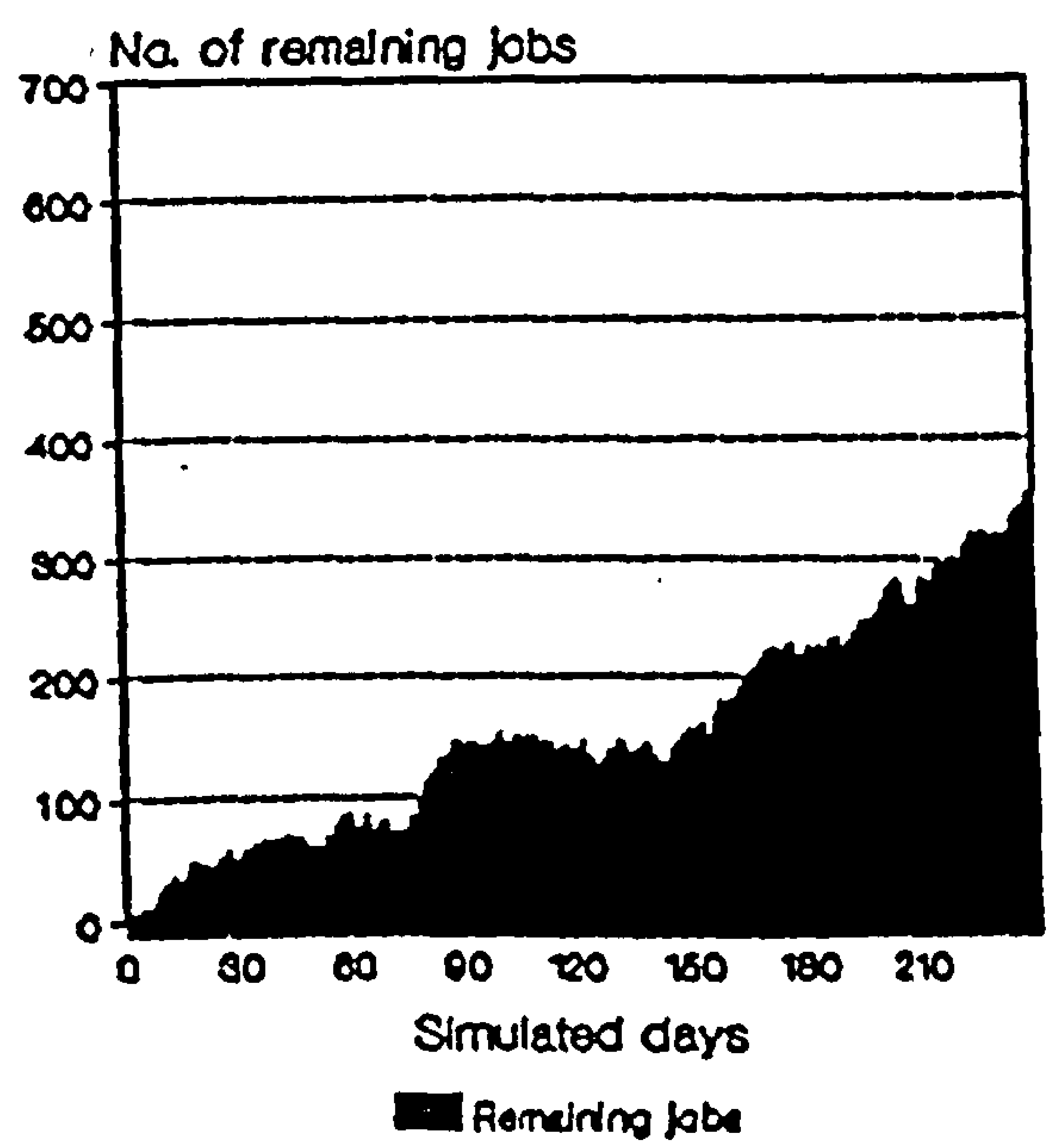
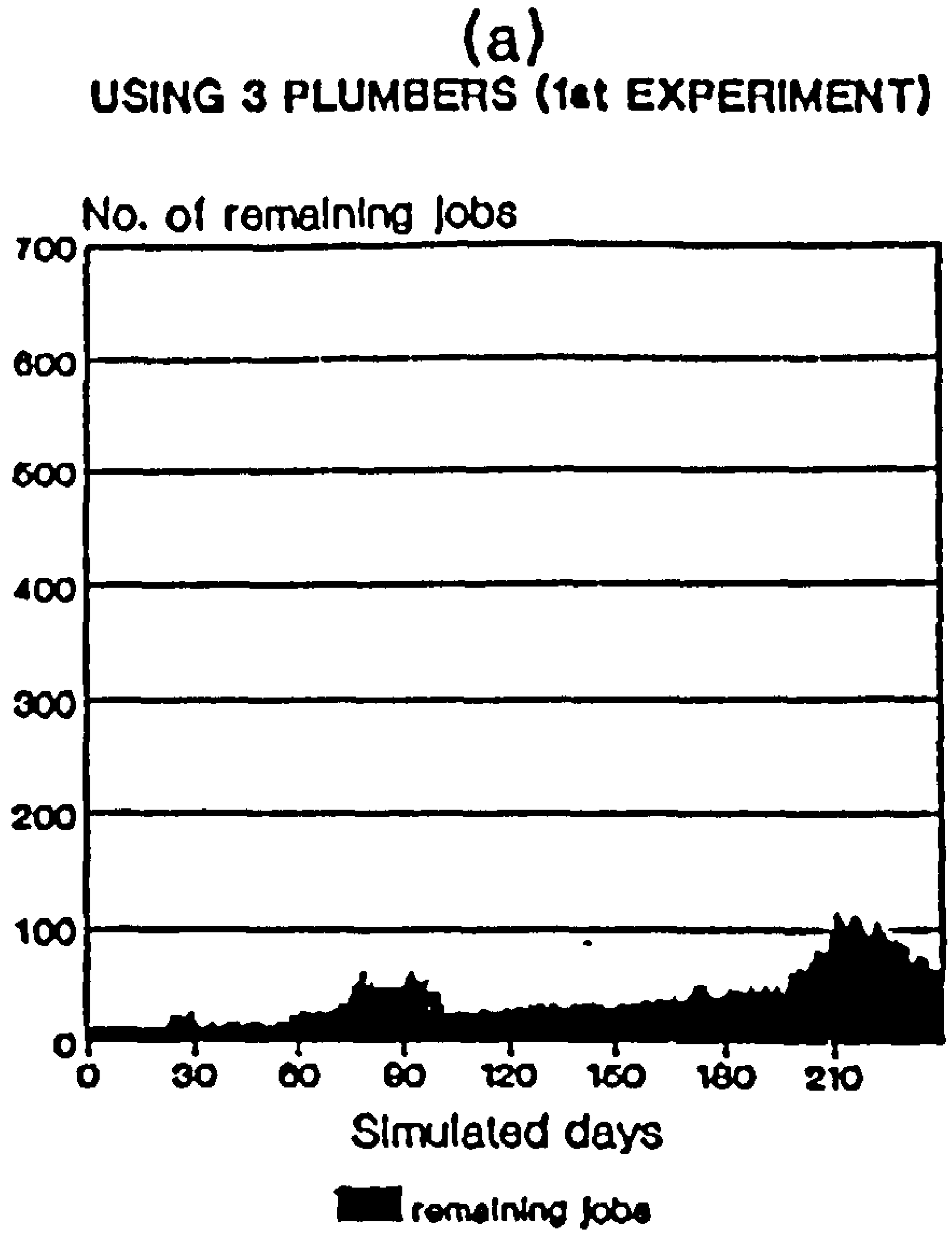


Figure 7.3: Shows the number of remaining jobs per simulated day in two experiments, by using different random number seeds in each experiment. Two tradesmen are employed using previewing policy.



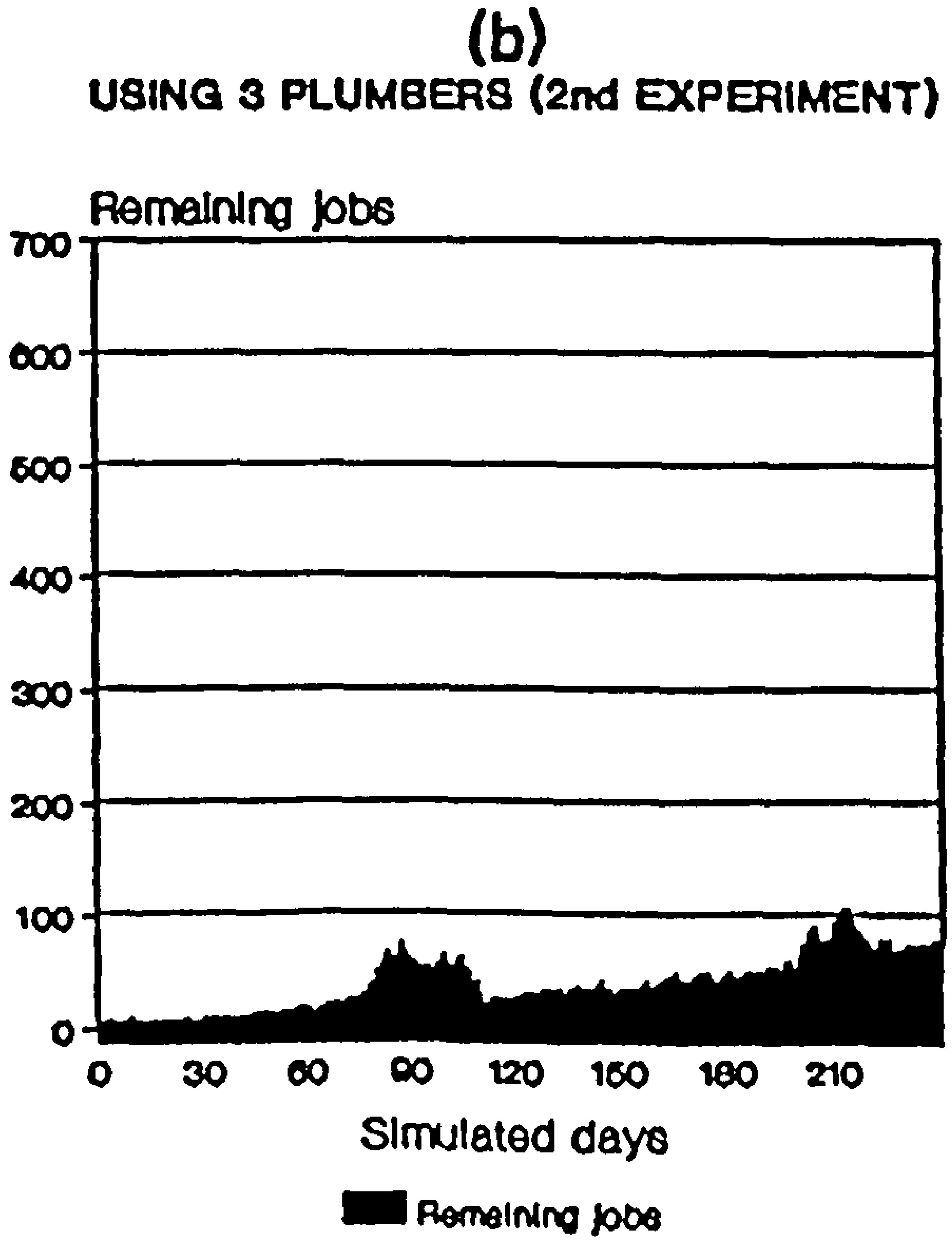
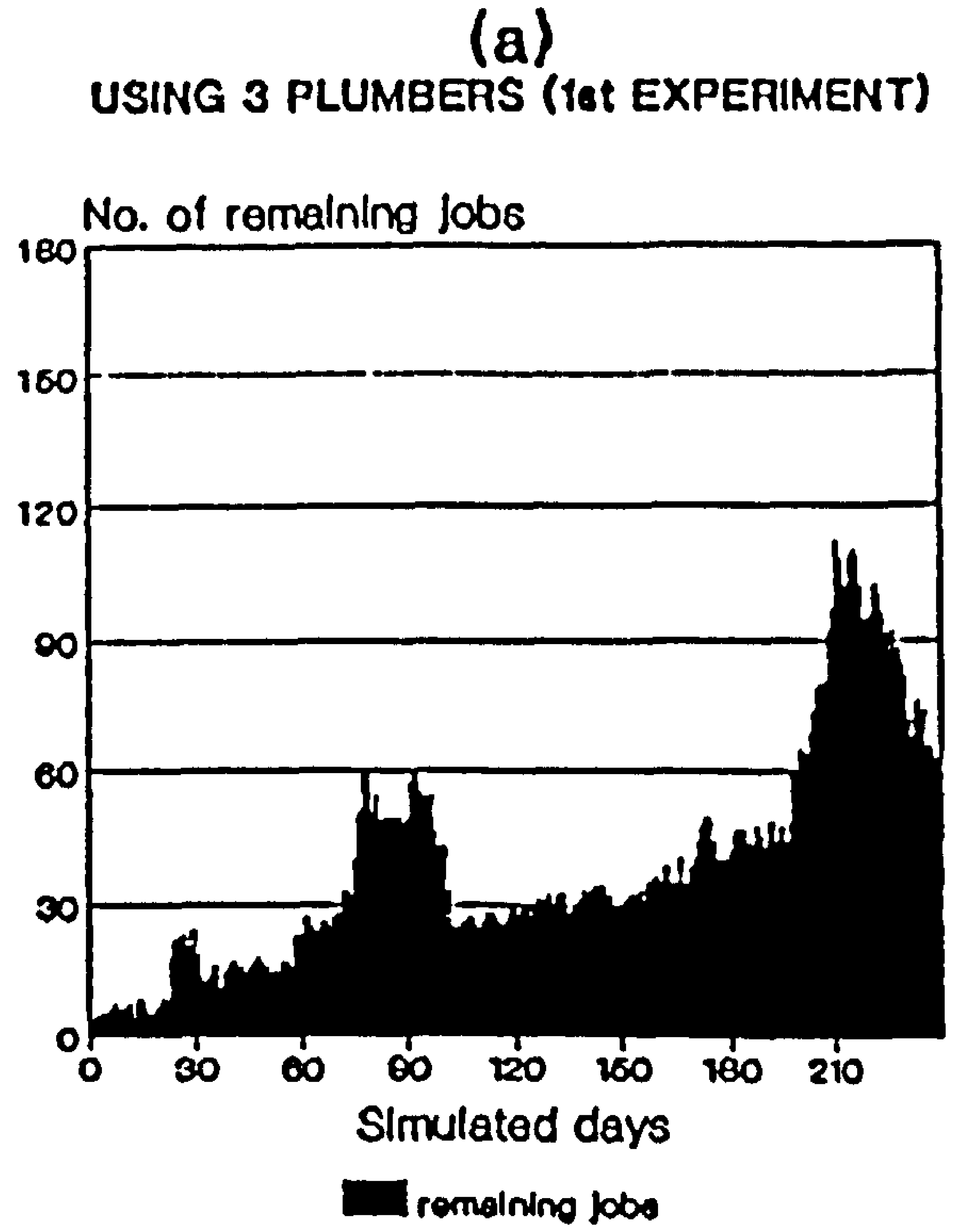


Figure 7.4: Shows the number of remaining jobs per simulated day in two experiments, by using different random number seeds in each experiment. Three tradesmen are employed using previewing policy.



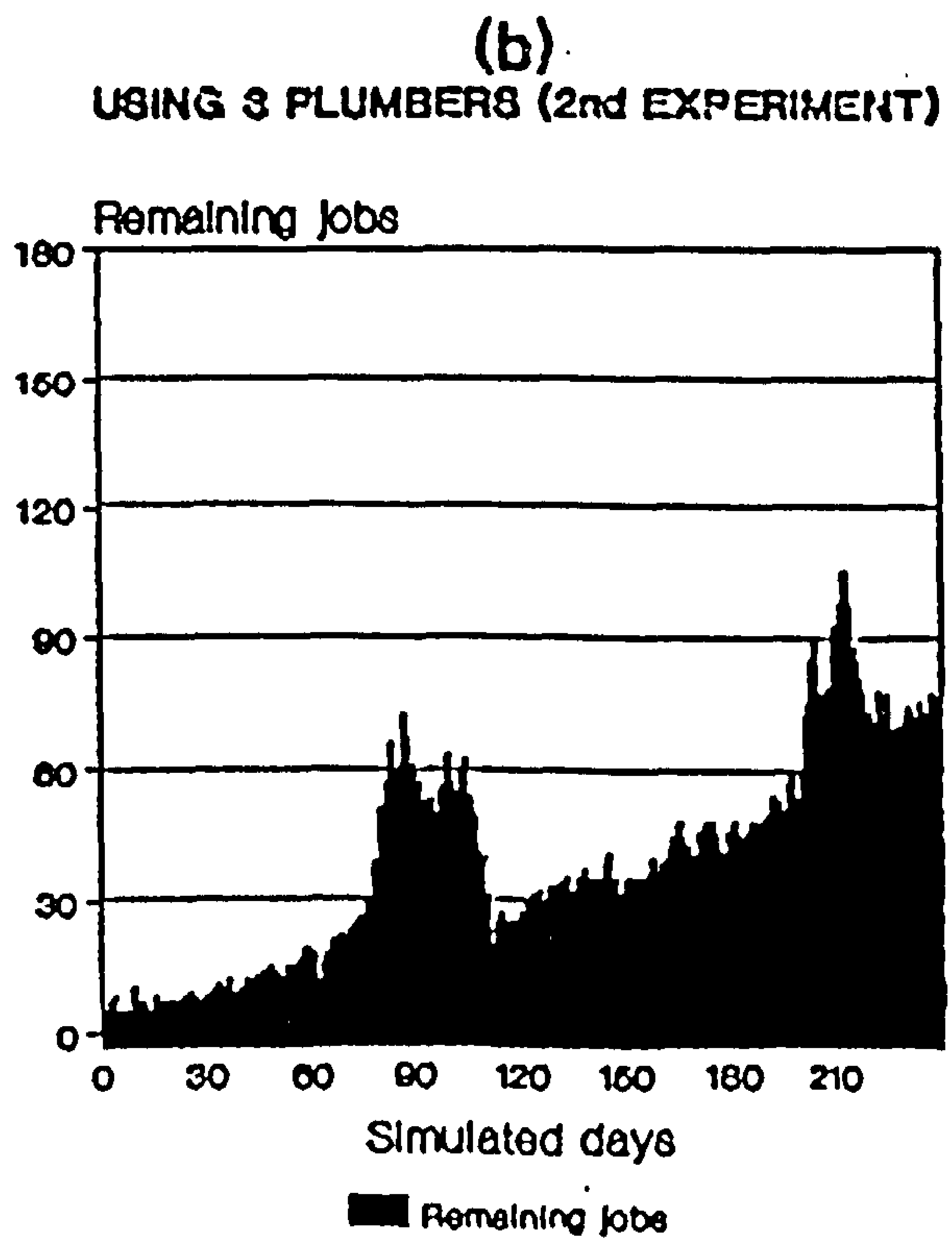
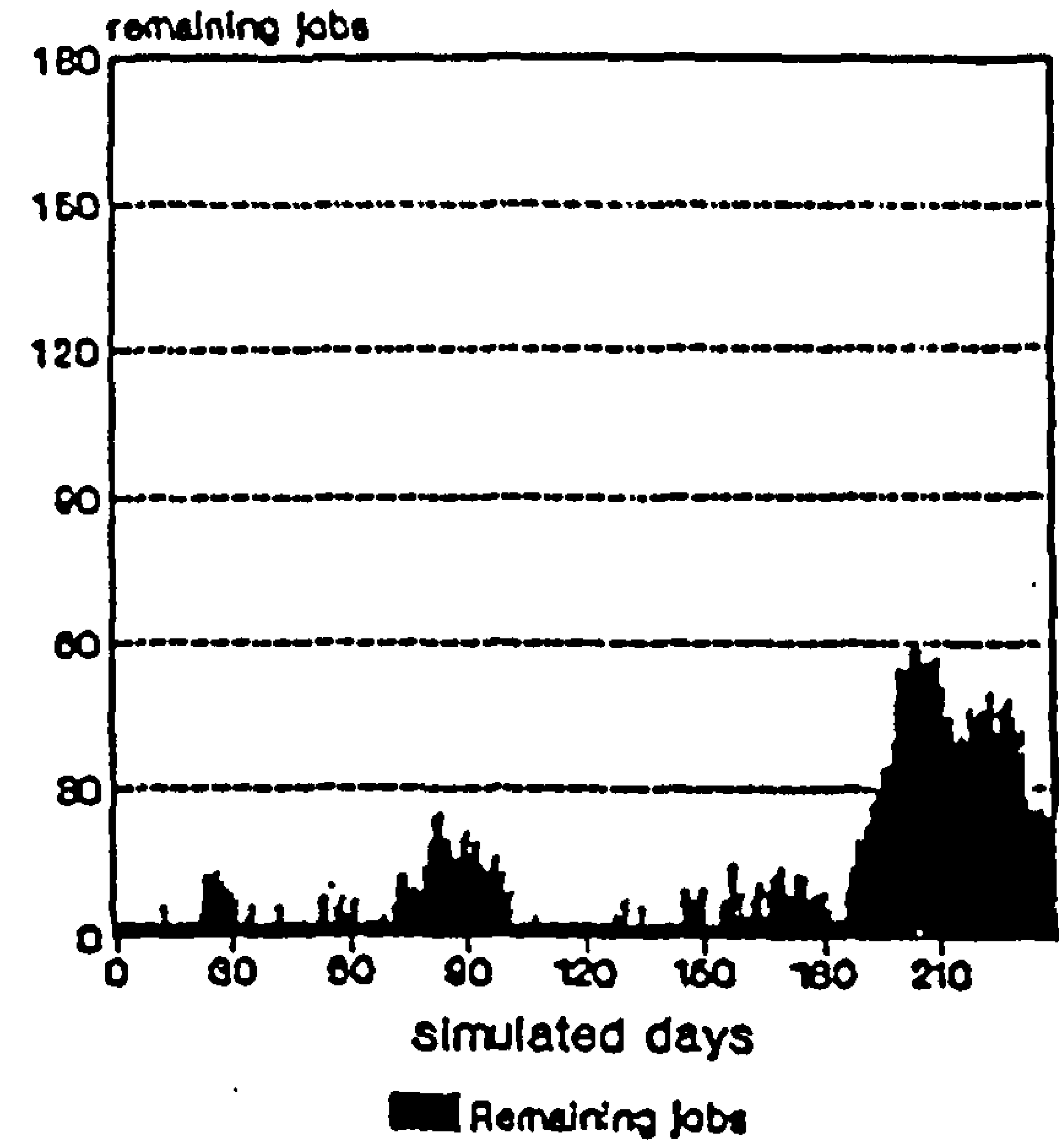


Figure 7.5: Magnifies figure 7.4 by using different Y scale level.

(a)
USING 4 PLUMBERS (1st EXPERIMENT)



(b)
USING 4 PLUMBERS (2nd EXPERIMENT)

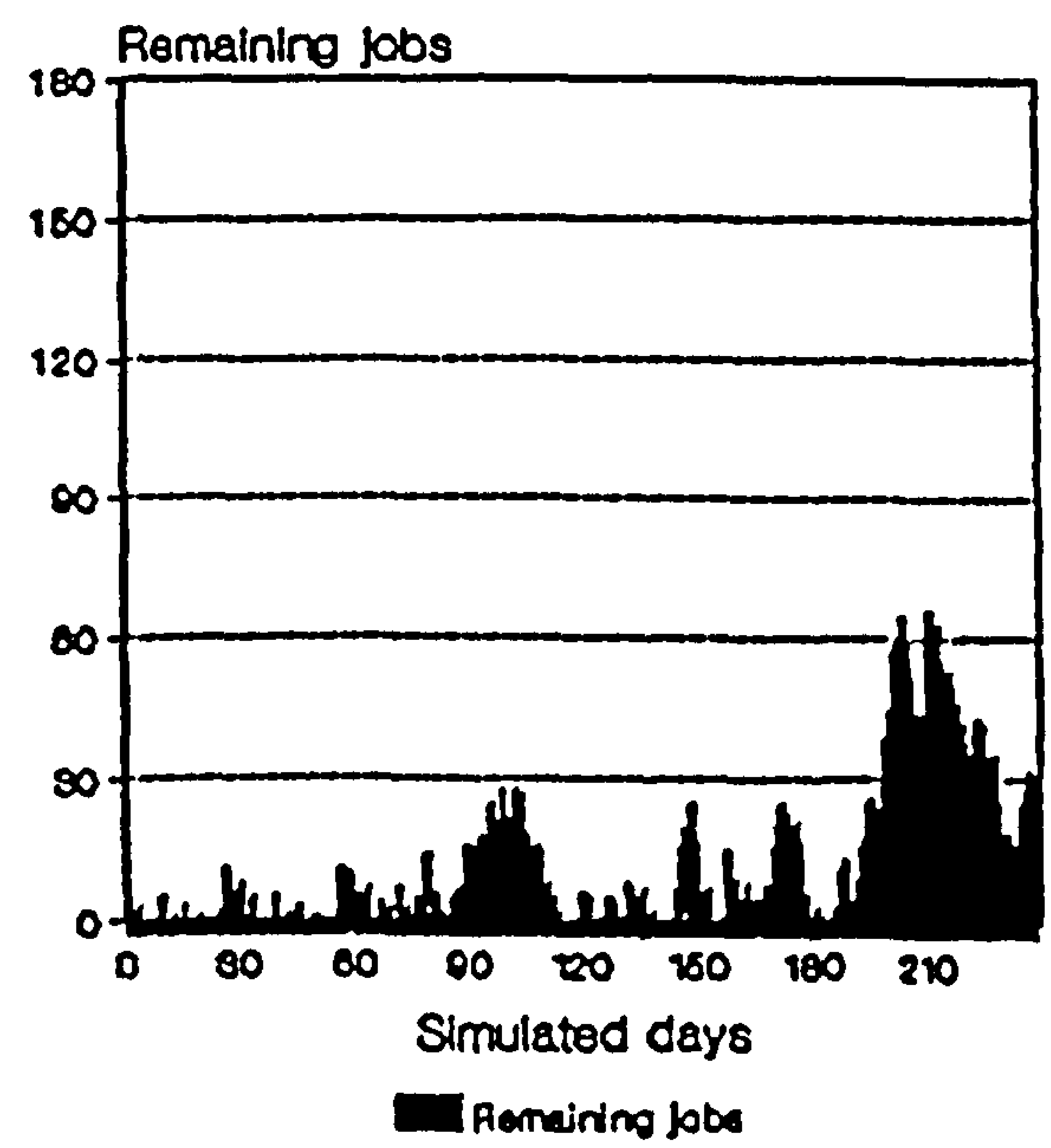
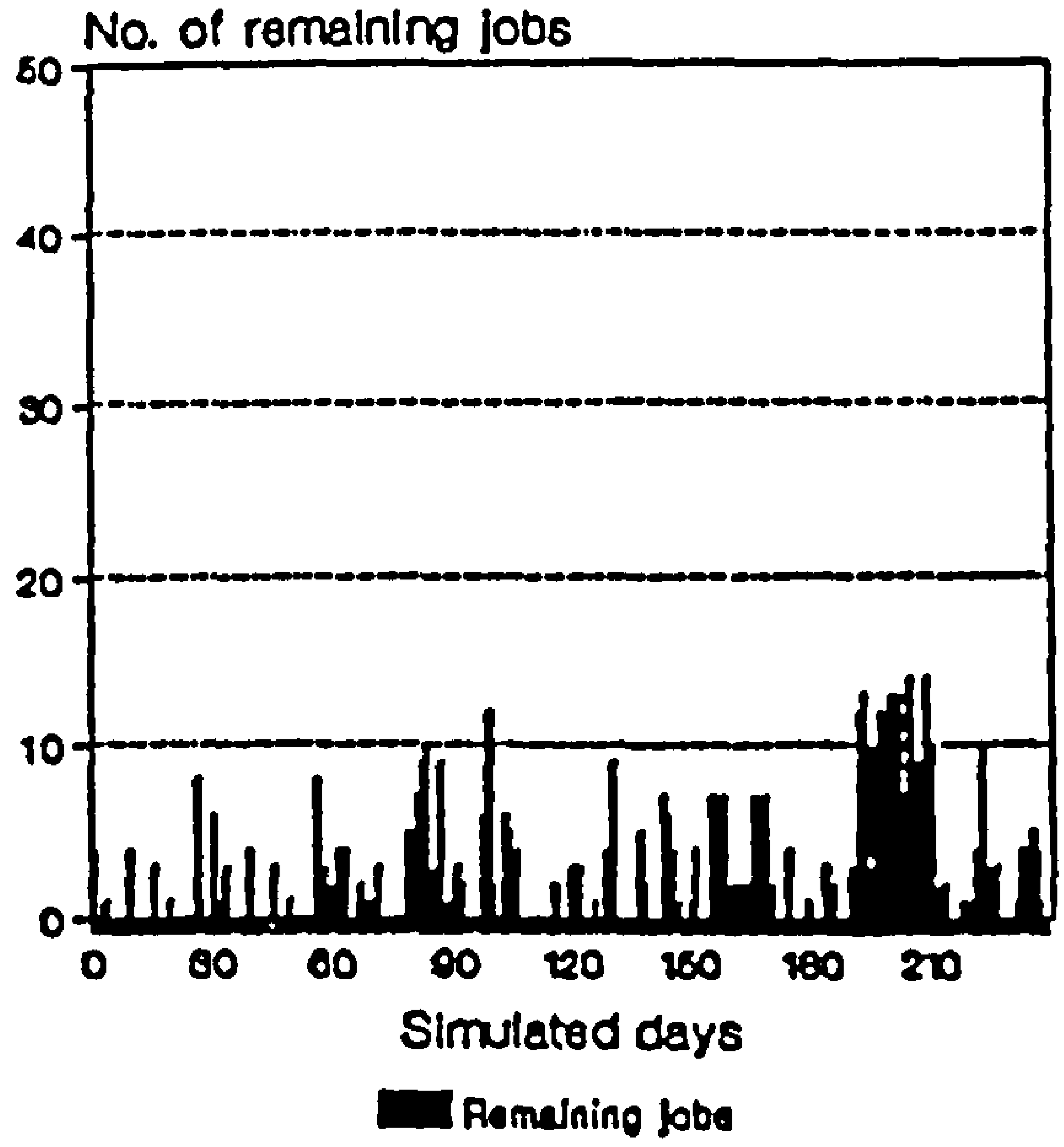


Figure 7.6: Shows the number of remaining jobs per simulated day in two experiments, by using different random number seeds in each experiment. Four tradesmen are employed using previewing policy.

(a)
USING 5 PLUMBERS (1st EXPERIMENT)



(b)
USING 5 PLUMBERS (2nd EXPERIMENT)

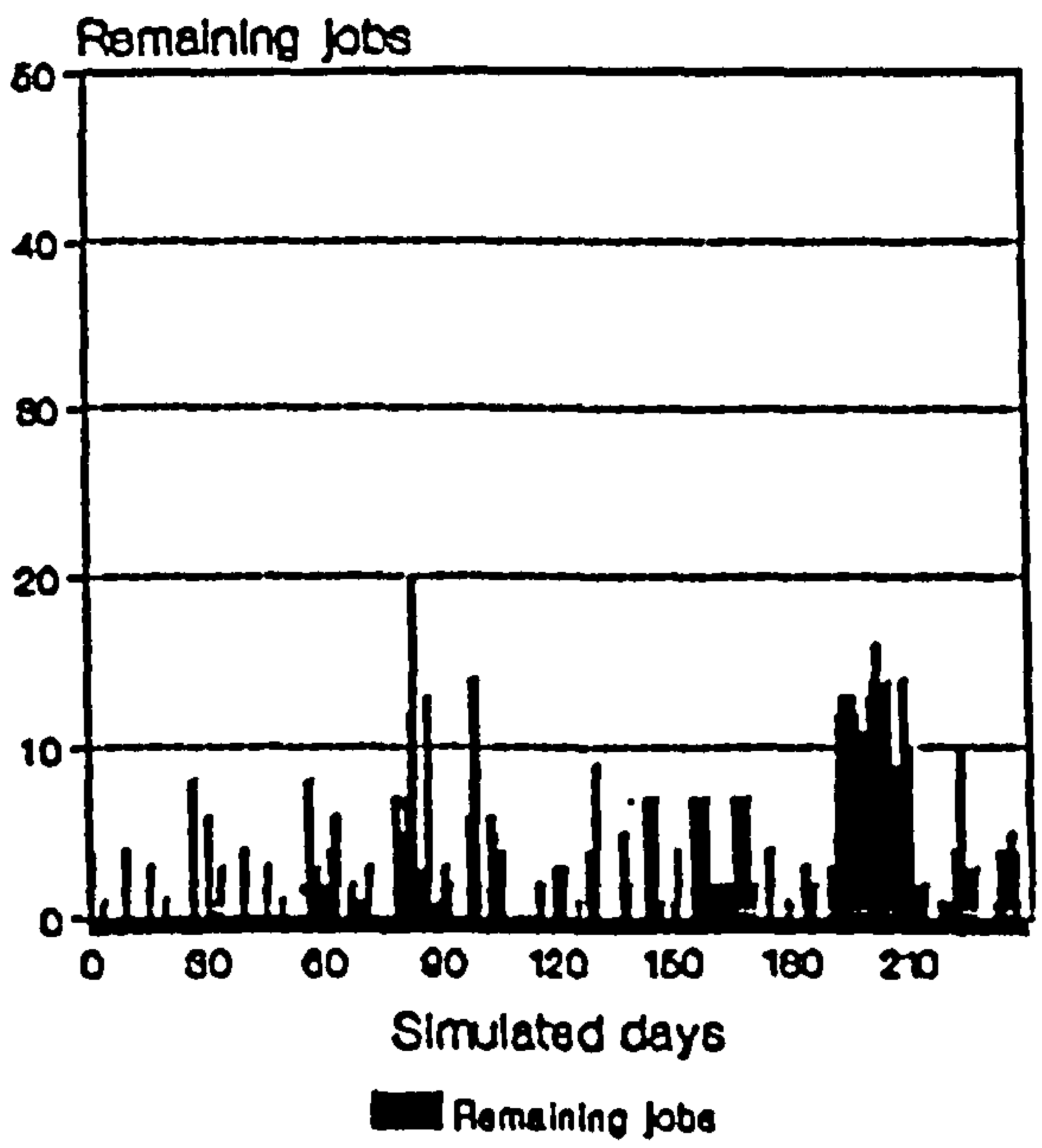
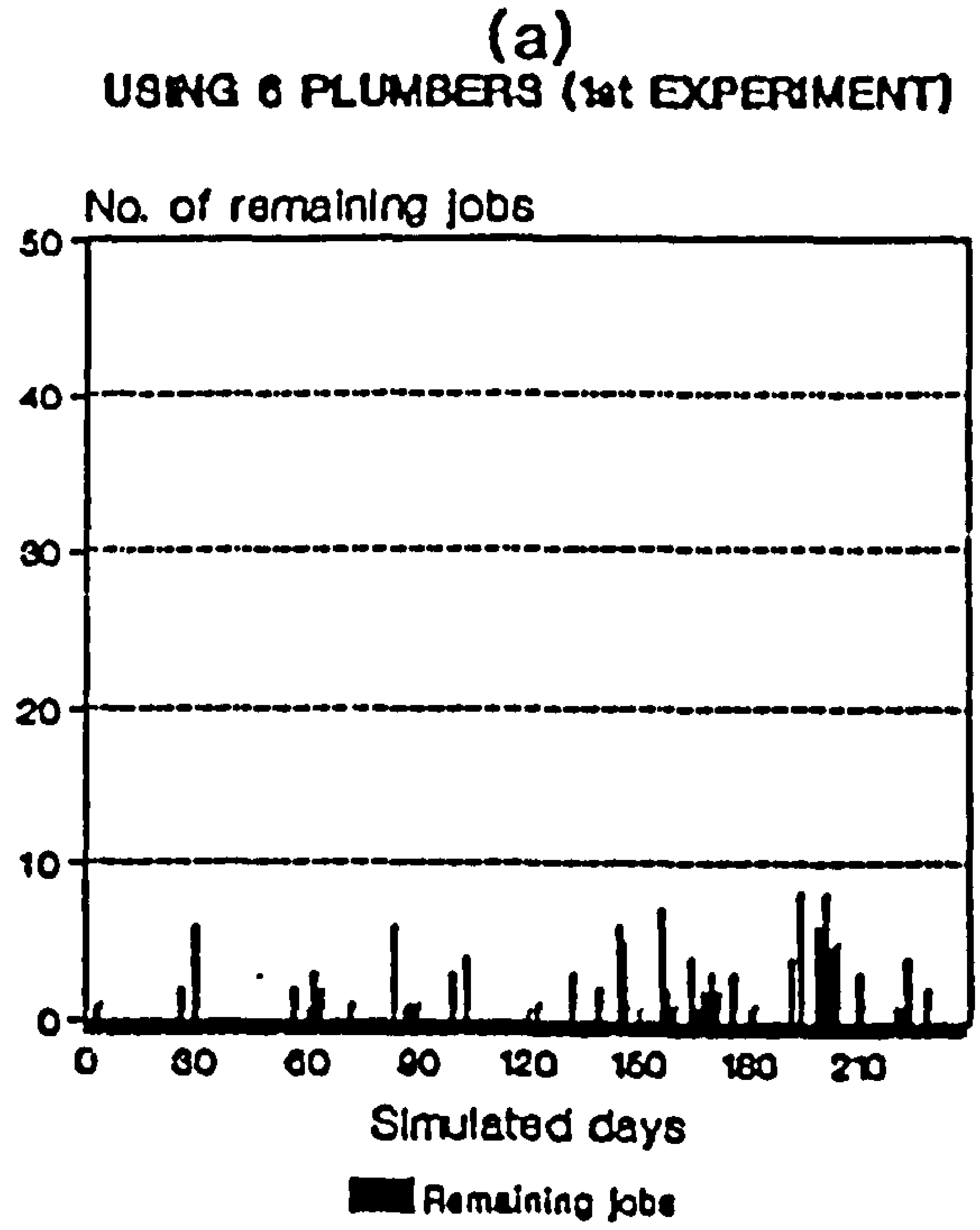


Figure 7.7: Shows the number of remaining jobs per simulated day in two exp^riments, by using different random number seeds in each experiment. Five tradesmen are employed using previewing policy. Note the change in the Y scale from previous figures.



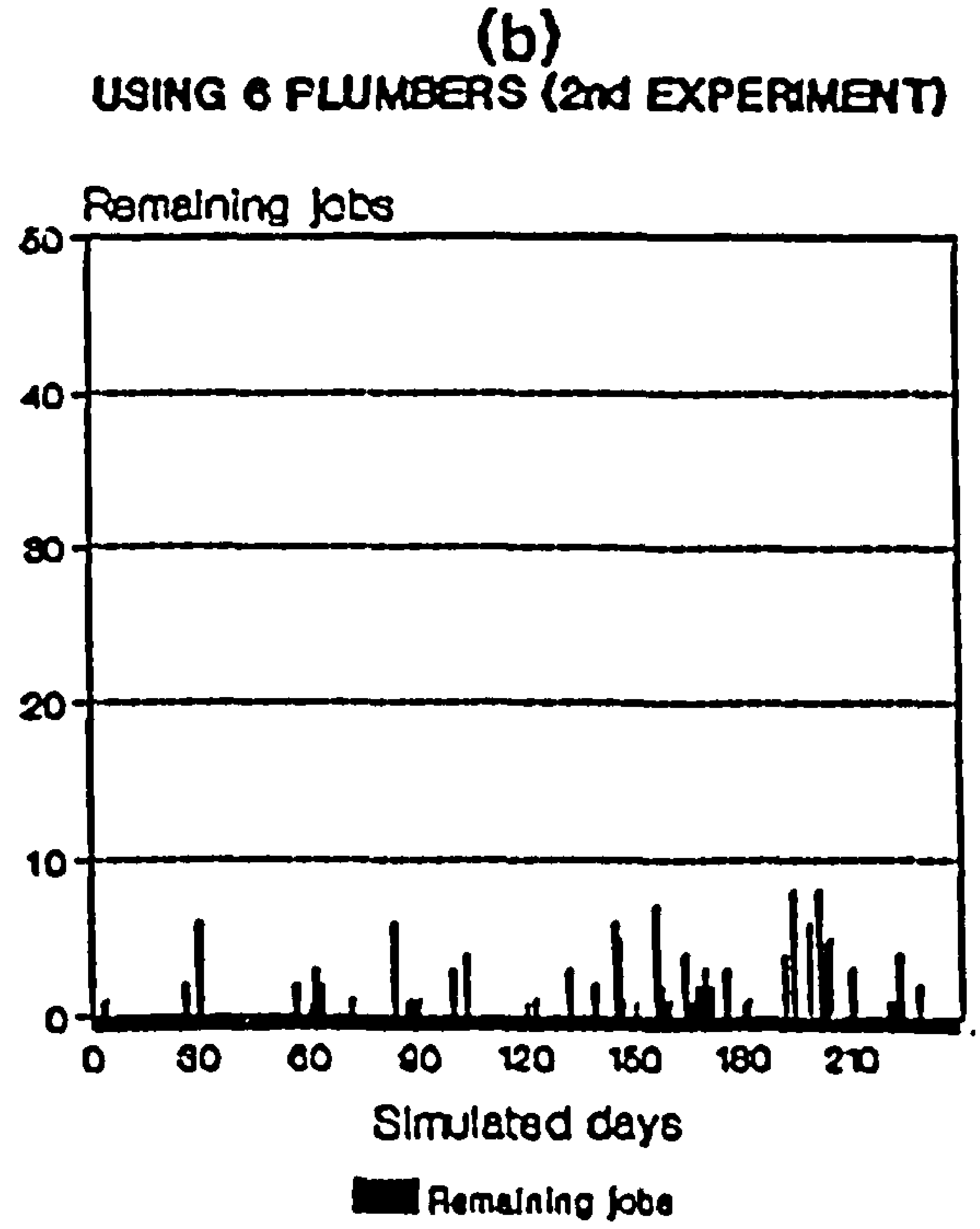


Figure 7.8: Shows the number of remaining jobs per simulated day in two experiments, by using different random number seeds in each experiment. Six tradesmen are employed using previewing policy. Note that the same Y scale has been used as in figure 7.7.

Assuming that the job arrival rate is very large, i.e. the interarrival time is very short, then the utilization of employing 2, 3, 4, .. , n plumbers remains at its highest level. That is, as the daily demand for a given trade is assumed very large and goes to infinity, then it is expected to have the same high utilization when employing 2, 3, .., n tradesmen. Therefore, we can assume that the cummulative or total active time for 'previewing policy' simulating plumbing trade in employing 1, 2, 3, 4, .. ,n tradesmen, can be represented by a straight line, say $y(x)$, as illustrated by the assumed total active time in figure 7.9(a).

In the real life, the day-to-day demand for maintenance per trade is finite and the job arrivals rate can be estimated with relative accuracy, but depends upon the availability of reliable data. For instance, simulating the 'previewing maintenance management policy', (section 6.6.1), using the first simulation program, i.e. 'collecting one job at a time', (section 6.3), and employing, say, 1, 2, .. ,6 plumbers, has shown that the utilization is high when employing 1-4 plumbers, namely between 47.5% - 43.7%, see figures 7.3-7.6. Employing 5, and 6 plumbers reduces the utilization considerably, to 37.0% and 30.83% respectively. This is evident in figures 7.7 and 7.8 which show relatively few remaining jobs per day. These remaining jobs shown in figures 7.7, and 7.8 which may either be arrived late in the working day or left incompleted for the following day because of the time constraints. The average active time per plumber when employing 5 & 6 plumbers is effectively at an asymptotic level and it is expected to be in the same level if more than 6 plumbers are employed. The cumulative distribution of the simulated or (observed) active time is shown in figure 7.9(b).

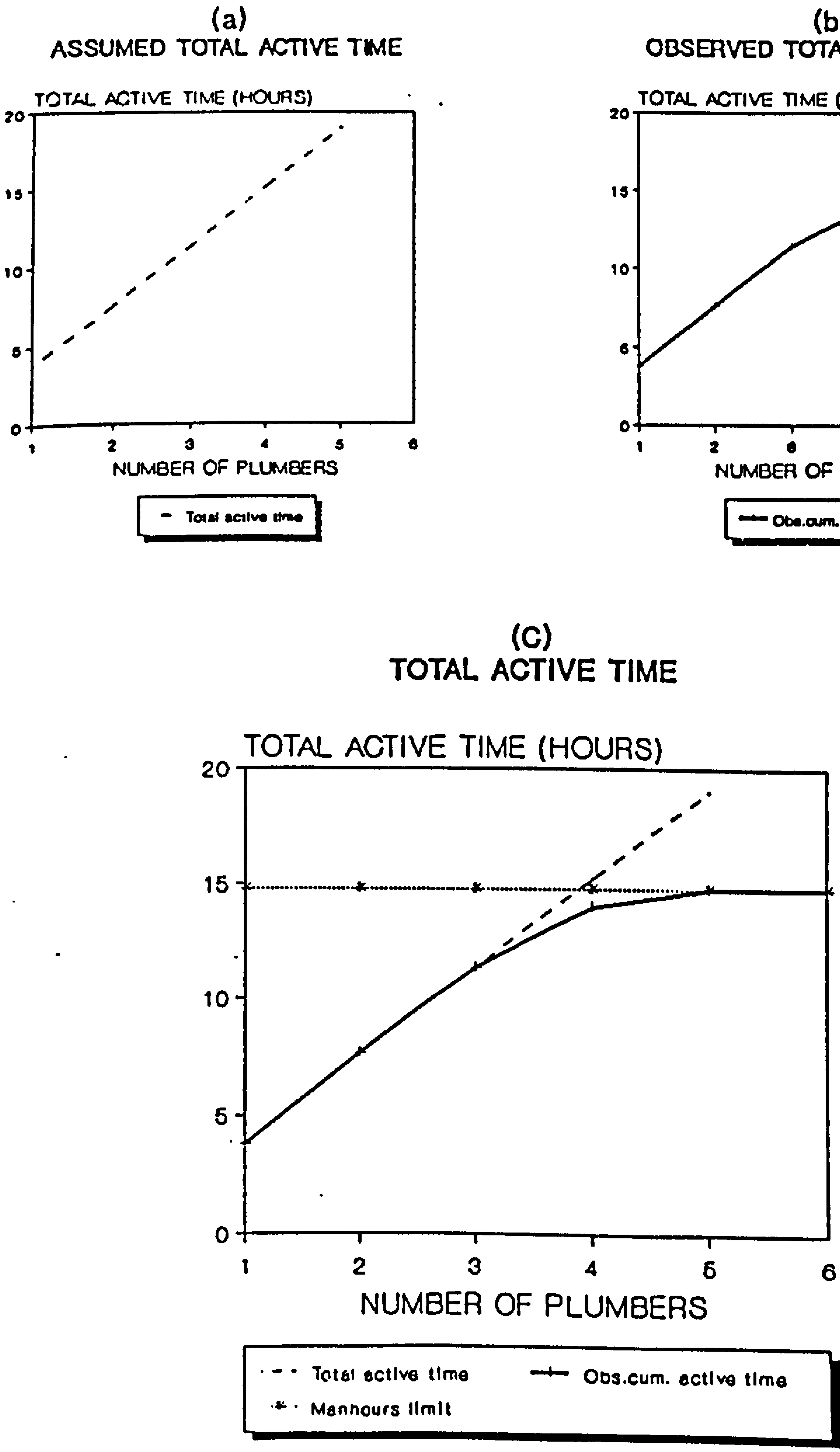


Figure 7.9: (a) Assumed total active time; (b) Observed, simulated, total active time; (c) Assumed, observed total active time, and the manhours limit, using 'previewing policy'.

As the number of tradesmen employed increases to more than 5, then we can observe no increase in the total active time, see figure 7.9(b), which means as the number of tradesmen increases, the daily work load is met, but with an increase in the idle time. Therefore, since the asymptotic level of the observed total active time is reached within the employment range considered, this asymptotic level can be considered to represent the manhours limit required to meet the day-to-day demand for maintenance per given trade for a given maintenance management policy. Therefore it can be represented by a horizontal straight line, say L, the manhours limit per simulated day, see figure (7.9c). The manhours limit is trade related, since it is dependent on the interarrival time of jobs, and the repairing and diagnosing time of jobs which are trade related. It is also policy related, since it is dependent on the method of deployment being used.

It is argued that the intersection point of the assumed total active time line, $y(x)$, with the manhours limit line L, see figure 7.9(c), represents the minimum number of maintenance staff that can meet the day-to-day demand for maintenance in the simulated maintenance management policy, given that the maintenance staff are expected to be busy all the time (not idle), that is there is always a backlog of jobs waiting to be done. The total active time, $y(x)$, the manhours limit, L, and the minimum number of maintenance staff per trade x_p are presented as follows:

$$y(x) = ax$$

$$L = b = ax_p$$

$$x_p = L/a \qquad (7.1)$$

where,

a, b : are constants;

$y(x)$: assumed total active time per simulated policy per trade;

L : manhours limit per simulated policy per trade;

x : the number of tradesmen; and

x_p : the minimum number of tradesmen.

In the example of 'previewing plumbing jobs', figure 7.9(c), x_p = 3.89 plumbers, i.e. 4 plumbers is the minimum number of tradesmen which can meet the day-to-day demand for maintenance when adopting a policy of collecting one job at a time and previewing all the jobs before repair.

When employing 4 plumbers, it can be noticed, in figure 7.9(c), that the observed (simulated) cumulative active time is still less than the manhours required limit L, even if the minimum number of plumbers calculated by the suggested procedure is slightly less than four. The level, of observed active time when employing 4 plumbers, has been investigated through examining the average number of remaining jobs when employing 4 plumbers as shown in figure 7.6. It can be noticed that during the (1st–70th) and (110th–160th) simulated days, figure 7.6, that there are a lot of days when zero or very few incomplete or remaining jobs are present, which implies that the plumbers are generally in control. Some of the 4 tradesmen may be idle for a while before the end of the simulated day, and be idle for periods in the next working simulated day waiting for the arrival of next jobs. It is this idle time that has reduced the observed level of active time per tradesman, and therefore the observed total active time for four tradesmen. Examining figure 7.6, it is evident, as mentioned before, that there are two periods when the remaining jobs are piling, and are explained by peak sickness and holiday seasons. It is possible that the maintenance department employs a number of temporary tradesmen during such periods to overcome this problem. This situation has already been observed by the maintenance management, in the real life, at Withington hospital, and their action was to employ a suitable number of tradesmen on temporary basis.

If we arguably assume that the 4 plumbers employed, figure 7.6, are under–utilized, that is, we are observing idle time, i.e. the arrival rate is lower than the service rate of jobs. If the process is subject to control through, for example, increasing the demand for plumbing trade. That is, speed up the job arrivals, i.e. reduce the interarrival time, until the idleness is reduced to the minimum or, equivalently, the utilization is increased to the maximum. This would occur when the arrival rate equals the service rate of jobs. Any further increase in the demand or, equivalently, further reduction in the interarrival times would result in a 'bottleneck' situation, i.e. the arrival rate is higher than the service rate. This case is similar to what have been shown when employing less than 4 plumbers in figures 7.2–7.5. If we repeat the process in the opposite direction, by assuming a decrease in the demand, i.e. an increase in the interarrival times, then more idleness is expected or, equivalently, the utilization of the four plumbers is lower than before. This would occur when the arrival rate is less than the service rate of jobs, and it is similar to the case when employing more than four plumbers shown in figures 7.7–7.8.

7.3. Comparisons and evaluations of alternative maintenance management policies

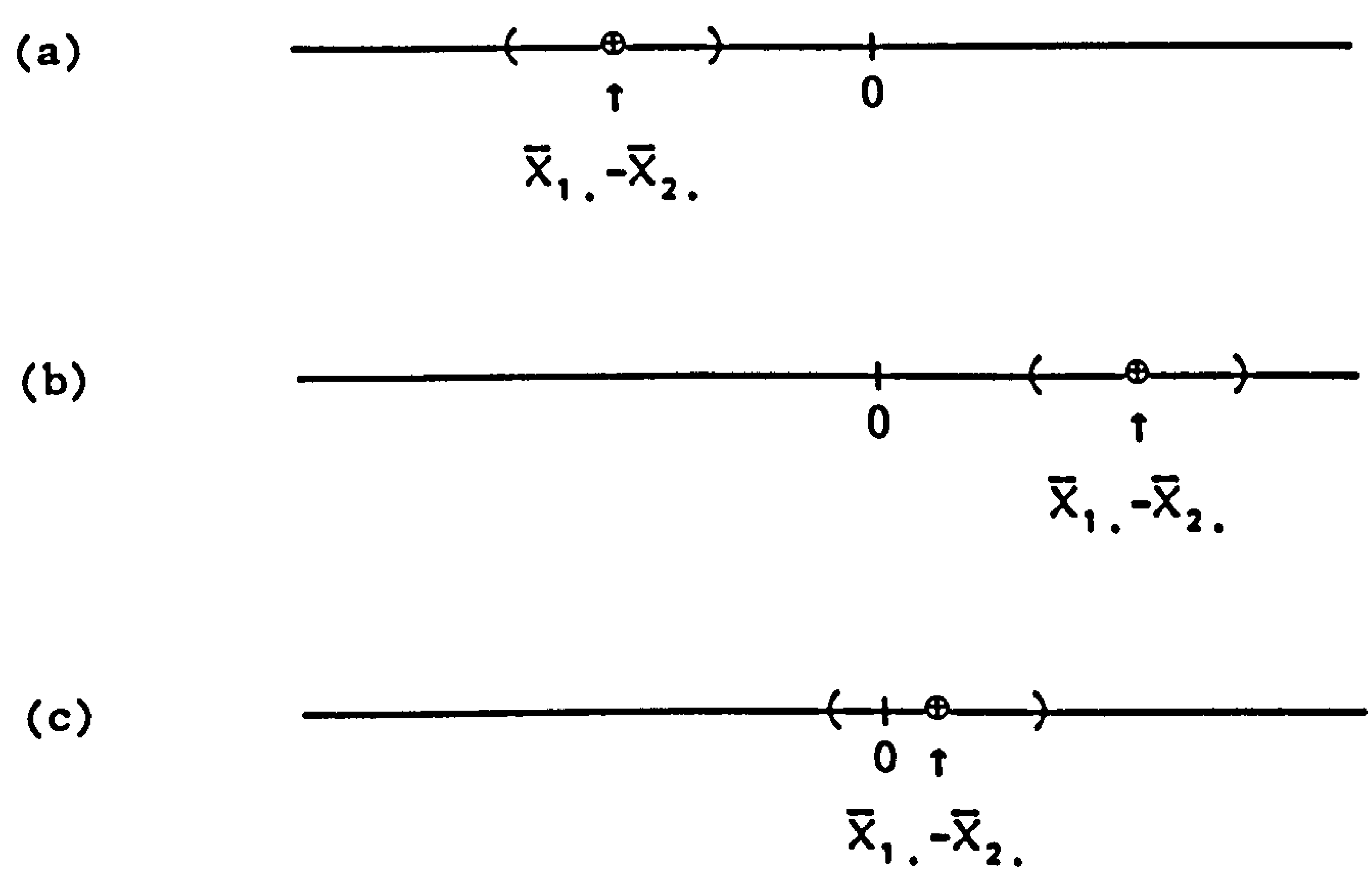
Four different simulated methods of deployment have been compared for evaluation. These methods are discussed in section 6.3 – 6.5, that is, (1) collecting one job at a time when 'previewing all the incoming jobs', (2) collecting one job at a time when 'not previewing all the incoming jobs',

(3) 'collecting a batch of jobs at a time', and (4) 'delaying non-urgent jobs and grouping them in time'. The comparison of maintenance management policies in terms of performance measures was proposed in order identify superior maintenance management policies for Withington hospital.

The first simulation model, i.e. 'collecting one job at a time', consists of two joined simulation programs presenting two simulated methods of deployments that is, (1) 'previewing' and (2) 'not previewing' defects before repair policies as discussed in sections 6.6.1 & 6.6.2. Depending upon the comparison of the results of the above two policies, the superior management policy is compared with alternative system that is, (3) 'collecting a variable batch size of jobs at a time policy', and the best of the late policies is then compared in turn with another method of deployment that is, (4) 'delaying non-urgent jobs and grouping them in time policy'.

The simulation programs have been run for one calendar year, equivalent to 312 working days execluding Sundays. From replication, or simulation run, j of policy i, an estimate X_{ij} can be obtained of the performance measure. The goal of the simulation experiment is to obtain point and interval estimates of the difference between the mean performance measures of pairs of the methods of deployment or policies, namely $\bar{X}_{1.}-\bar{X}_{2.}$ for policy (1) and (2). The confidence interval is used to answer two questions (Banks & Carson 1984): (1) How large is the mean difference, and how accurate is the estimator of the mean difference? (2) Is there a significant difference between the two policies? This second question will lead to one of three possible conclusions:

(1) If the confidence interval (c.i.) for $\overline{X}_{1.}-\overline{X}_{2.}$ is totally to the left of zero, as shown in figure 7.10(a) below, there is strong evidence for the hypothesis that $\overline{X}_{1.}-\overline{X}_{2.}<0$, or equivalently $\overline{X}_{1.}<\overline{X}_{2.}$. If X measures mean active time, we conclude here that the mean active time for policy (1) is smaller than that for policy (2).



Figur 7.10: Three possible confidence intervals when comparing two systems.

(2) If the c.i. for $\overline{X}_{1.}-\overline{X}_{2.}$ is totally to the right of zero, as shown in figure 7.10(b), there is strong evidence that $\overline{X}_{1.}-\overline{X}_{2.}>0$, or equivalently $\overline{X}_{1.}>\overline{X}_{2.}$, which can be interpreted as policy (2) being better than policy (1) in reducing the total manhours required to meet the demand for maintenance.

(3) If the c.i. for $\overline{X}_{1.}-\overline{X}_{2.}$ contains zero, then, there is no strong statistical evidence that one policy is better than the other, in terms of the measure of performance considered.

In addition to the possible three conclusions, the confidence interval provides a measure of the accuracy of the estimator of $\overline{X}_{1.}-\overline{X}_{2.}$.

A two-sided $100(1-\alpha)\%$ confidence interval for $\overline{X}_{1.}-\overline{X}_{2.}$ will be of the form:

$$(\overline{X}_{1.}-\overline{X}_{2.}) \pm t_{\alpha/2,\nu}\ S.E.(\overline{X}_{1.}-\overline{X}_{2.}) \qquad (7.2)$$

where $\overline{X}_{i.}$ is the sample mean performance measure for policy i over all replications or simulation runs:

$$\overline{X}_{i.} = \frac{1}{r} \sum_{j=1}^{r} X_{ij}$$

where ν is the degree of freedom associated with the variance estimation, $t_{\alpha/2,\nu}$ is the $100(1-\alpha/2)$ percentage point of a t distribution with ν degree of freedom, and S.E. represents the standard error of specific point estimator which equals $\sigma/\sqrt{r}$. This statistical technique assumes that the basic data, X_{ir}, are approximately normally distributed. This assumption is reasonable, according to the central limit theorem, since each X_{ir} is itself a sample mean of observations from replication r.

By design of the simulation experiment, X_{1j} ($j = 1, 2, .., r$) are identically and independently distributed (i.i.d.) with mean $\overline{X}_{1.}$ and standard deviation σ_1. Similarly, X_{2j} ($j = 1, 2, .., r$) are i.i.d. with mean $\overline{X}_{2.}$ and standard deviation σ_2.

There are three techniques for computing the confidence interval in inequality 7.2, which are based on three different assumptions (Banks & Carson 1984), these are: (1) Independent sampling with equal variances; (2) Independent sampling with unequal variances; And (3) correlated sampling, or common random numbers. The technique for computing the confidence interval in inequality 7.2 used for the maintenance management simulation models is based on the correlated sampling which means that, for each replication j, the same streams of random numbers are used to simulate both systems or maintenance management policies. Thus the number of replication in system 1, are r_1, and the number of replications in system 2, are r_2, and they must be equal, i.e.

$r_1 = r_2 = r.$

Policy i	Replication j				sample mean	sample variance
	1	2	...	r		
1	X_{11}	X_{12}		X_{1r}	$\bar{X}_{1.}$	S_1^2
2	X_{21}	X_{22}		X_{2r}	$\bar{X}_{2.}$	S_2^2

Table 7.1: Summary measures of simulation output data when comparing two policies.

Thus for each replication r, the two estimates, X_{1r} and X_{2r}, are no longer independent but rather are correlated. Since independent streams of random numbers are used on any two replications, the pairs (X_{i1}, X_{i2}) are mutually independent. For example, in table 7.1, the observation X_{11} is correlated with X_{21}, but X_{11} is independent of all other observation. The purpose of using correlated sampling is to induce a positive correlation between X_{1r} and X_{2r} for each r and thus to achieve a variance reduction in the point estimator of mean difference $\bar{X}_{1.} - \bar{X}_{2.}$ (Kleijnen 1974/1975, Kleijnen & Groenendaal 1992). In general, the variance, may call it V_{corr}, is given by,

$$\mathrm{var}(\bar{X}_{1.}-\bar{X}_{2.}) = \mathrm{var}(\bar{X}_{1.}) + \mathrm{var}(\bar{X}_{2.}) - 2\mathrm{cov}(\bar{X}_{1.},\bar{X}_{2.})$$

$$= \frac{\sigma_1^2}{r} + \frac{\sigma_2^2}{r} - \frac{2\rho_{12}\,\sigma_1\,\sigma_2}{r}$$

where ρ_{12} is the correlation coefficient between X_{1r} and X_{2r}.

When using independent sampling, $\bar{X}_{1.}$ and $\bar{X}_{2.}$ are statistically independent, the variance of $\bar{X}_{1.}-\bar{X}_{2.}$, may call it V_{ind} is

$$\mathrm{var}(\bar{X}_{1.}-\bar{X}_{2.}) = \mathrm{var}(\bar{X}_{1.}) + \mathrm{var}(\bar{X}_{2.})$$

$$= \frac{\sigma_1^2}{r_1} + \frac{\sigma_2^2}{r_2},$$

therefore

$$V_{corr} = V_{ind} - \frac{2\rho_{12}\sigma_1\sigma_2}{r} . \qquad (7.3)$$

If correlated sampling works as intended, the correlation ρ_{12} will be positive; hence, the second term on the right hand side of equation 7.3 will be positive and therefore $V_{corr} < V_{ind}$.

That is, the variance point estimator will be smaller when using correlated sampling than when using independent sampling. A smaller variance, for the same sample size, implies that the estimator based on correlated sampling will generally produce shorter and therefore more accurate confidence interval (Law & Kelton 1982). Table 7.2, shows the correlation coefficients between the output (the active time) of the simulated maintenance management policies of the plumbing trade when employing 4 plumbers, which is the asymptotic level in most of the management policies. All the correlation coefficients are positive, most of them are highly correlated; just one exception, that the correlation coefficients between "working 7 days policy" and the other policies have shown positive but low correlation coefficient. That is related to the additional working days, that is Sundays. Table 7.3 shows a sample of four weeks data, chosen at random, of average active time per day per all the simulated policies, when employing 4 plumbers per policy.

Policy	1	2	3	4	5	6
7	0.209	0.170	0.145	0.216	0.220	0.191
6	0.603	0.479	0.492	0.968	0.783	
5	0.629	0.553	0.608	0.770		
4	0.591	0.471	0.492			
3	0.490	0.412				
2	0.659					

Table 7.2: Table shows the correlation coefficients between the output of the active time of the simulated policies of plumbing trade, when employing 4 plumbers. The policies are: (1) previewing, (2) not previewing, (3) batch of jobs, (4) delaying non-urgent jobs, (5) employing extra part-time plumber, (6) no sickness model, and (7) working 7 days a week.

Anoher variance reduction techniques, beside the common random numbers or correlated sampling have been used that is, 'antithetics' random numbers.

The 'antithetic random numbers' are usually implemented for simulation by generating one simulation run from the random numbers u_1, u_2, u_3, .., and the second, antithetic run from the random numbers $(1-u_1)$, $(1-u_2)$, $(1-u_3)$, ...

Suppose the random variable X_1 result from the first run and the random variable X_2 results from the antithetic run. Thus

$$\bar{X} = \frac{(X_1 + X_2)}{2}$$

is an unbiassed estimator of E(X) and

$$var(X) = \tfrac{1}{4}[var(X_1) + var(X_2) + 2cov(X_1,X_2)].$$

If $cov(X_1,X_2)$ is negative, then the variance of the average X decreases. Hence a reduced variance is to be expected provided strong negative correlation is introduced between the two runs. The random variables u and (1-u) are both distributed uniformaly on (0,1). The correlation coefficient for u and (1-u) is -1. The simulation model is a non-linear transformation of a sequence of pseudorandom numbers, and gives X_1 and X_2 as result. Hence X_1 and X_2 do not have a correlation coefficient of -1. But it is hoped that an outlier in X_1 will be compensated by an opposite oulier in X_2, that is we assume that $cov(X_1,X_2)$ is negative (Kleijnen & Groenendaal 1992). Antithetic sampling should be employed in conjunction with common random numbers in order to control some of the variation effects (Pidd 1988).

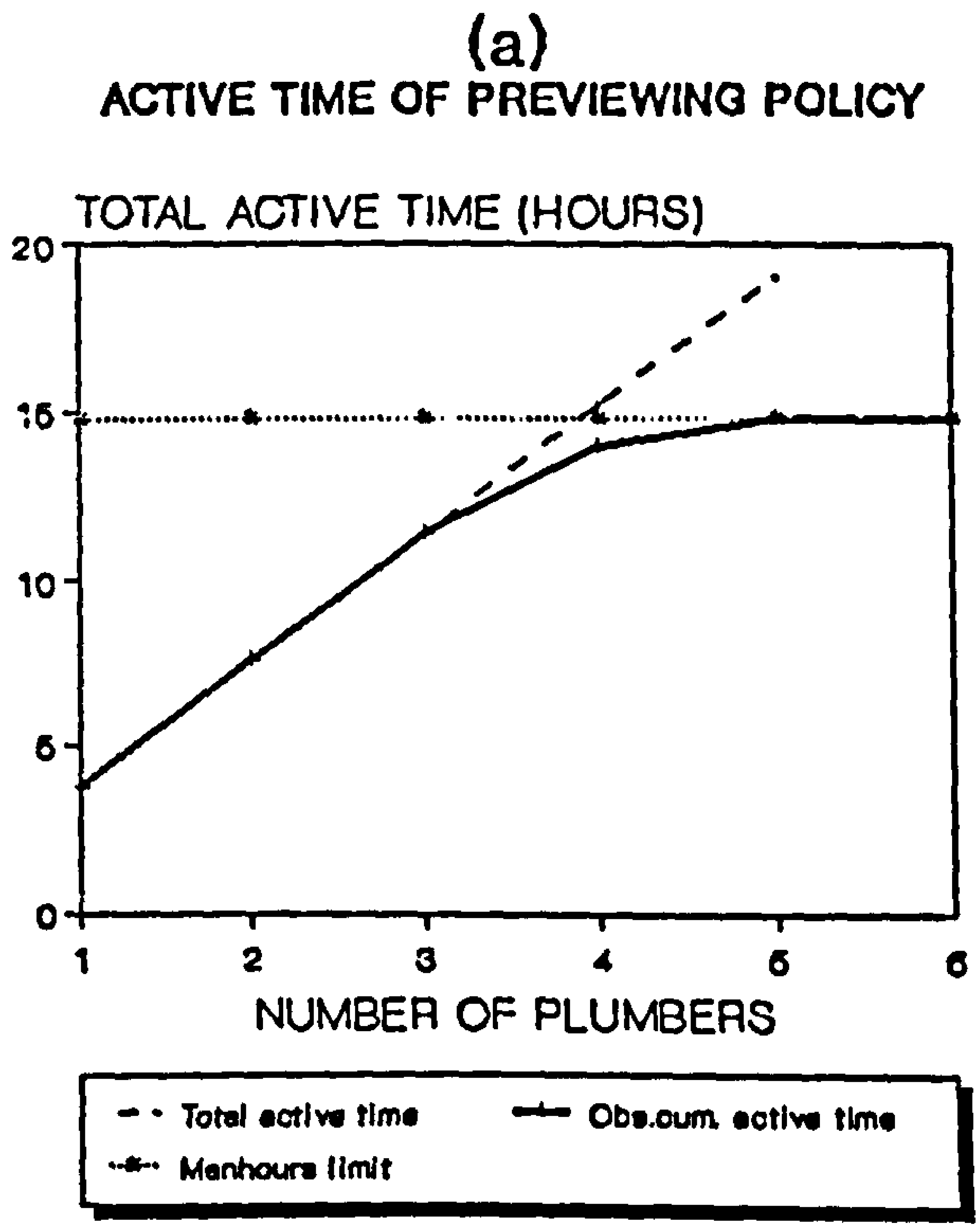
The variance reduction techniques imply that the pseudorandom numbers are sampled such that the expected value of the estimator does not change, but its variance decreases. Those methods are discussed in Kleijnen & Groenendaal (1992) and Pidd (1988).

7.3.1. Comparing and evaluating previewing and not previewing policies

Using the first method of deployment which has been discussed in section 6.3 that is, "collecting one job at a time model", 'previewing (1)' and 'not previewing (2)' policies have been simulated in order to evaluate the gain of changing from "previewing all the defects before repair policy (1)" prescribed by the South of Manchester District Health Authority, to a policy which relies on the experience of the supervisors to specify resources needed. It is possible that thought could be given to developing a computer data base system capable of predicting the required resources for most of the jobs arriving.

The minimum number of tradesmen which can meet the day-to-day demand for maintenance in 'previewing policy (1)', see figure 7.11(a), has been calculating using equation 7.1, x_p=3.89 plumbers, while x_p=3.07 is the minimum number of plumbers to meet the same day-to-day demand for maintenance when not previewing most of the defect, see figures 7.11(b). The gain to be made by implementing a 'not previewing policy (2)' is estimated to be around 21.07% of the minimum workforce required for 'previewing policy (1)'.

The level of productive time gained by reducing the travelling time to and from the job locations, is shown in figure 7.12(b). The reduction in the percentage of observed travelling time when not previewing most of the defects implies time is available for more productive use such as repairing and diagnosing the defects.



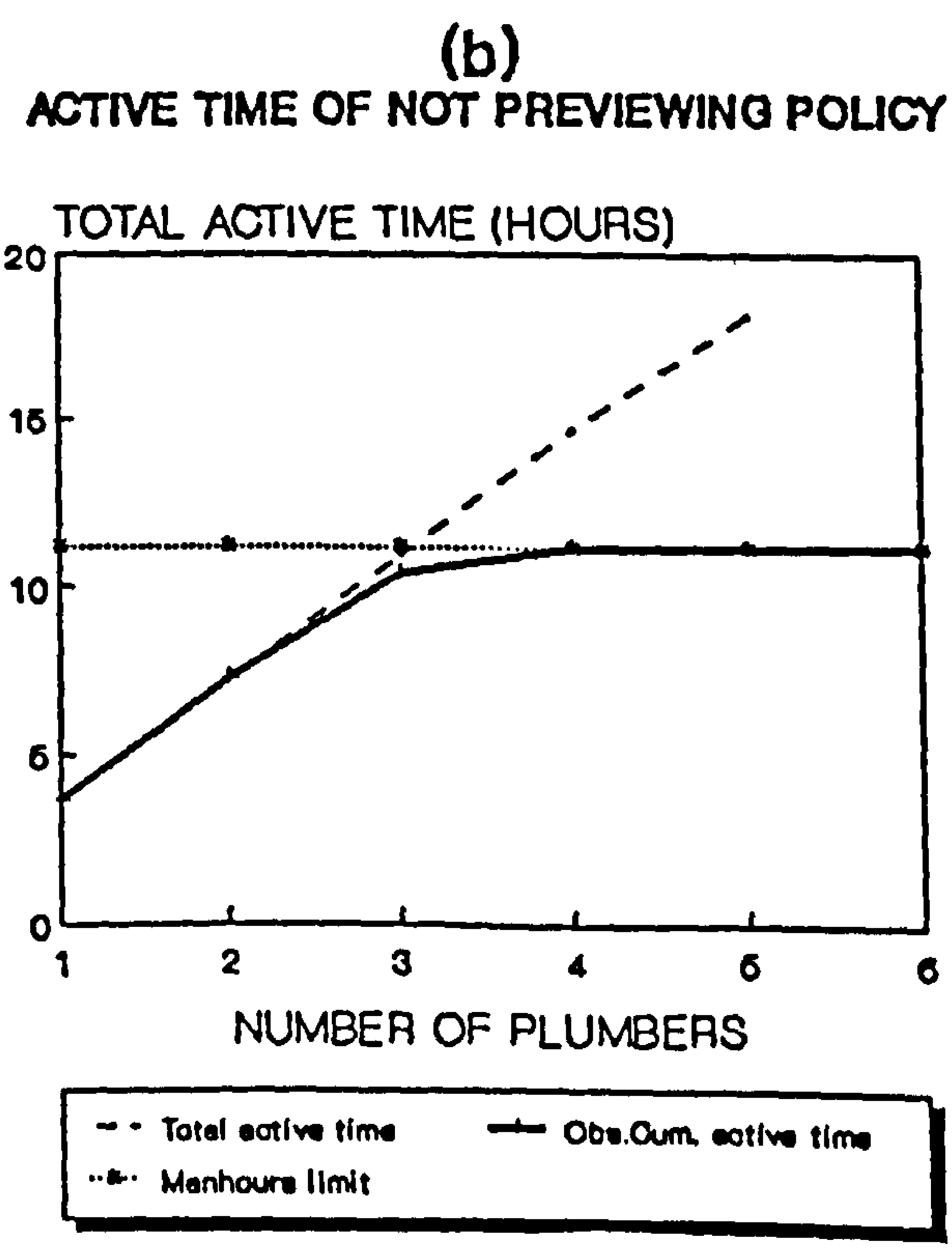


Figure 7.11: Assumed, observed total active time, and manhours limit, using; (a) previewing policy; (b) Not previewing policy.

The results of adopting a 'not previewing policy (2)' can be summarised by: First, the manhours limit required to meet the daily demand for plumbing trade per working day has been reduced from 14.8 to 11.2 manhours per day, see figures 7.11(a) and 7.11(b), with a 24.32% reduction in the manhours required to meet the daily demand for maintenance. Second, the average number of jobs completed per day has increased when adopting not previewing policy, see figure 7.12(a). Third, and as a consequence of the first two points, the average number of remaining jobs outstanding at the end of each working day when 'not previewing' are less than in 'previewing policy', figure 7.12(c). Therefore the service time, i.e. the time since the job arrival until it's completion, is less than the service time in the previewing policy, see figure 7.12(d).

For the two sets of correlated runs of 'previewing' and 'not previewing' policies, the observations are paired and analyzed. To Compute a $100(1-\alpha)\%$ confidence interval with the correlated data of the two policies, first the difference, between the total active time under both policies when employing 4 plumbers, has been computed

$$D_j = X_{1j} - X_{2j}$$

where D_j are i.i.d., by the definition of correlated sampling; then the sample mean difference D and the variance $S_D{}^2$ have been computed in the ordinary way,

$$D = 3.6 \text{ hours}$$

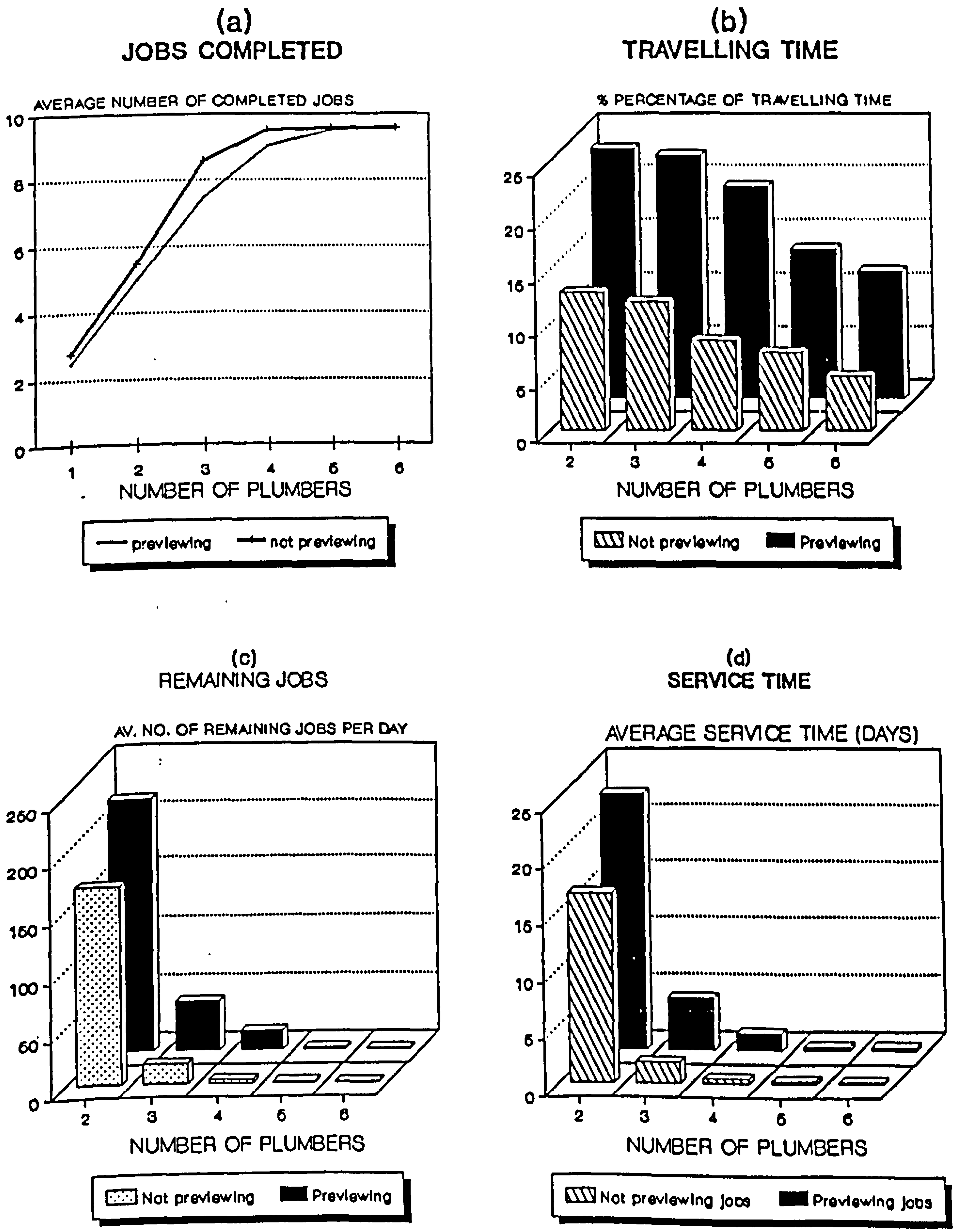


Figure 7.12: Comparison between 'previewing' and 'not previewing' policies in terms of; (a) Average number of jobs completed per day; (b) Percentage travelling time; (c) Average number of remaining jobs; (d) Average service time per job.

the standard deviation σ of the sample D_j = 1.52 hours (with ν = 311 degrees of freedom), and the standard error S.E.(D)=0.086. Thus, a 100(1−α)% confidence interval with the correlated sets of data when α=0.01, i.e. 99% c.i. for the true mean difference in response times, is

$$3.6 \pm 2.58\ (0.086)$$

or

$$3.378 \leq \bar{D} \leq 3.822$$

Since the 99% confidence interval is positive, then there is strong statistical evidence that adopting a 'not previewing policy (2)' can significantly reduce the total manhours limit required to meet the day-to-day demand for maintenance by 3.6 manhours per day, saving 24.3% of the manhours limit required in 'previewing policy (1)'. Therefore, the "not previewing policy" has been considered as a superior to the 'previewing policy' and the maintenance department is encouraged to develop the skills of the supervisors, or introducing a data base computer system in order to help in establishing the required information for identifying the required resources and spares needed for each job arriving.

7.3.2. Evaluating 'collecting a batch of jobs policy (3)'

'Collecting a variable batch size of jobs policy (3)' has been simulated by '*not previewing*' most of the incoming jobs but depending upon the supervisor's opinions since, as shown in the previous section, 'not previewing policy (2)' can save about 24% of the required manhours to meet the demand for maintenance of the 'previewing policy (3)'.

The minimum number of plumbers required to meet the demand for plumbing trade, has been calculated, using equation 7.1, x_p= 3.005 plumbers, see figure 7.13(b), compared to a minimum average of 3.07 plumbers, figure 7.13(a), required to meet the same demand for maintenance when 'collecting one job at a time', shown in section 7.3.2.

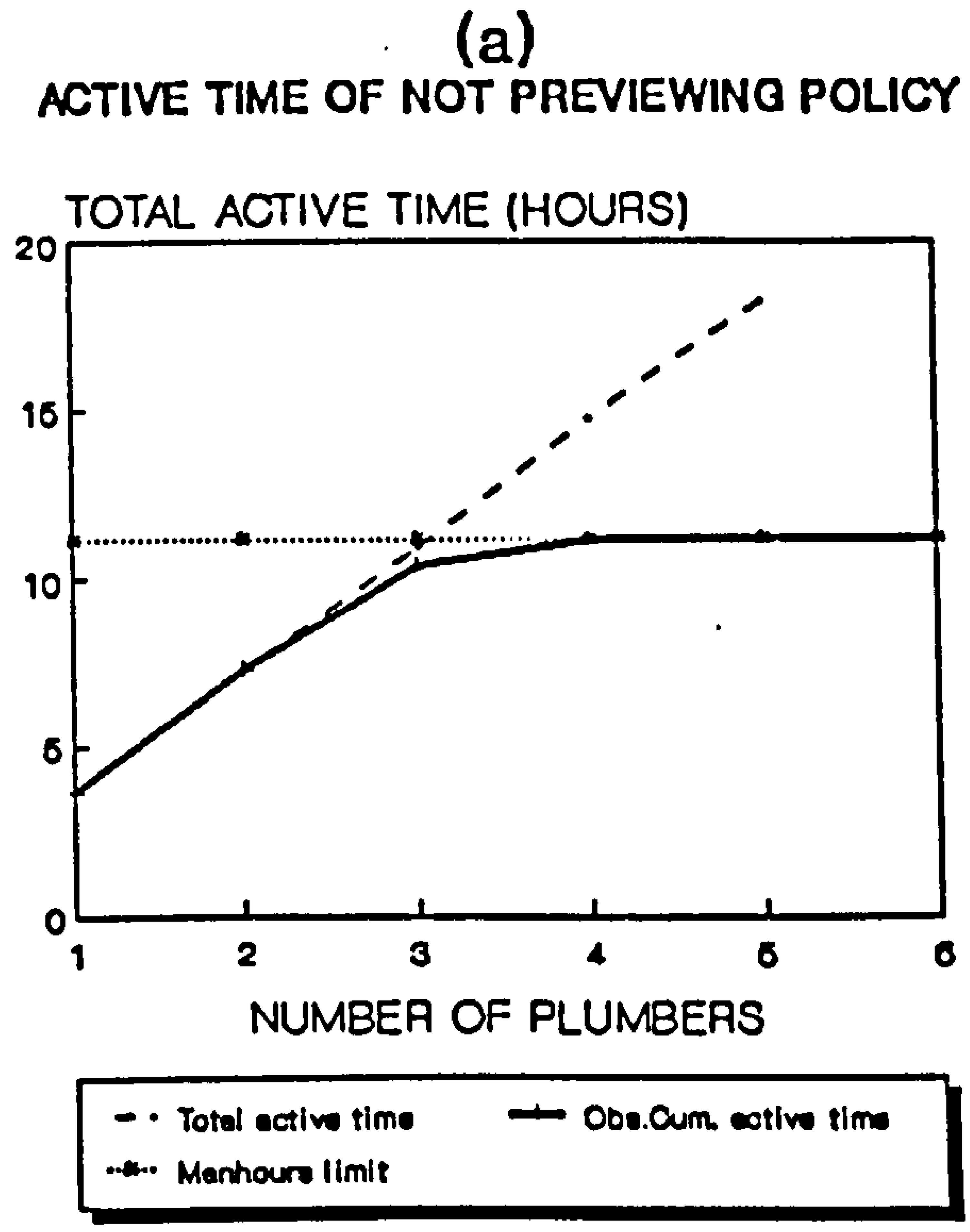
The gain of adopting 'collecting a batch of jobs policy (3)' is estimated as 2.11% of the minimum workforce required of 'not previewing policy (2)', and 22.75% of the minimum workforce in the 'previewing policy (1)'. The gain in manhours limit is estimated to be 5.53%, and 28.51% of the total manhours of 'not previewing (2)' and 'previewing (1)' policies respectively, see table 7.4 in the Appendix.

The observed (simulated) travelling time, figure 7.14(b), is reduced when a batch of jobs is being simulated. This gain in travelling time, has been used for more productive activities such as repairing jobs. Therefore the average number of jobs completed in the 'batch policy (3)' is higher than for the non-batch 'not previewing policy (2)', specially when employing 1-3 plumbers, see figure 7.14(a).

In order to evaluate this policy, the point estimator of the difference of the total active time, between the compared policies, when employing 4 plumbers was calculated , namely

$$\bar{D} = 0.62 \text{ hours}$$

with the standard deviation σ of the sample D_j = 2.14 hours, with 311 degree of freedom, the standard error S.E.(D)= 0.12 hours. The 99% c.i. for the true mean difference in the total active time is



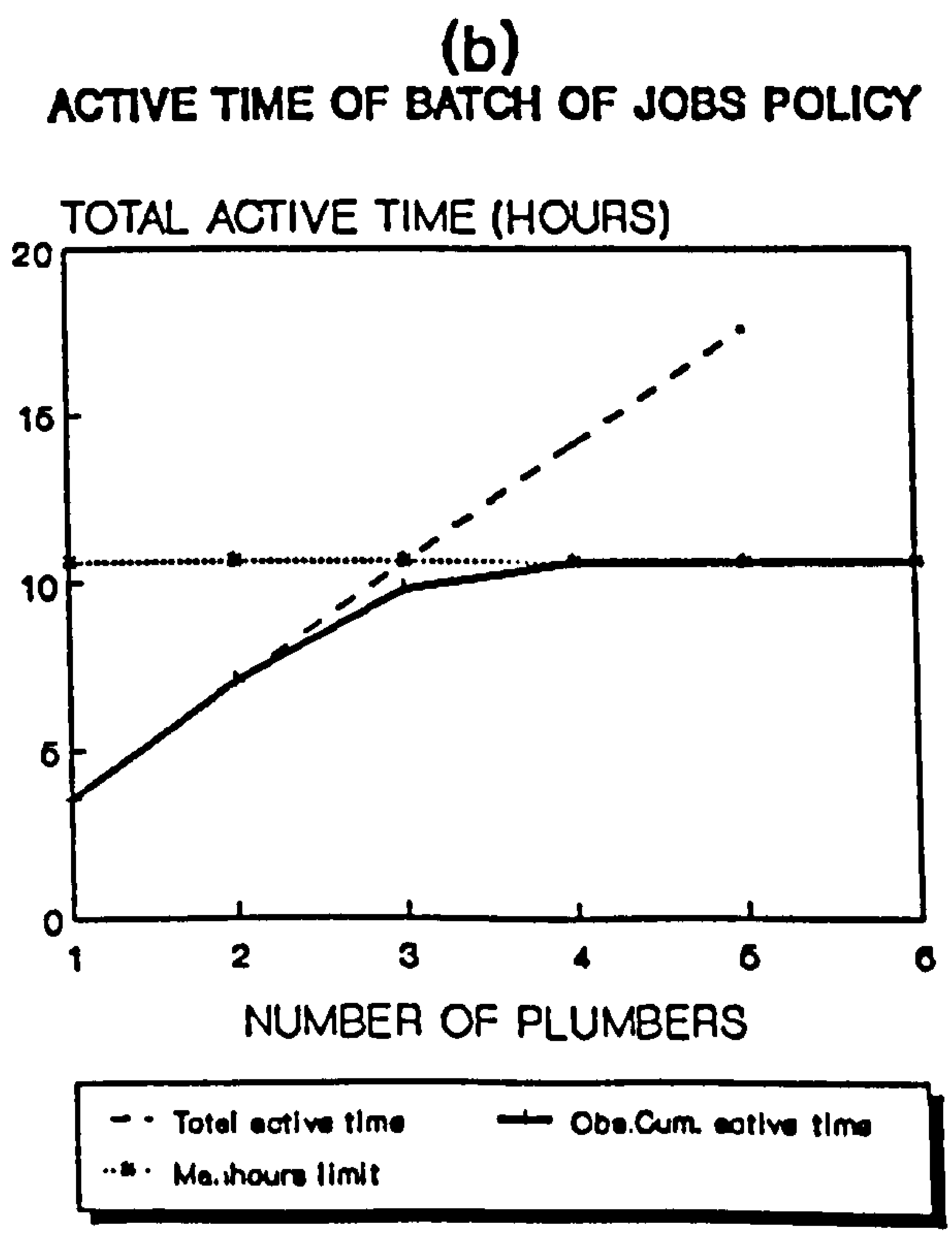


Figure 7.13: Assumed, observed total active time, and manhours limit, using; (a) Not previewing policy; (b) Issuing a variable batch size of jobs policy.

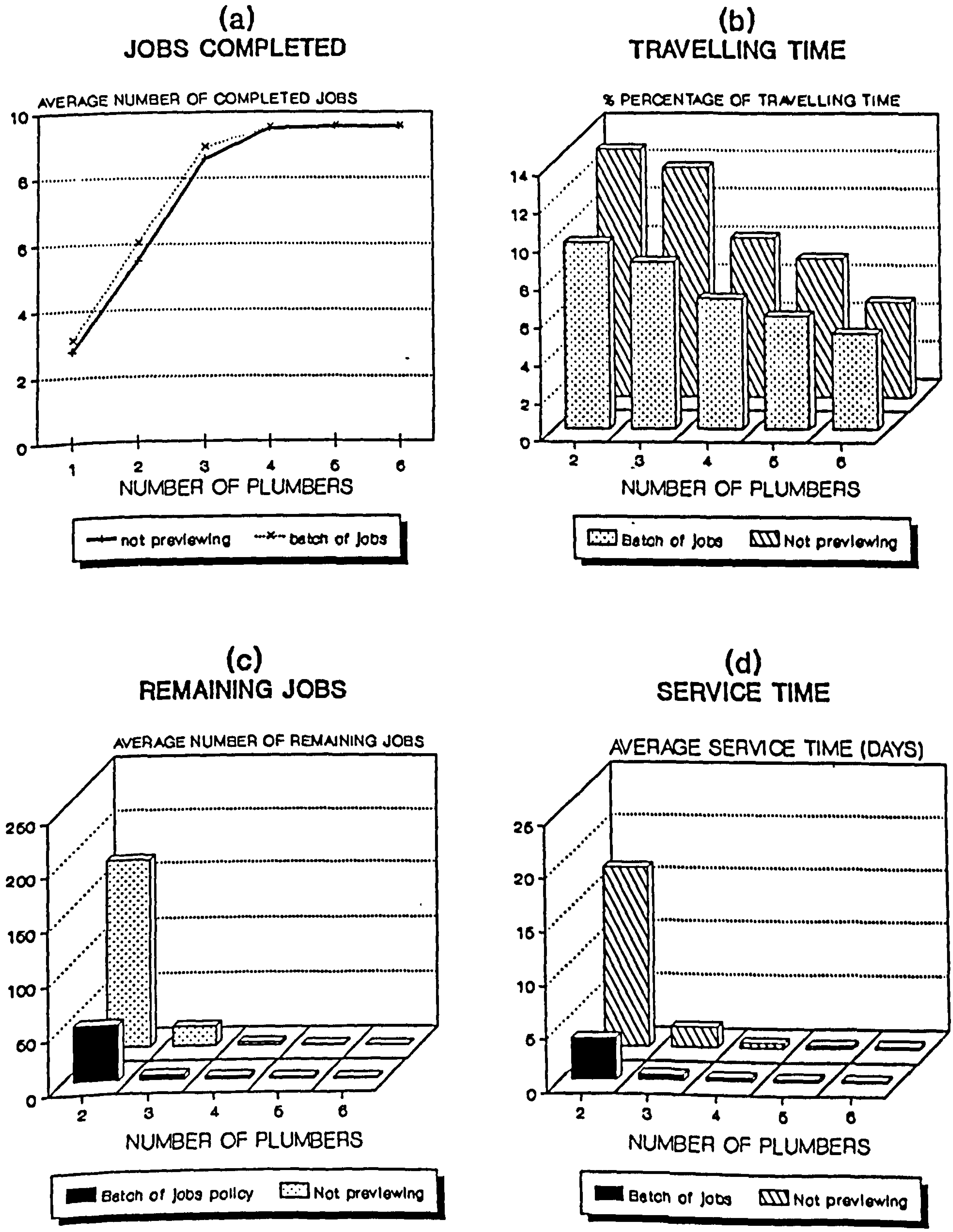


Figure 7.14: Comparison between 'not previewing' and 'issuing a variable batch size of jobs' policies in terms of; (a) Average number of jobs completed per day; (b) Percentage travelling time per day; (c) Average number of remaining jobs per day; (d) Average service time per job completed.

$$0.62 \pm 2.58\ (0.12)$$

or

$$0.31 \leqslant \bar{D} \leqslant 0.93$$

Again, there is a strong evidence that 'collecting a batch of jobs policy (3)' can reduce the manhours limit required to meet the daily plumbing demand for maintenance, which is around half an hour per day. The gain in the manhours limit in this policy is modest when employing 4 plumbers. The gain in this policy can be increased as the number of tradesmen employed decreases, or as the number of jobs arriving increases, which allows the batch size of jobs to be increased and then maximise the saving in total travelling time. Figure 7.14(c) shows that the average remaining jobs outstanding at the end of the simulated days per calander year decreases dramatically compared to those in 'collecting one job at a time when not previewing' when 1-3, tradesmen are employed. As the number of tradesmen increases, the batch size of jobs decreases until it reaches a state where the batch size of jobs equals one, i.e. it is similar to 'collecting one job at a time'. This can be noticed clearly in figures 7.14(a), 7.14(c), and 7.14(d), where the difference between the two policies diminish when employing 4 or more tradesmen, but an obvious difference in the performance measures can be observed when employing 1-3 tradesmen. Therefore this policy is most effective with larger backlogs of jobs. Figure 7.14(d) also shows the evident reduction in the service time, compared to that of 'not previewing policy (2)', which is related to the reduction in the average number of remaining jobs, which in turn is the result of increasing the service rate.

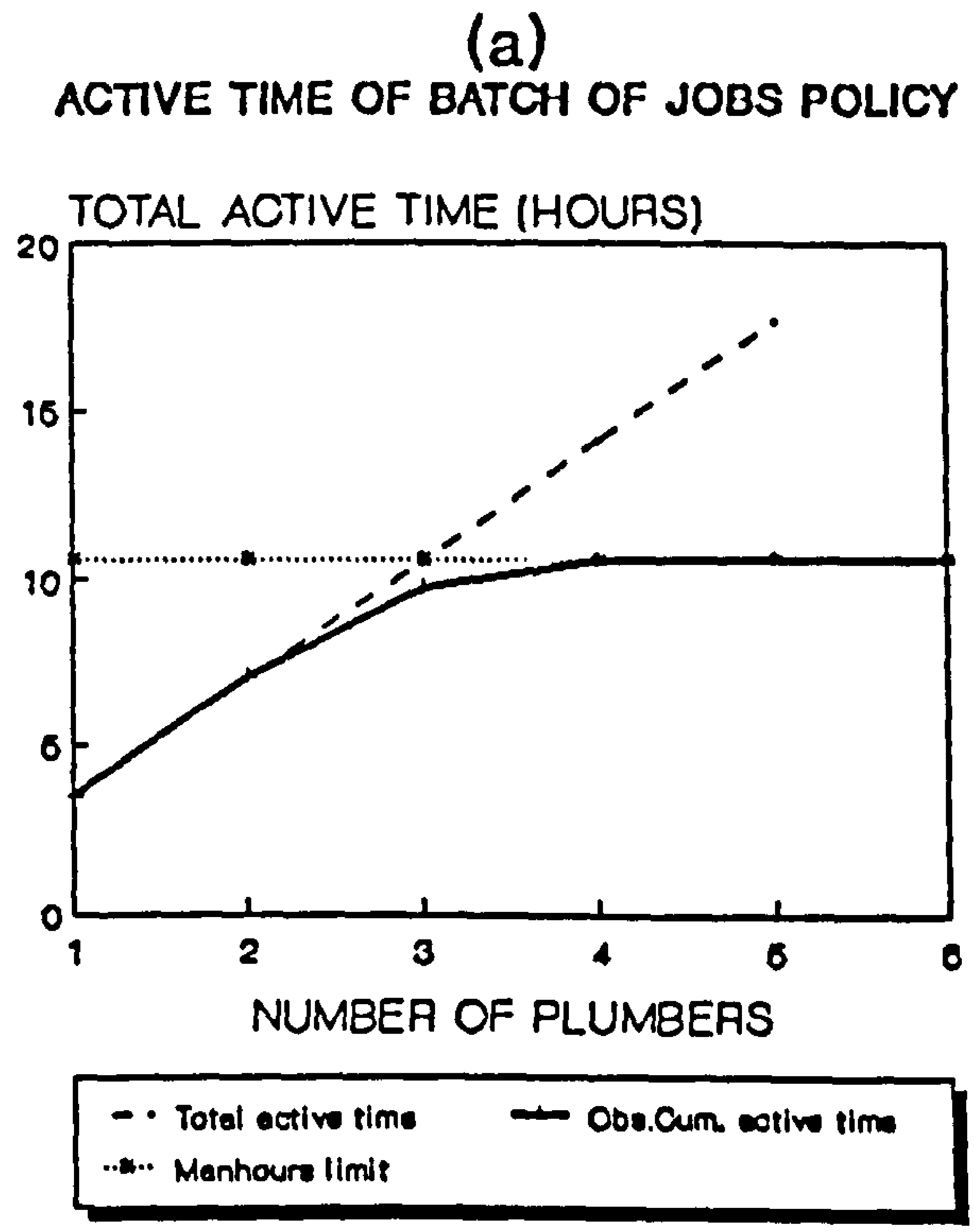
Withington hospital occupies only few square miles of land, thus the gain in the travelling time is limited, and related to the average travelling time within the hospital complex, and is estimated around 3-4% compared to the travelling time when 'collecting one job at a time and not previewing jobs (2)', see figure 7.14(b). This policy can give a better performance when using it in a large housing estate which covers tens of square miles, Christer (1981), where the travelling time may take about half an hour to travel to or from the job locations.

7.3.3. Evaluating delaying non-urgent jobs and grouping them in time (4)

'Delaying non-urgent jobs and grouping them in time policy (4)' has been examined in order to estimate the gain and the consequences of introducing this policy.

The minimum number of plumbers required to meet the daily demand for plumbing trade, as shown in figure 7.15(b), has been calculated by equation 7.1, x_p = 2.506 plumbers. There is an obvious improvement in the maintenance performance measures, when using this policy, estimated by 16.6% reduction in the minimum number of plumbers, and 13.98% reduction in the manhours limit from the previous policy of 'issuing a batch of jobs (3)' figure 7.15(a), see table 7.4 in the Appendix, which contains the percentage gain in each policy.

A significant gain when adopting a 'delaying non-urgent jobs policy (4)' compared to a 'previewing policy (1)' also has been estimated, which is around 35.57% reduction in the minimum maintenance staff and 38.51% reduction in the manhours limit required to meet the same demand for maintenance per day, see figures 7.11(a) for 'previewing policy (1)', and 7.15(b) for 'delaying jobs policy (4)', which show the active time in both policies respectively.



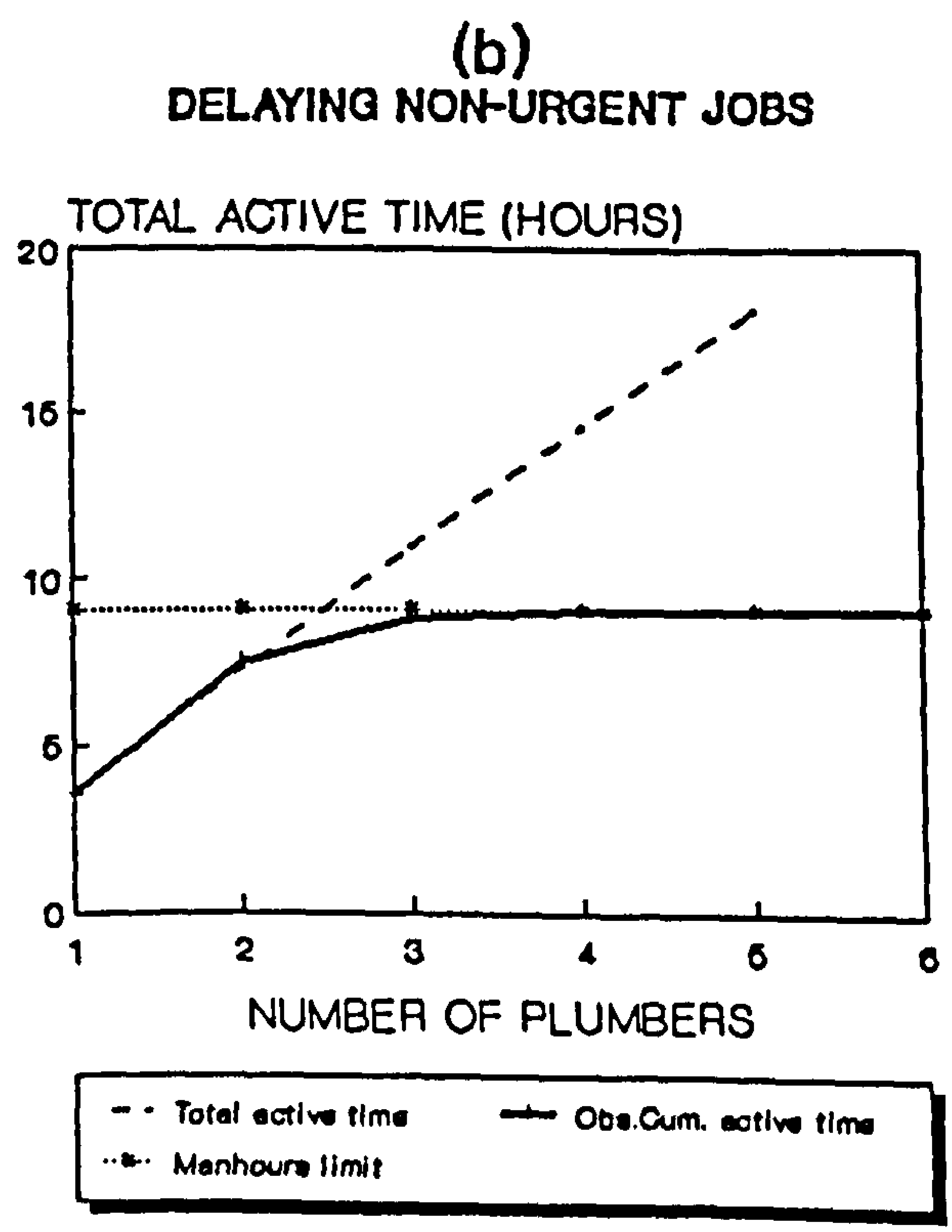


Figure 7.15: Assumed, observed total active time, and manhours limit, using; (a) Issuing a variable batch size of jobs policy; (b) Delaying non-urgent jobs and grouping them in time policy.

The point estimate of the difference in active time between 'collecting a batch of jobs policy (3)' and 'delaying non-urgent jobs policy (4)' $\bar{D}$=1.48 hours, the standard deviation of D =1.89 hours with 311 degree of freedom, and the standard error S.E. of D= 0.107. The 99% c.i. is

$$1.48 \pm 2.58\ (0.107)$$

or

$$1.2 \leqslant \bar{D} \leqslant 1.75$$

When comparing the point estimate of the difference between the total active time in the 'previewing policy (1)' and 'delaying non-urgent jobs policy (4)' when employing only four plumber is $\bar{D}$= 4.9 hours, with standard deviation σ = 1.568, and standard error S.E. of D = 0.0889. The 99% c.i. is

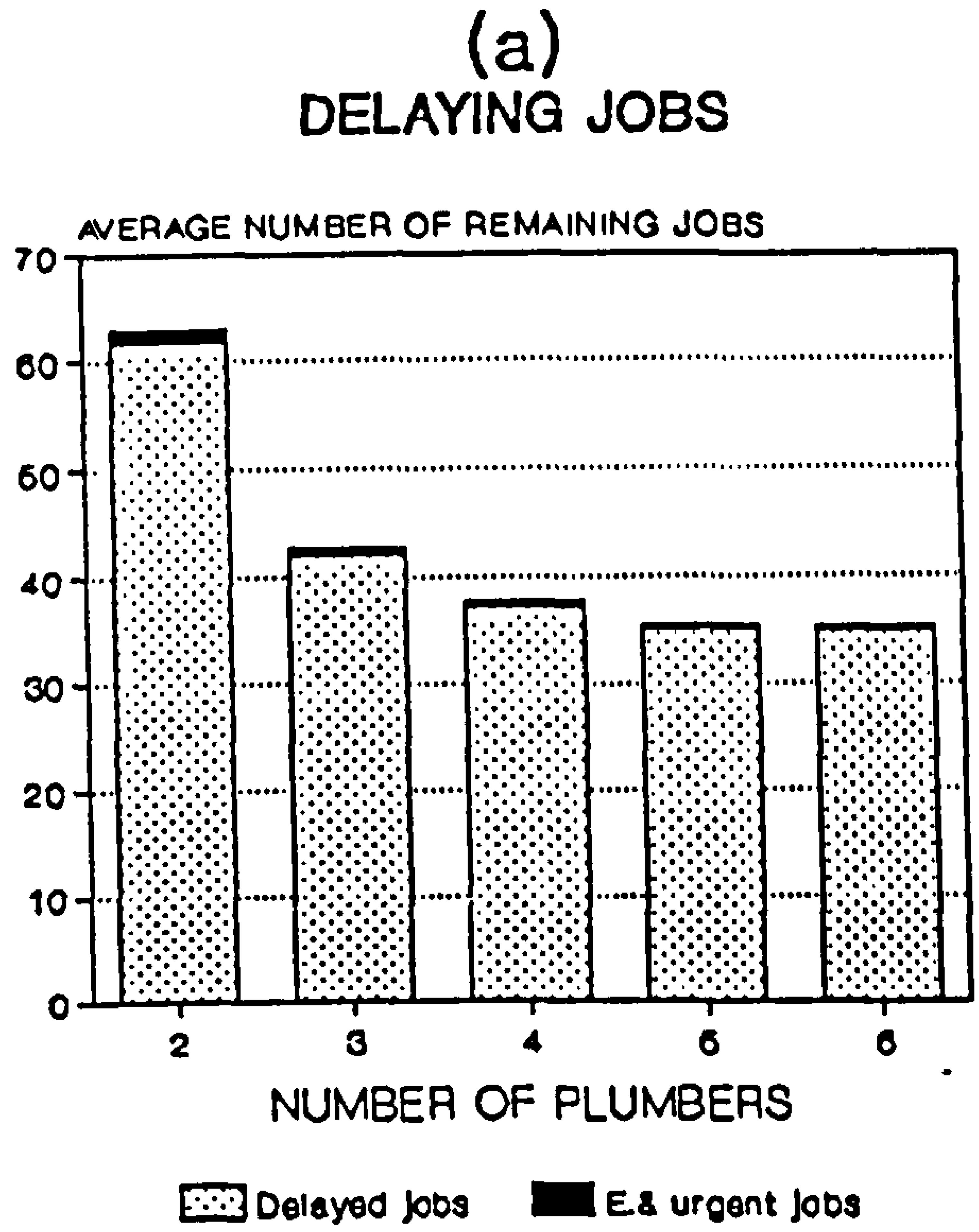
$$4.9 \pm 2.58\ (0.0889)$$

or

$$4.67 \leqslant \bar{D} \leqslant 5.129$$

It is evident from the above results that this policy has accomplished a significant improvement in reducing the non productive time through organising the priorities of the jobs arriving, and grouping the non-urgent jobs, according to their location, to be delayed to a preplanned working day of the week, usually in a weekly cycle, for repair for each giving area in the hospital.

Figure 7.16(a) shows the average number of remaining jobs outstanding at the end of each simulated day. When employing just 2 plumbers the average number of remaining urgent jobs is 1.51, with an average service time of 14 hours per jobs, which means some urgent jobs wait to the day following the reporting of the job. When employing say, 3 plumbers, the average number of



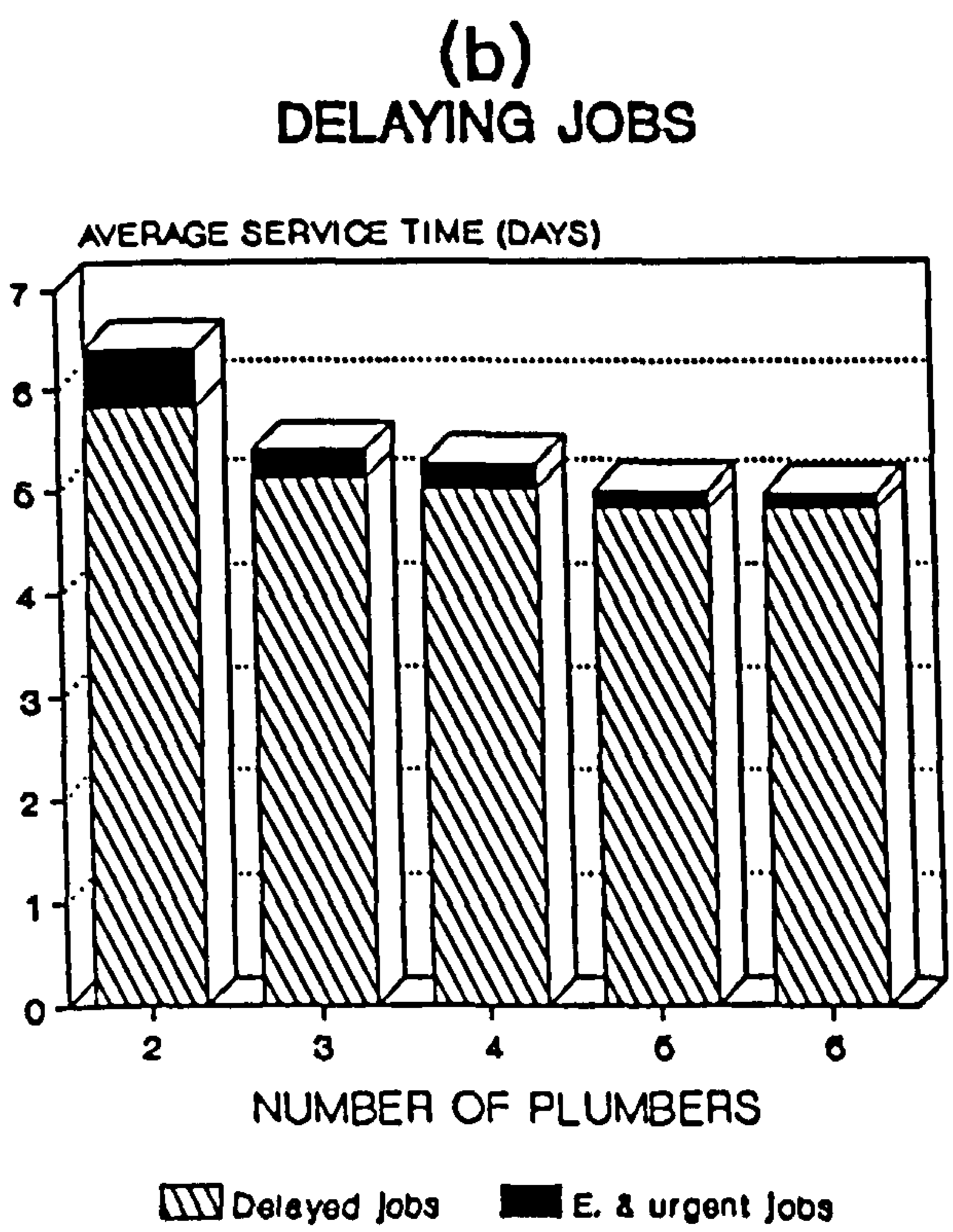


Figure 7.16: Shows two performance measure when using 'delaying non-urgent jobs and grouping them in time policy', these are; (a) Average number remaining jobs per day; (b) Service time per completed job.

urgent jobs drop to 0.63 remaining jobs per day, with an average service time of 7 hours per job, which is good enough for urgent jobs classified to be dealt with 48 hours. That is, on average these jobs can be dealt with in on the same working day. Therefore employing 3 plumbers reduces both measure of remaining job and service time about 50% of those when employing 2 plumbers.

The average number of non-urgent jobs remained at the end of each simulated day, when employing more than three tradesmen, figure 7.16(a), are not significantly affected by the increase in the number of plumbers employed, since these jobs are delayed to a preplanned working day, even if the level of maintenance staff employed is sufficient to satisfy the demand for maintenance. Figure 7.16(b) shows the service time of emergency & urgent, and delayed non-urgent jobs. The average service time of delayed non-urgent jobs per simulated day, when employing more than three tradesmen, figure 7.16(b), is not significantly affected by the increase in the number of plumbers employed, since these jobs are delayed to preplanned day of the week on a weekly cycle. Therefore the level of service time remains about 5 days on average per delayed job. The service time and the remaining jobs changed little when employing 5 or 6 tradesmen, which is about double the minimum workforce estimated. This suggests there is an asymptotic level of return to be achieved by employing extra manpower, and there is a corresponding expectation of observing increasing idle time per tradesman.

As far as the number of jobs completed per day is concerned, see figure 7.17(a), the average number of jobs completed per day when employing just one tradesman was less than that of simulating 'collecting a batch of jobs policy (3)', this is due to employing the only tradesman in repairing the emargency and urgent jobs only. Employing 2 plumbers has shown an

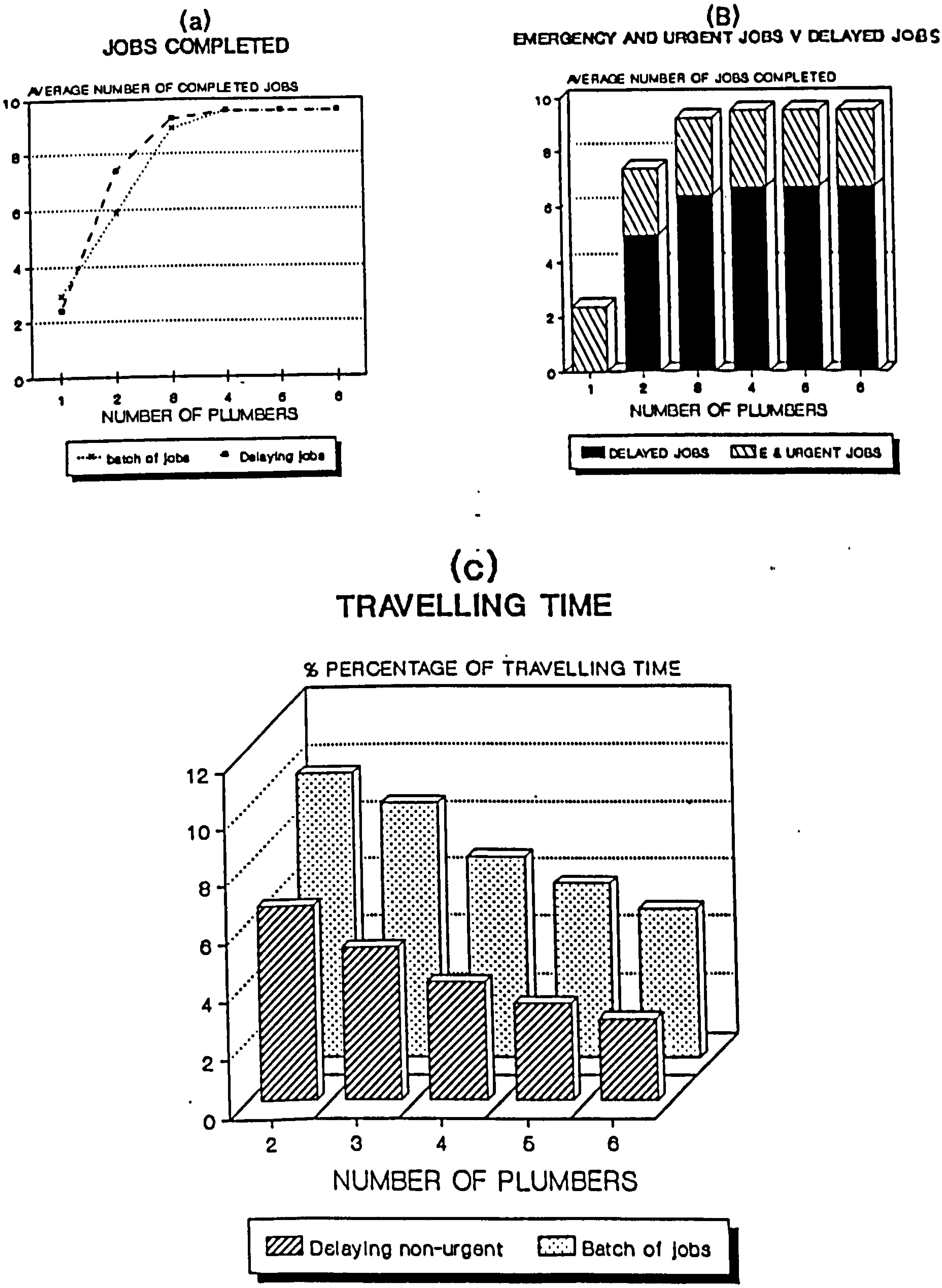
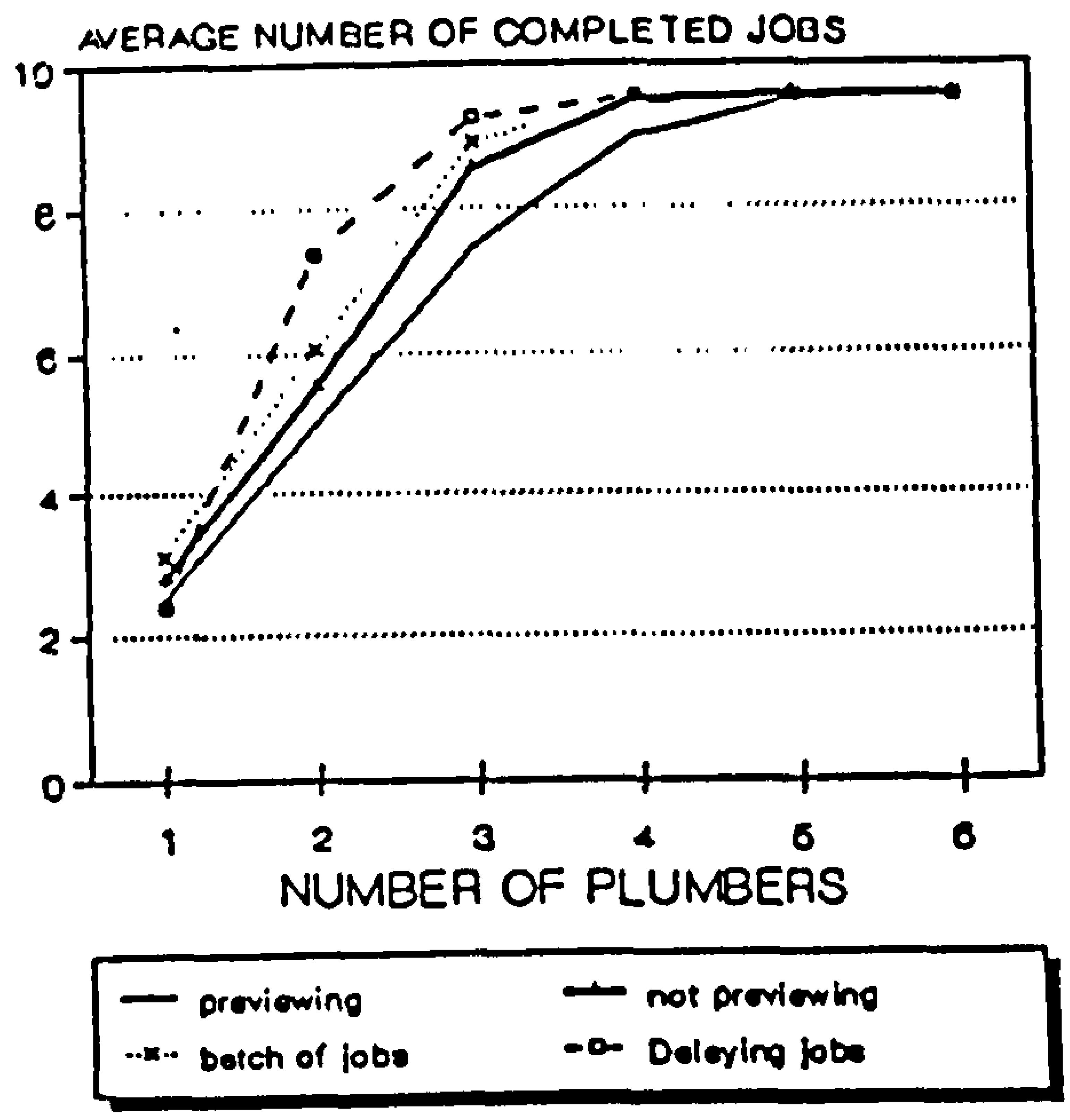


Figure 7.17: Comparison between 'issuing a variable batch size of jobs', and 'delaying non-urgent jobs' policies in terms of; (a) Av. No. of jobs completed per day; (b) Shows details of average number of jobs completed using delaying non-urgent jobs; (c) Percentage travelling time.

obvious increase in the average number of jobs completed compared to that of 'collecting a batch of jobs policy (3)', that is because the 2nd tradesman has worked in repairing the delayed jobs and can possibly help in case of emergencies as required. Employing 3 plumbers, one is dedicated to emergency & urgent jobs as before, and the other 2 plumbers are available to work in the delayed jobs, and help in the case of emergencies as required, and so on. The average number of jobs completed per day when employing 3 plumbers has decreased compared to when employing 2 plumbers. This fall is due to the level of the maintenance jobs arriving per day, i.e. if the demand for maintenance increases then it is likely to see an increase in the average number of jobs completed per day at this level of employment. See figure 7.17(b) which splits the emergency & urgent job, and the delayed non-urgent jobs in (delaying non-urgent jobs policy only (4)).
Figure 7.17(c) shows the obvious reduction in the travelling when simulating delaying non-urgent jobs compared to 'issuing a batch of jobs policy (3)'.

This policy, "delaying non-urgent jobs and grouping them in time (4)", is considered as the best choice to the maintenance management in improving the efficiency of the workforce through reducing the non productive time, as well as in reducing the number of complaints, from the hospital staff (Christer 1981). A summary of the average number of jobs completed per day and the percentage of travelling time observed in the four methods of deployment are shown in figures 7.18(a) and figure 7.18(b) respectively. A summary of the remaining jobs per simulated day and the service time per completed job in the four method of deployment are shown in figures 7.18β(a) and 7.18β(b) respectively. the gain from the reducing the travelling time in the proposed policies, figure 7.18(b), has been used in a more productive activity which result in an increase in the number of jobs completed per day, specially

(a)
JOBS COMPLETED



(b)
TRAVELLING TIME

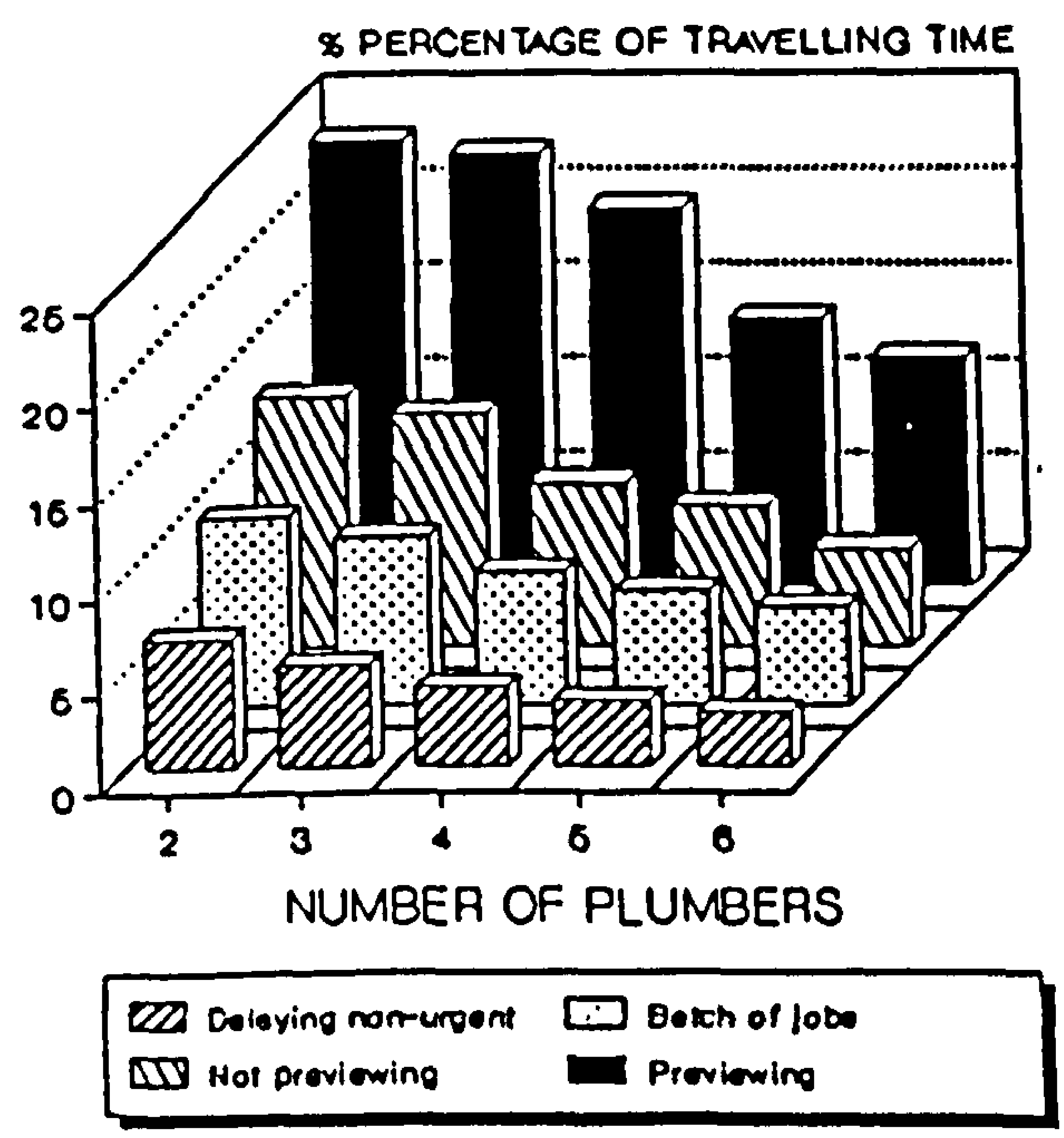


Figure 7.18: Shows a summary of two response variables using the four methods of deployment, these response variables are: (a) Average number of jobs completed per day; (b) Percentage of travelling time.

when employing 2 and 3 plumbers, see figure 7.18(a). This gain is, as an expected result, has influenced the number of remaining jobs and the average service time, Figures 7.18β(a) & 7.18β(b) respectively. As the number of plumbers increases to more than 3 plumbers, the gain in the travelling time is thought to become an increase in the idle time, because of the limit in the demand for maintenance.

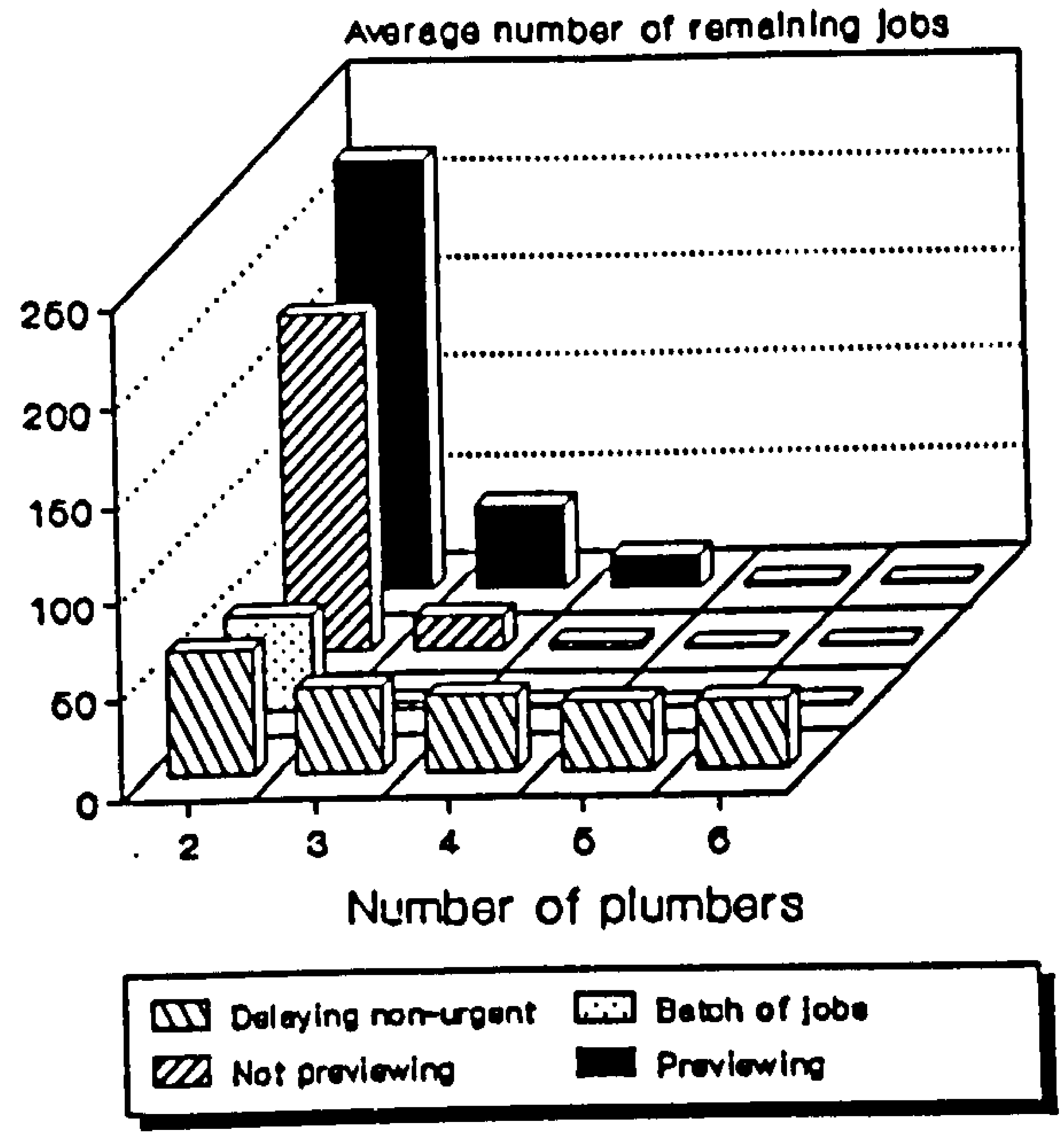
In order to reduce the possible number of comparisons between other proposed maintenance management policies mentioned in sections 6.3-6.5, these are: (a) no sickness model; (b) employing part-time tradesmen; and (c) working 7 days instead of 5 days a week. These policies are simulated, using 'delaying non-urgent jobs model', and compared with this policy as a base for comparison in the following sections.

7.3.4. Evaluating 'no sickness policy (5)'

This policy has been proposed in order to assess the impact of the sickness factor on the performance of the maintenance department. The policy of "delaying non-urgent jobs and grouping them in time (4)" has been run with and without the sickness factor in order to compare the outcome of both experiments.

The minimum number of plumbers which is necessary to meet the plumbing jobs has been calculated, for no sickness model, from equation 7.1, see figure 7.19(b), x_p= 2.11 plumbers compared to 2.506 plumbers in 'delaying jobs policy with sickness factor (4)', figure 7.19(a). There is 15.8% gain in the minimum workforce required if the sickness factor is eliminated.

(a)
REMAINING JOBS



(b)
SERVICE TIME

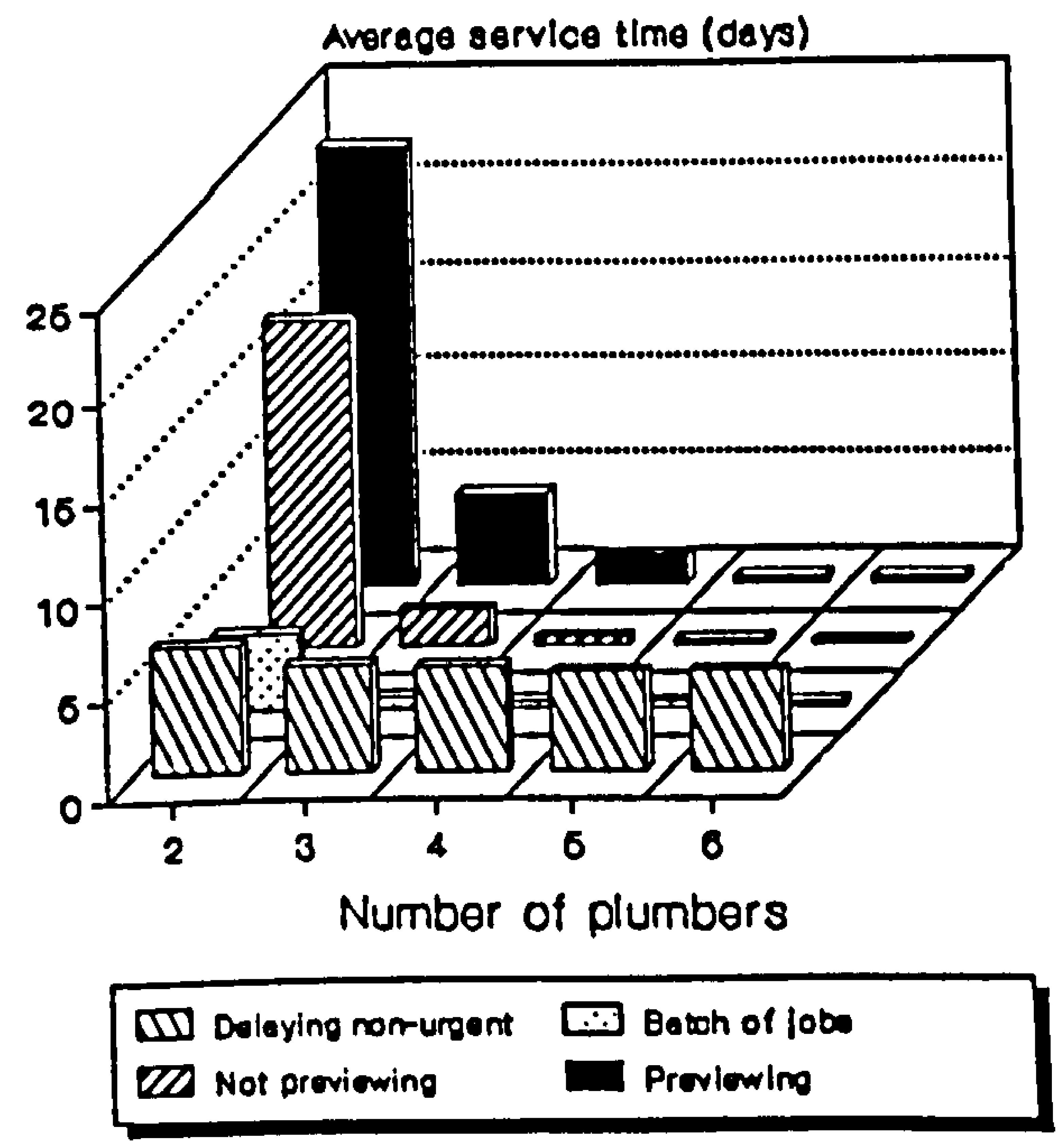
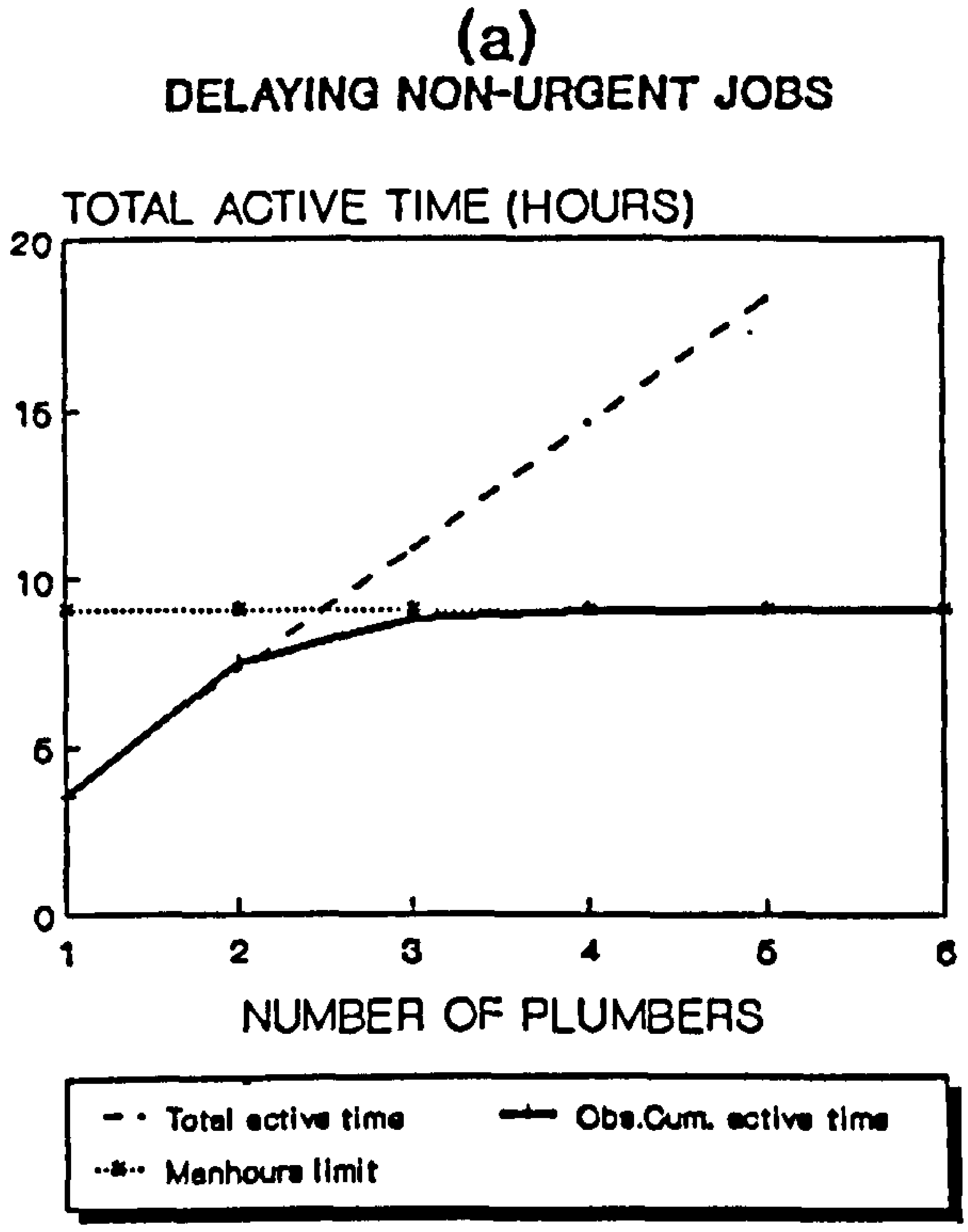


Figure 7.18β; Shows a summary of two response variables using the four methods of deployment, these response variables are: (a) Average number of remaining jobs per simulated day; (b) Average service time in (days) per completed job.



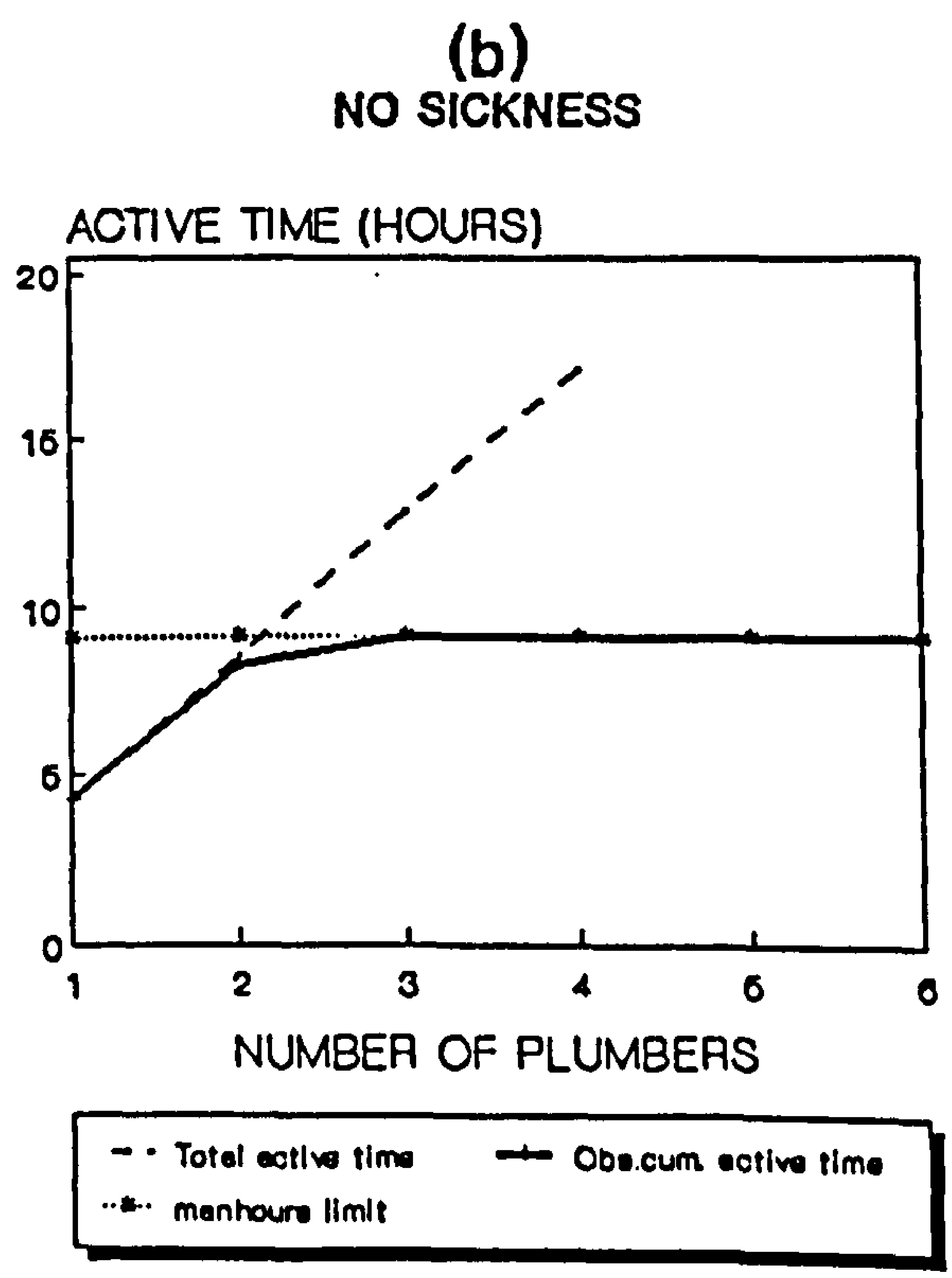


Figure 7.19: Assumed, observed total active time, and manhours limit, using; (a) Delaying non-urgent jobs and grouping them in time policy; (b) Eliminating the sickness factor.

For the two sets of correlated runs of 'delaying jobs policy (4)' and 'no sickness policy (5)', the observations are paired and analysed. The point estimate of the active time when employing four tradesmen is $\bar{D}$ = 0.03 hours per day, and the sample standard deviation = 0.374, with 311 degree of freedom. The standard error S.E. of D is 0.0212. Thus, a 99% c.i. for the true mean difference in average active time is

$$0.03 \pm 2.58\ (0.0212)$$

or

$$-0.0247 \leqslant \bar{D} \leqslant 0.0847,$$

and the 95% c.i. for the true mean difference in average active time is

$$0.03 \pm 1.96(0.0212)$$

or

$$-0.01155 \leqslant \bar{D} \leqslant 0.0715$$

As the 99% and 95% c.i. include zero, then there is no strong statistical evidence of a difference in the active time between the two models when employing four plumbers. This is an acceptable conclusion since we are using the same method of deployment and the same input variables.

Examining the average number of remaining jobs and the average service time per job in both models, when employing 2 and 3 tradesmen, it is clear that the average number of remaining jobs, figure 7.20(a) is less than in the corresponding case simulated with a no sickness policy (5)' seen in figure 7.20(b). The same result holds for the average service time, see figures 7.20(c) and 7.20(d). This is due to the increase in the manhours available to undertake maintenance in the absence of sickness.

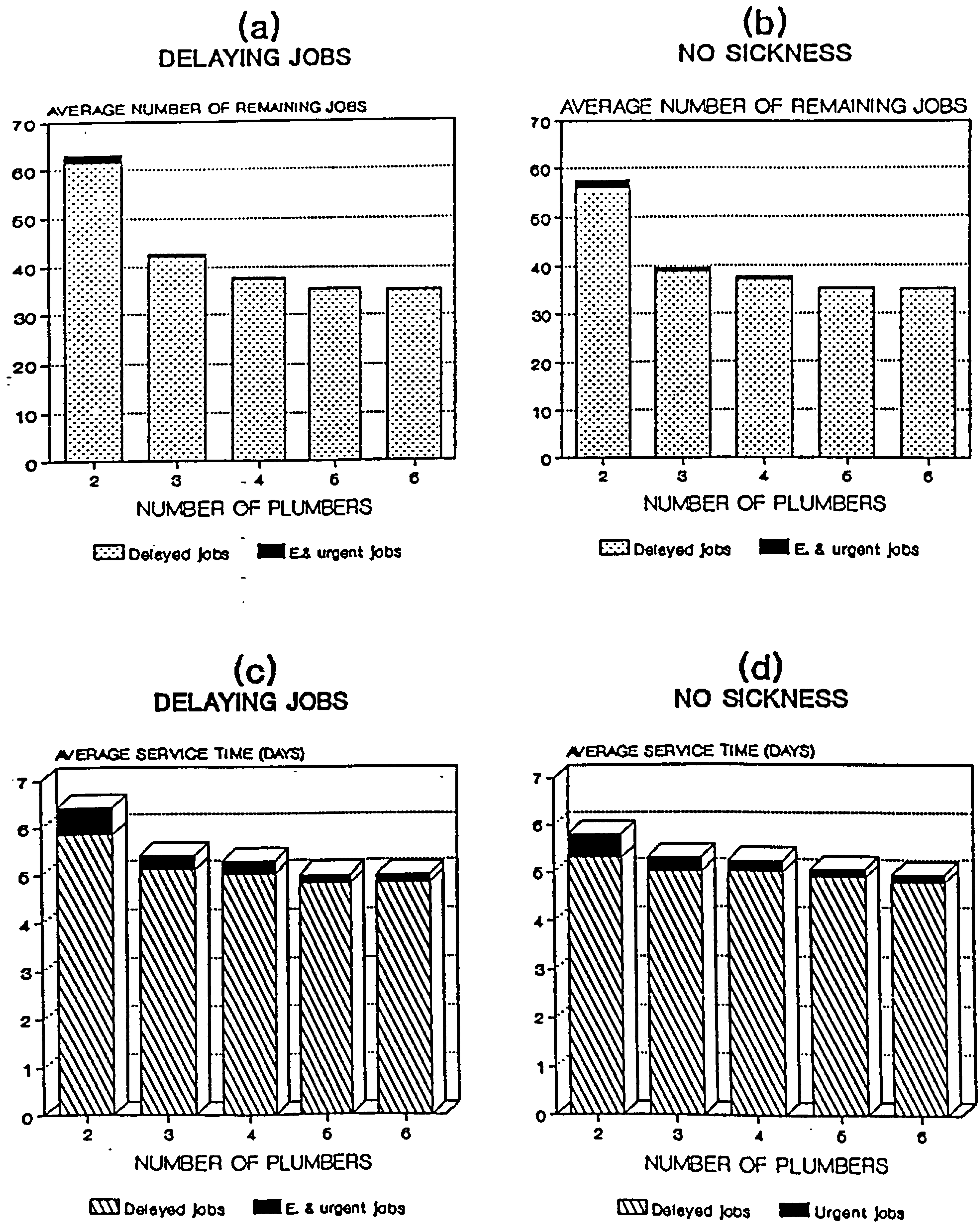


Figure 7.20: Shows average service time and remaining jobs in delaying non-urgent jobs and no sickness policies;
* Remaining jobs: (a) Delayed jobs; (b) No sickness.
* Service time: (c) Delayed jobs; (d) no sickness.

It seems that the effect of sickness diminishes as the number of tradesmen increases, i.e. when employing 4, 5, and 6 tradesmen the average number of remaining jobs are almost the same, this is due to being in control, though at the possible cost a higher level of idle time per tradesmen employed. This explains the reduction in the effect of sickness on the performance of the plumbing trade as a manpower variable.

The average number of jobs completed per day, when 'no sickness factor' is simulated, has shown an increase, specially when 2, 3 tradesmen are employed, compared to that in 'delaying non-urgent jobs', see figure 7.21(a). There is no obvious difference in the travelling time, see figure 7.21(b), which is to be expected since we are using the same method of deployment.

7.3.5. Evaluating 'employing part-time tradesmen policy (6)'

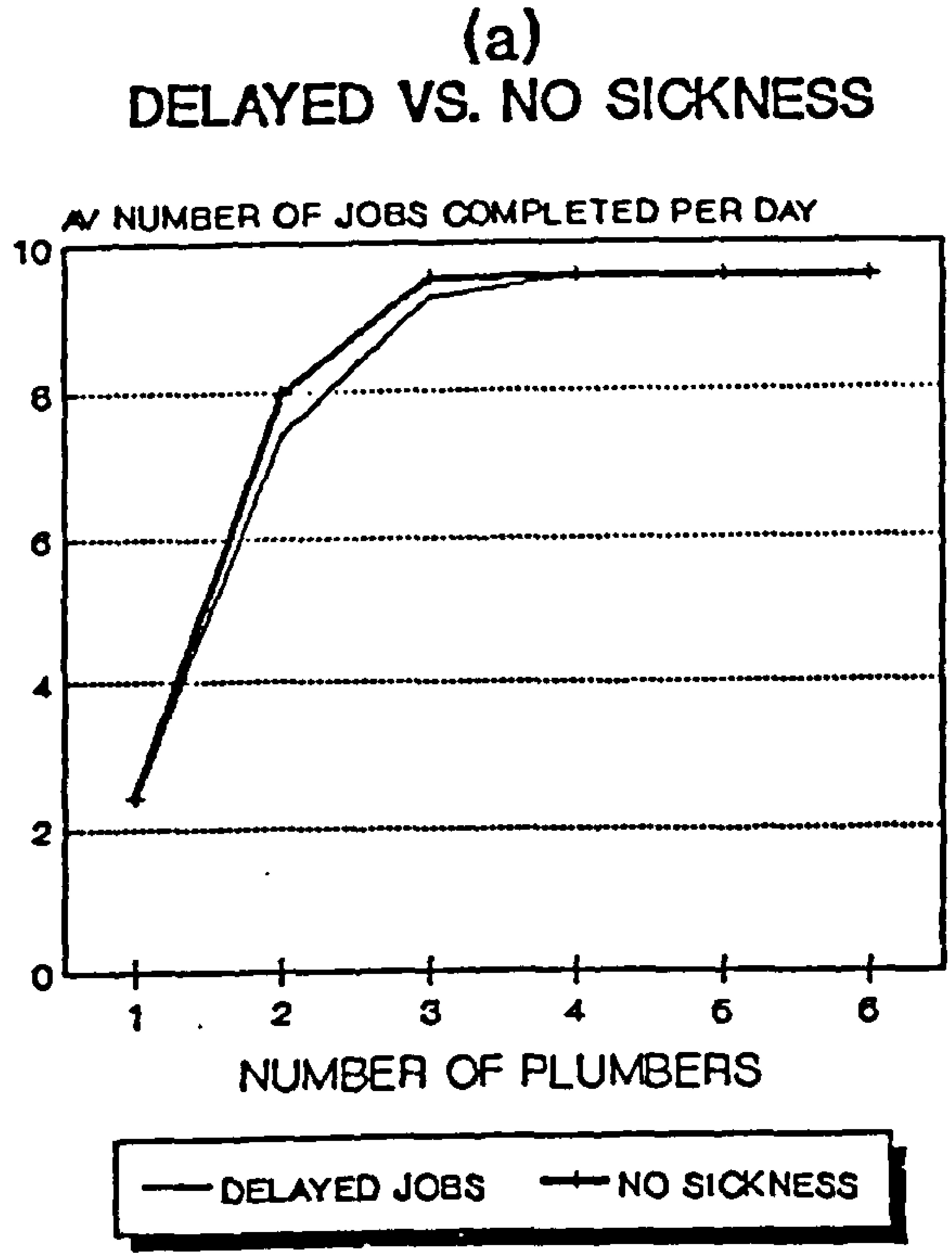
Employing an extra part-time tradesman during the busy days, Mondays and Tuesdays, has been assessed by runing the policy on the "delaying non-urgent jobs simulation model (4)" in order to compare the outcome of it with the outcome of not employing extra part-time tradesman.

The average number of plumbers employed per day, S_n, when employing n tradesmen on Monday-Friday and an extra plumber on Mondays and Tuesdays is

$$S_n = n + (2/5) = n + 0.4,$$

that is, n+0.4 is the average number of tradesmen employed per day when employing extra part-time tradesmen on Mondays and Tuesdays.

The suggested number of full-time plumbers required to meet the demand for plumbing maintenance under operating 'employing extra part-time tradesman policy (6)' has been calculated, x_p=2.42+0.4, i.e. the minimum number of



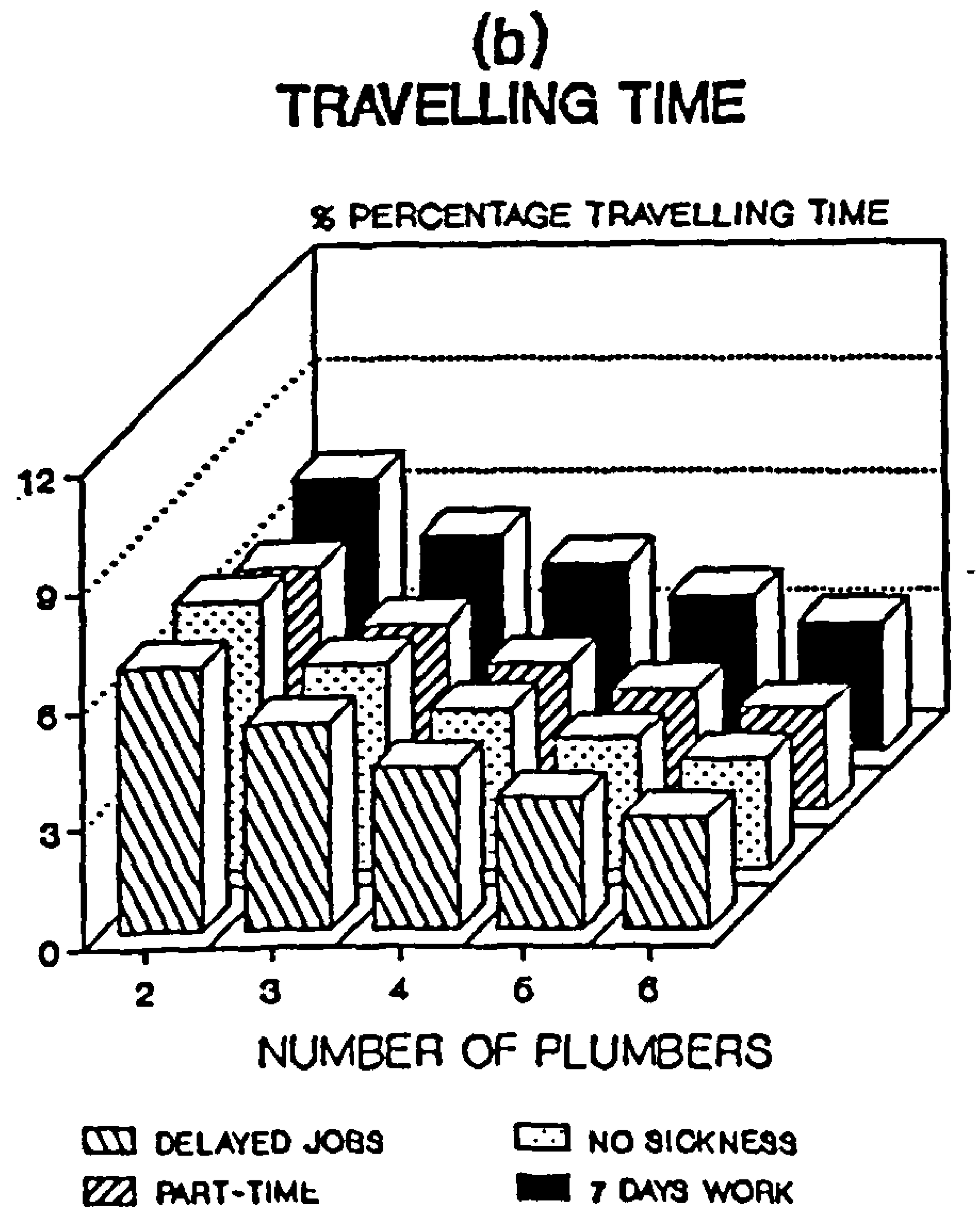


Figure 7.21: (a) Average number of jobs completed per day in delayed jobs versus no sickness model.
(b) A summary of the percentage of travelling time in proposed policies experimented on delaying non-urgent jobs.

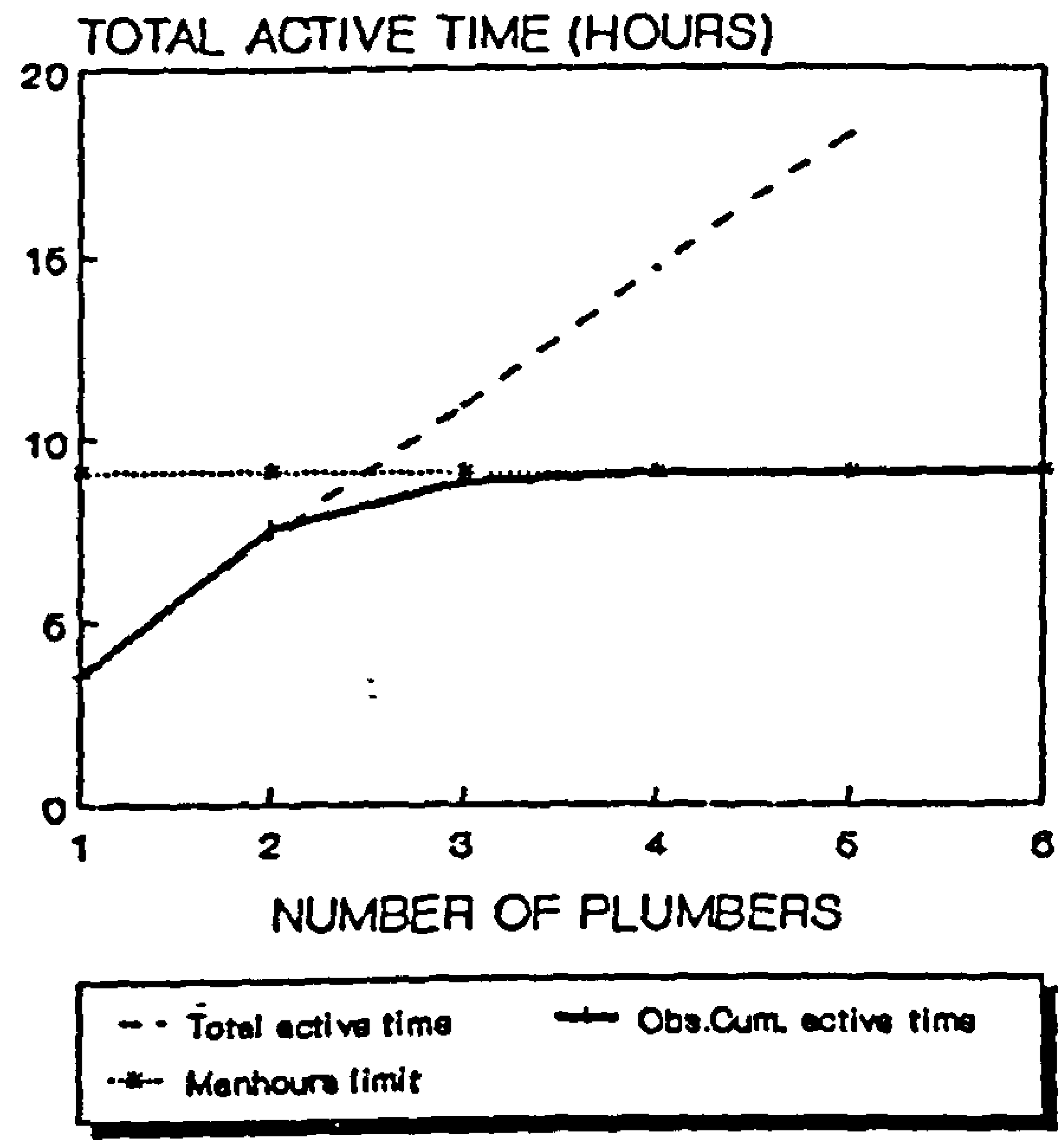
full-time and part-time plumbers equals 2.82, this is compared to those in delaying non-urgent jobs, x_p=2.506, see figure 7.22(a) for 'delaying policy (4)', and figure 7.22(b) for 'employing part-time tradesman policy (6)'. The estimated increase in the minimum workforce when employing extra part-time tradesman is 16.5%.

When examining the average number of remaining jobs per day, shown in figure 7.23(c), and the average service time per completed job figure 7.23(d), using part-time policy, and comparing them with the corresponding figures 7.23(a) and figure 7.23(b) for the delaying jobs policy, it is obvious that when employing 5 and 6 plumbers, which is about double the estimated minimum workforce, there is no difference between the both policies in terms of both performance measures considered; but there is an evidence that the 'employment of an extra part-time plumber (6)' can reduce the average number of remaining jobs per day specially when employing 2 plumbers.

More jobs completed per day on average can be noticed when 'employing an extra part-time tradesman (6)' when the base level is 2 & 3 tradesmen, see figure 7.24. The effect of the extra manhours available to complete jobs is clear, and the average number of jobs completed per day, when employing 3 full time and an extra part-time plumber, is the same as that expected under the 'delaying non-urgent work policy (4)' and employing 4 or more tradesmen, figure 7.24.

Thus, this policy can be more effective as the backlog of jobs increases, and the effectiveness diminishes as the backlog of jobs decreases, or as the number of tradesmen increases which imply that there is a slack time in the system. The decision to adopt this policy has been put to the maintenance management for study.

(a)
DELAYING NON-URGENT JOBS



(b)
EMPLOYING PART-TIME

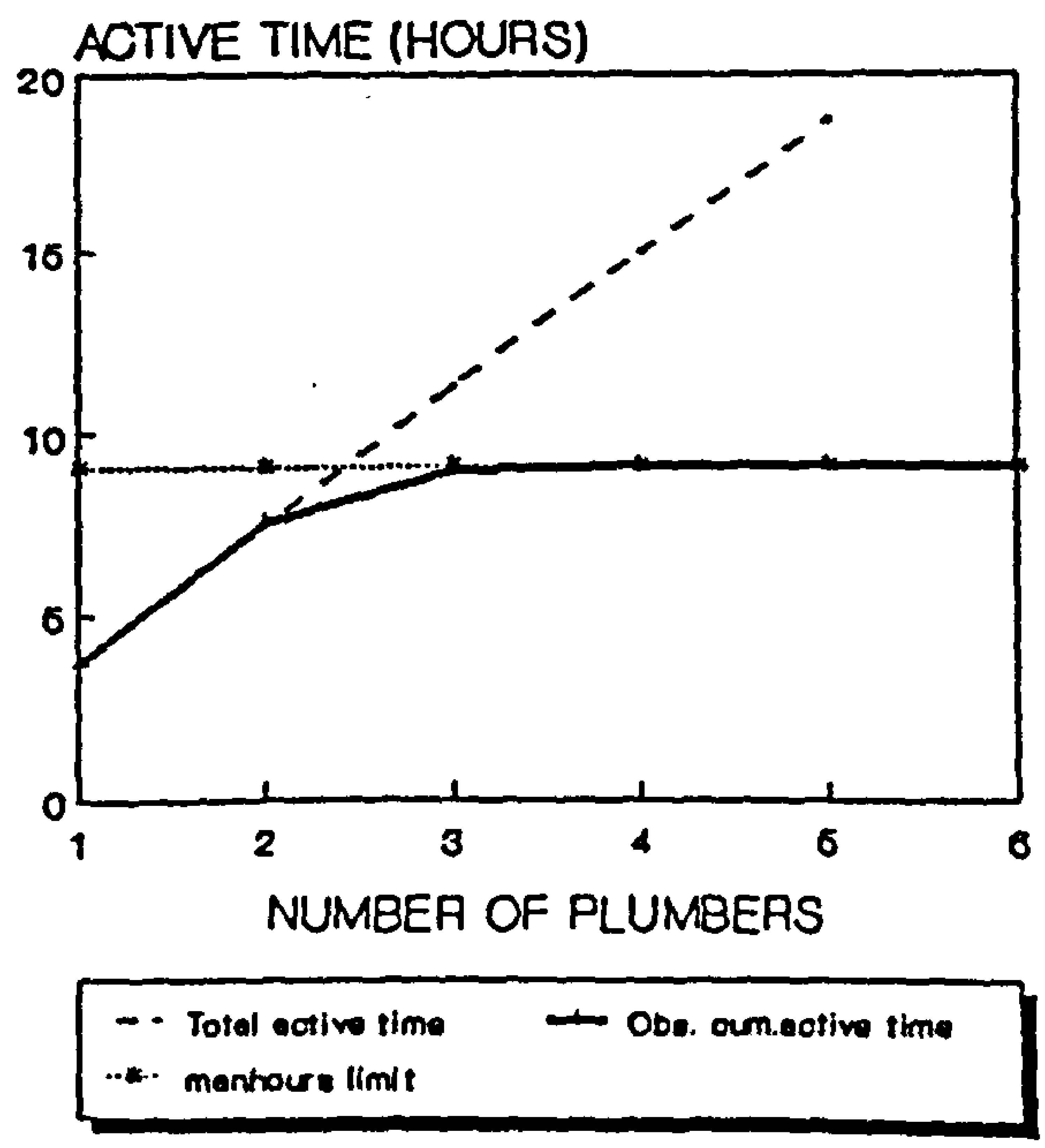


Figure 7.22: Assumed, observed total active time, and manhours limit, using; (a) Delaying non-urgent jobs and grouping them in time policy; (b) Employing extra part-time trademan.

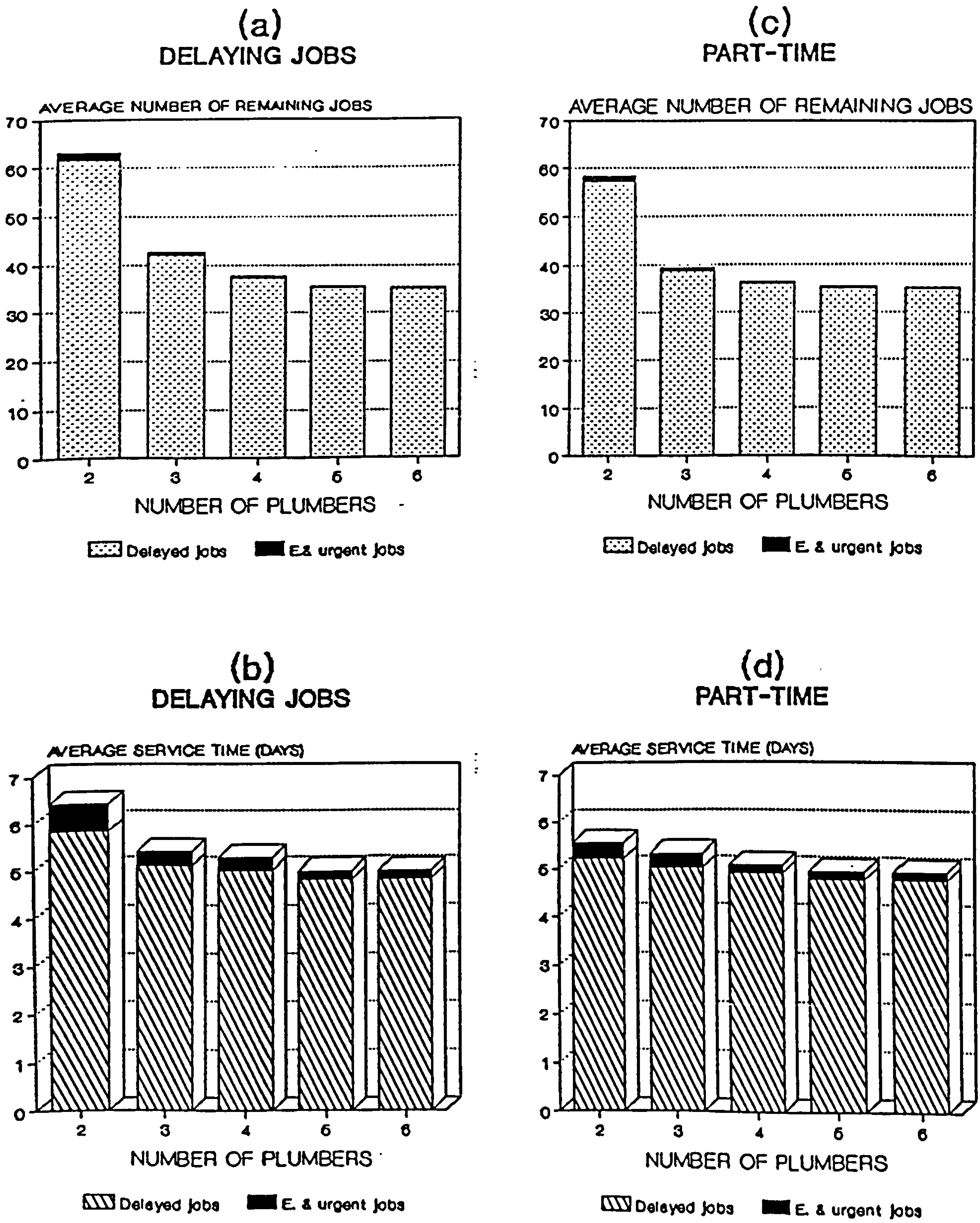


Figure 7.23: Shows average service time and remaining jobs in delaying non-urgent jobs and employing part-time trademan policies;
* Remaining jobs: (a) Delayed jobs; (b) Part-time.
* Service time: (c) Delayed jobs; (d) Part-time.

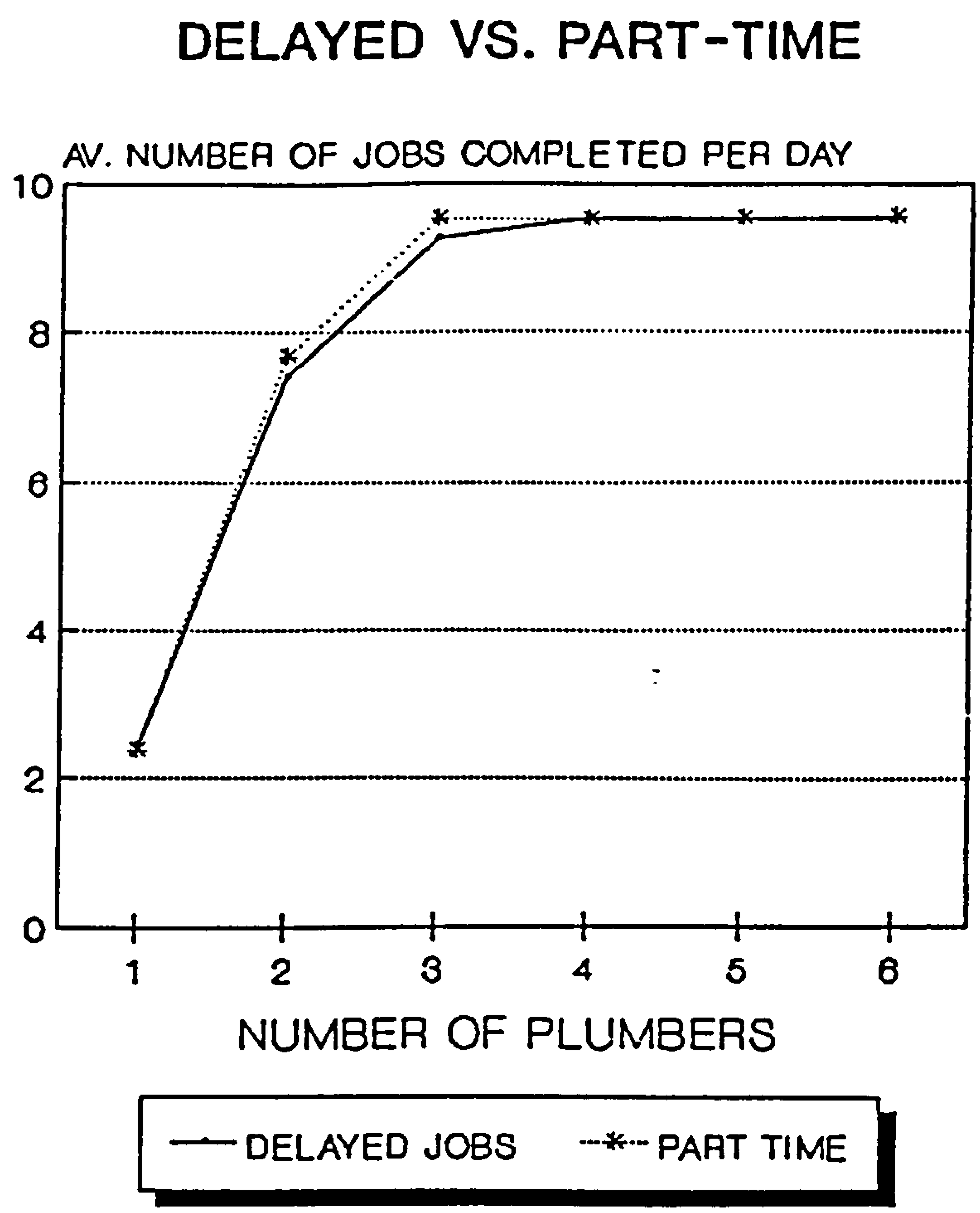


Figure 7.24: Average number of jobs completed per day in delaing non-urgent jobs versus employing part-time tradesman.

This policy, 'employing an extra part-time tradesman (6)', has been proposed as a result of observing a high rate of job arrivals during Mondays & Tuesdays under the current practice of the maintenance management at Withington hospital. Introducing the 'delaying non-urgent jobs policy (4)' has considerably influenced the distribution of the jobs arriving within the hospital, whether the jobs arriving during peak days, Mondays & Tuesdays, or during the rest of the week days. Jobs are either repaired on the same day or replanned for some later day. Therefore, there is no obvious need to employ an extra part-time tradesman since these peak days are no longer existing after the grouping of jobs in this policy. That is why the 'employment of extra part-time tradesman (6)' has increased the minimum workforce required by 16.5% compared to the 'policy of delaying non-urgent jobs by not employing an extra part-time tradesman (4)'. It must be remembered that these observations related to the demand level being experienced at Withington hospital. If the demand increased, the use of part-time employees even with a 'delay policy (4)' could be beneficial to reduce the average service time, though would not be expected to have any other substantive effect.

7.3.5. Evaluating 'working seven days a week policy (7)'

Another proposed policy with the objective of delivering a continuous maintenance service to the hospital and reducing the fluctuation in the arrival rates of jobs during the working days of the week is to work seven days a week. The minimum number of maintenance staff which is appropriate to meet the plumbing demand for maintenance, given that they work 7 days a week, has been calculated when using this 'seven days working a week policy (7)', see figure 7.25(b), suggesting x_p= 2.39 plumbers, compared to 2.506 plumbers when working five days a week assuming the 'delaying non-urgent jobs policy (4)', figure 7.25(a).

If every plumber employed is working only five days per week, then the average number of plumbers required per day, S_n, when working 7 days a week is:

$$Sn = (1.4)n$$

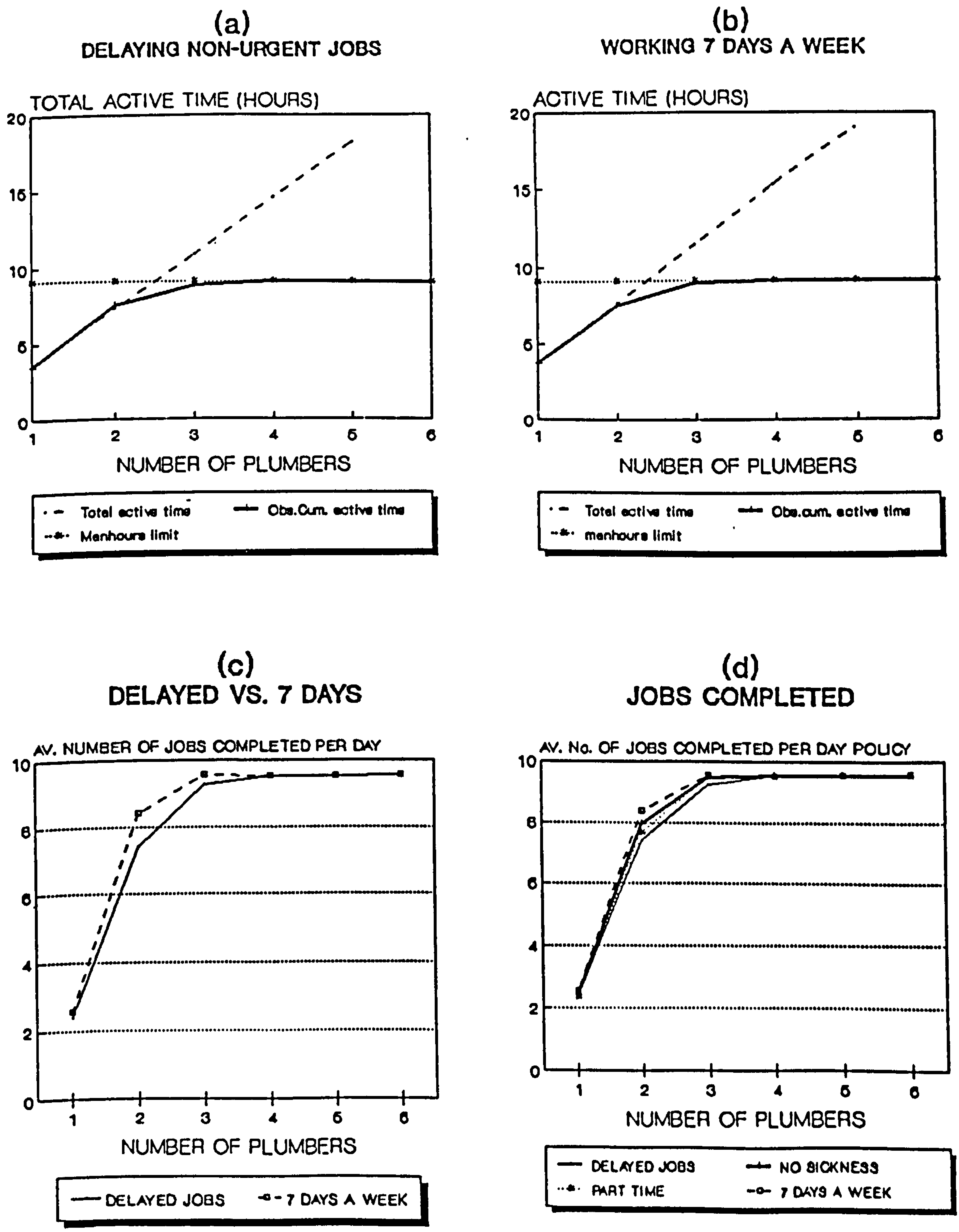


Figure 7.25: (a) & (b): Assumed, observed total active time, and manhours limit, using; (a) Delaying non-urgent jobs and grouping them in time policy; (b) Working 7 days a week.
(c) & (d): Average number of jobs completed per day; (c) Using delaying non-urgent jobs versus working 7 days a week. (d) All proposed policies experimented on delaying non-urgent jobs.

Therefore, the suggested number of plumbers employed in the policy of working 7 days a week is 3.34. This shows an increase of 33% in the minimum workforce required compared to that in 'delaying non-urgent jobs policy (4)', see table 7.4 in the Appendix.

The influence of this policy on the performance measures can be compared with some similarities with 'employing an extra part-time tradesman policy (6)'. Employing less than three plumbers working 7 days a week, the average remaining jobs and average service time per completed job per day, figures 7.26(b) and figure 7.26(d), are very similar to those of 'employing an extra part-time plumber (6)', figures 7.26(a) and 7.26(c). But when comparing the remaining jobs and the service time measures of working 7 days a week, shown in figures 7.27(b) and 7.27(d), with the corresponding measure of 'delaying non-urgent jobs policy (4)', figures 7.27(a) and 7.27(c), it is clear that when employing 2 plumbers working 7 days a week can notably reduce the average number of remaining jobs at the end of each simulated day and, therefore, the average service time per completed job.

Employing 4 or more tradesmen, the influence of 'working 7 days a week' on the remaining job, figure 7.27(b), and service time per completed job 7.27(d), diminishes compared to the same measures when 'working five days a week, policy (4)' as shown in figures 7.27(a) & 7.27(c) respectively.

As far as the average number of jobs completed per day is concerned, figure 7.25(c), shows that 'working 7 days' can give a higher average than all the policies considered, see figure 7.25(d) which shows the average number of jobs per day under all policies studied. This result is due to the continuous nature of maintenance activity during the days of the week which allows non-urgent jobs of the 7 areas within the hospital to be separately grouped for attention on a given day of the week. The decision to consider this policy has to be studied carefully by the maintenance management because it has other

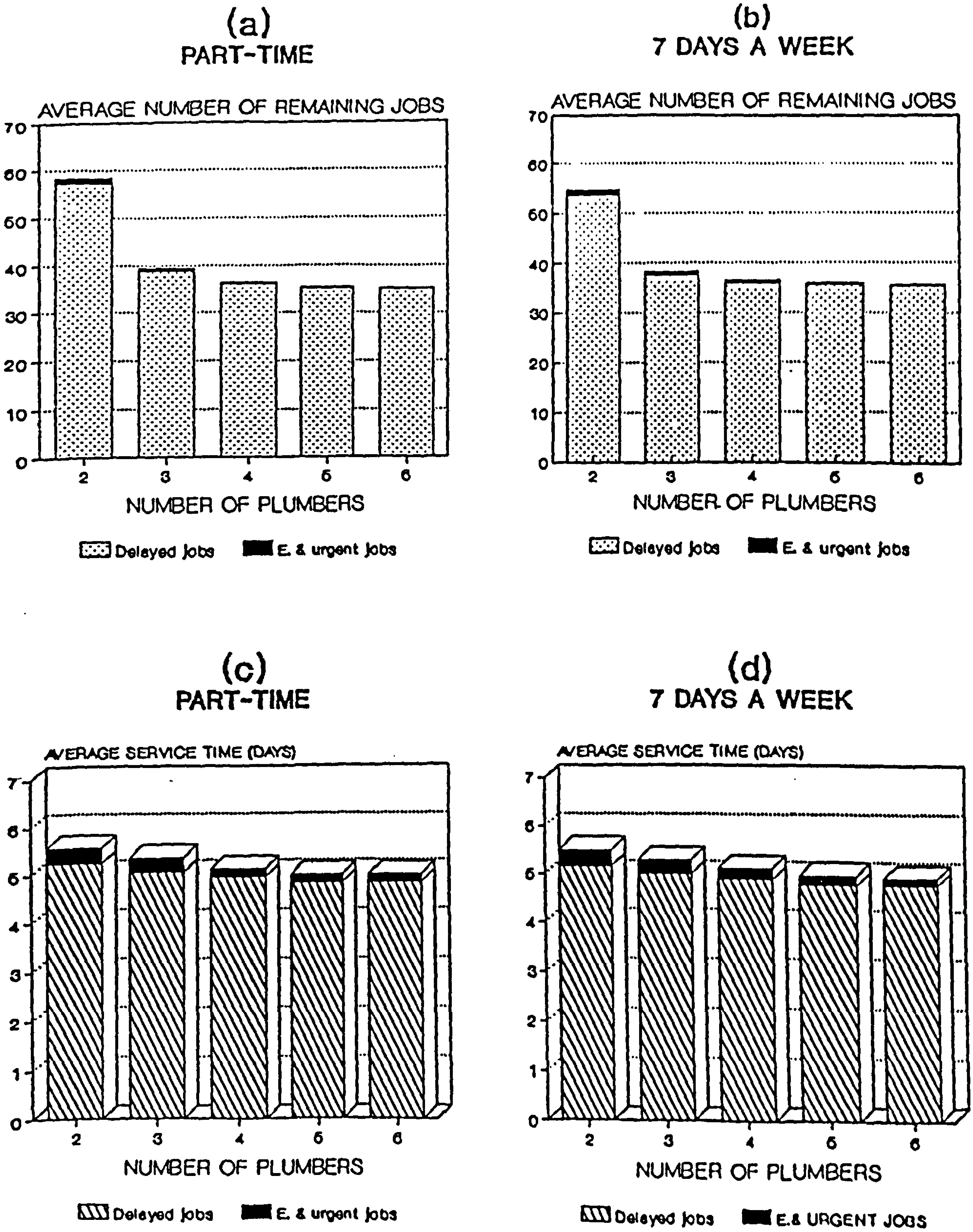


Figure 7.26: Shows average service time and remaining jobs in employing part-time tradesman and working 7 days a week policies;
* Remaining jobs in: (a) Part-time; (b) working 7 days a week.
* Service time in: (c) Part-time; (d) Working 7 days a week.

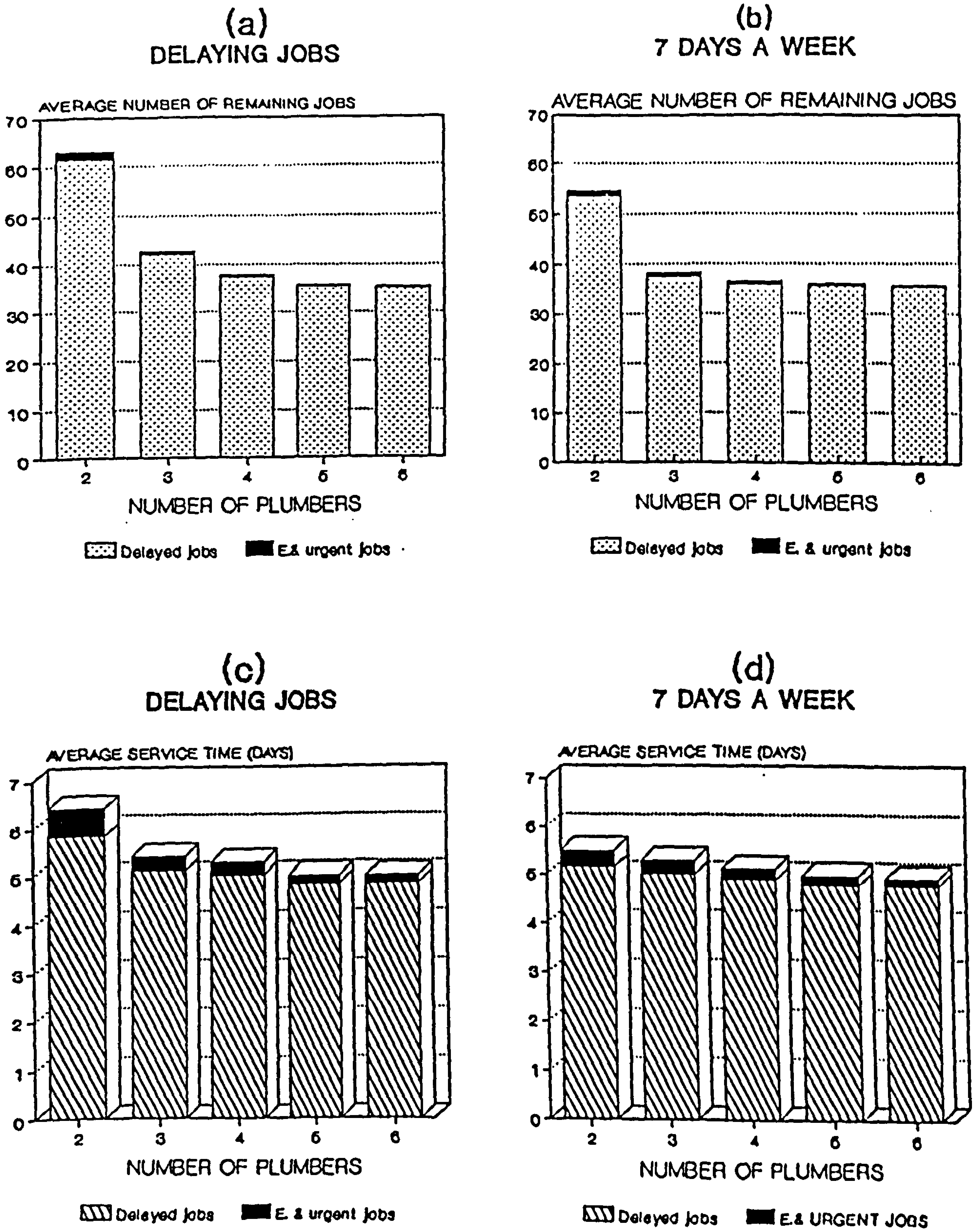


Figure 7.27: Shows average service time and remaining jobs in delaying non-urgent jobs, and working 7 days policies;

* Remaining jobs: (a) Delayed jobs; (b) Working 7 days.
* Service time: (c) Delayed jobs; (d) Working 7 days.

implications such as, employing an extra, perhaps part-time, tradesman to help in circulating the off days per tradesmen per week, as well as considerations about the social implications of working during the weekends. However, the analysis has highlighted the potential benefits and, therefore, the effort worth investing in considering it.

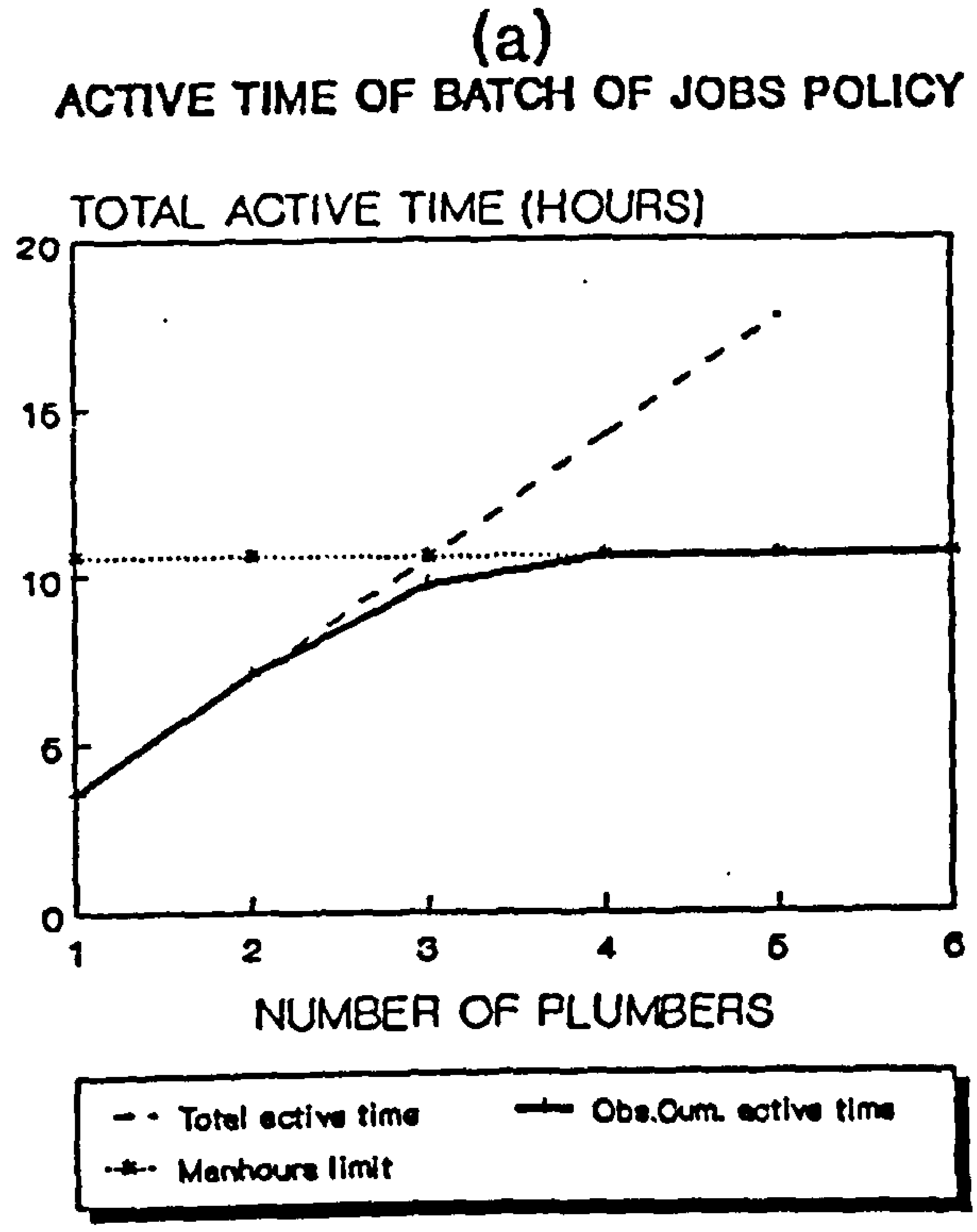
7.3.7. Evaluating 'multi-skilled tradesmen policy (8)'

This policy proposes mixing and training the building trades (plumbers and joiners), and engineering trades (electricians and mechanics), in order to enable them to repair jobs of both trades, i.e. to promote building and engineering multi-skilled tradesmen.

This policy has been simulated and analysed for building trades only, that is combining plumbing and joinery trades into a building multi-skilled trade; it has been run on two methods of deployments, namely: (1) 'collecting a batch of jobs model (3)', and (2) 'delaying non-urgent jobs model (4)'. The results of both experiments are compared with the sum of the plumbing and joinery trades experiments runs for both methods of deployment separately.

Recalling the results of runing 'collecting a batch of jobs policy (3)' for the plumbing trade discussed in section 7.3.2, the minimum number of plumbers required to meet the day-to-day demand for plumbing maintenance equals 3.005 plumbers, with manhours limit equal to, 10.58 manhours per day, figure 7.28(a).

Running the joinery trade on the same policy, 'collecting a batch of jobs policy (3)' shown in figure 7.28(b), the minimum number of joiners are calculated, at 3.316 joiners, with manhours limit required to meet the demand equal to 12.9 manhours per day.



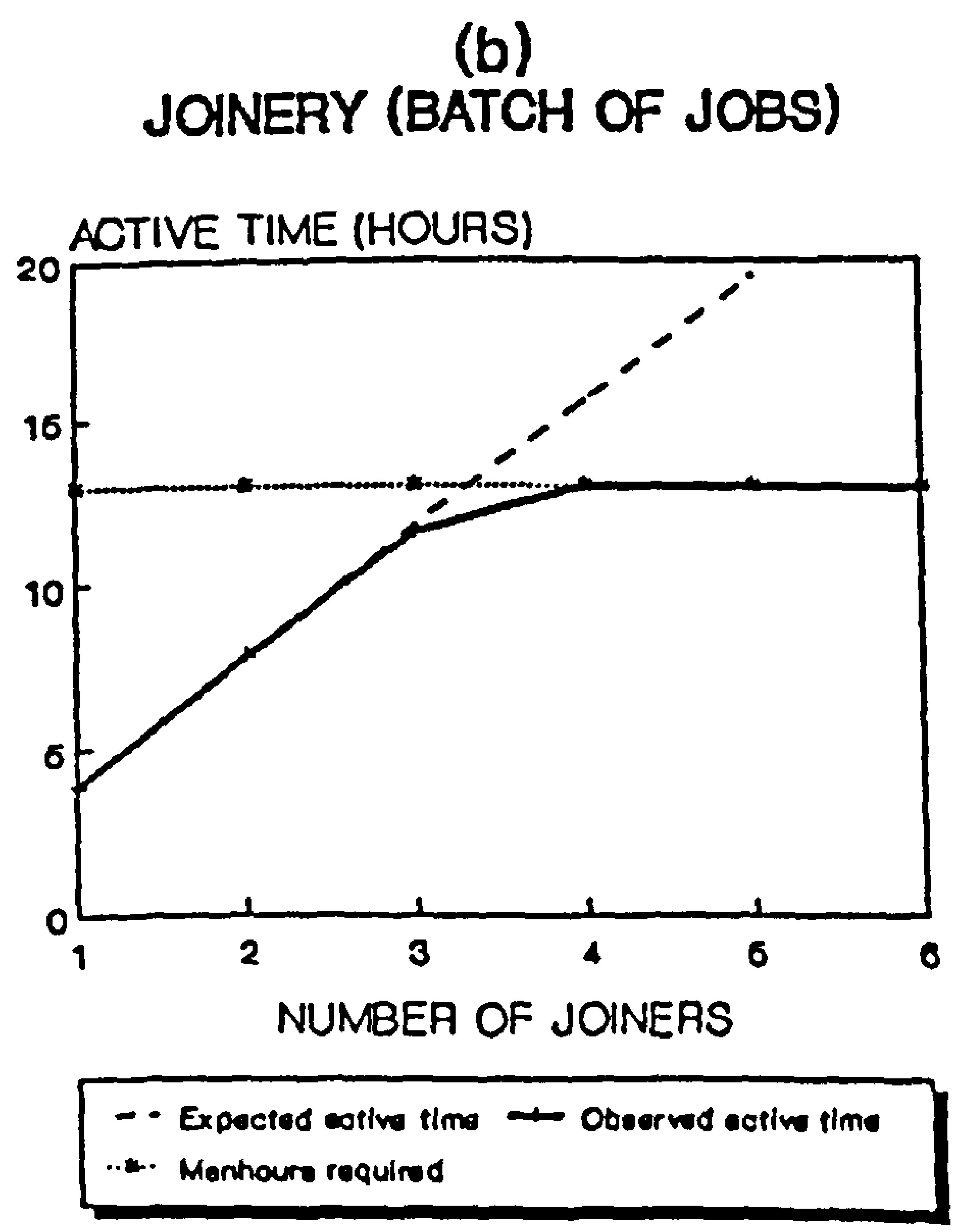
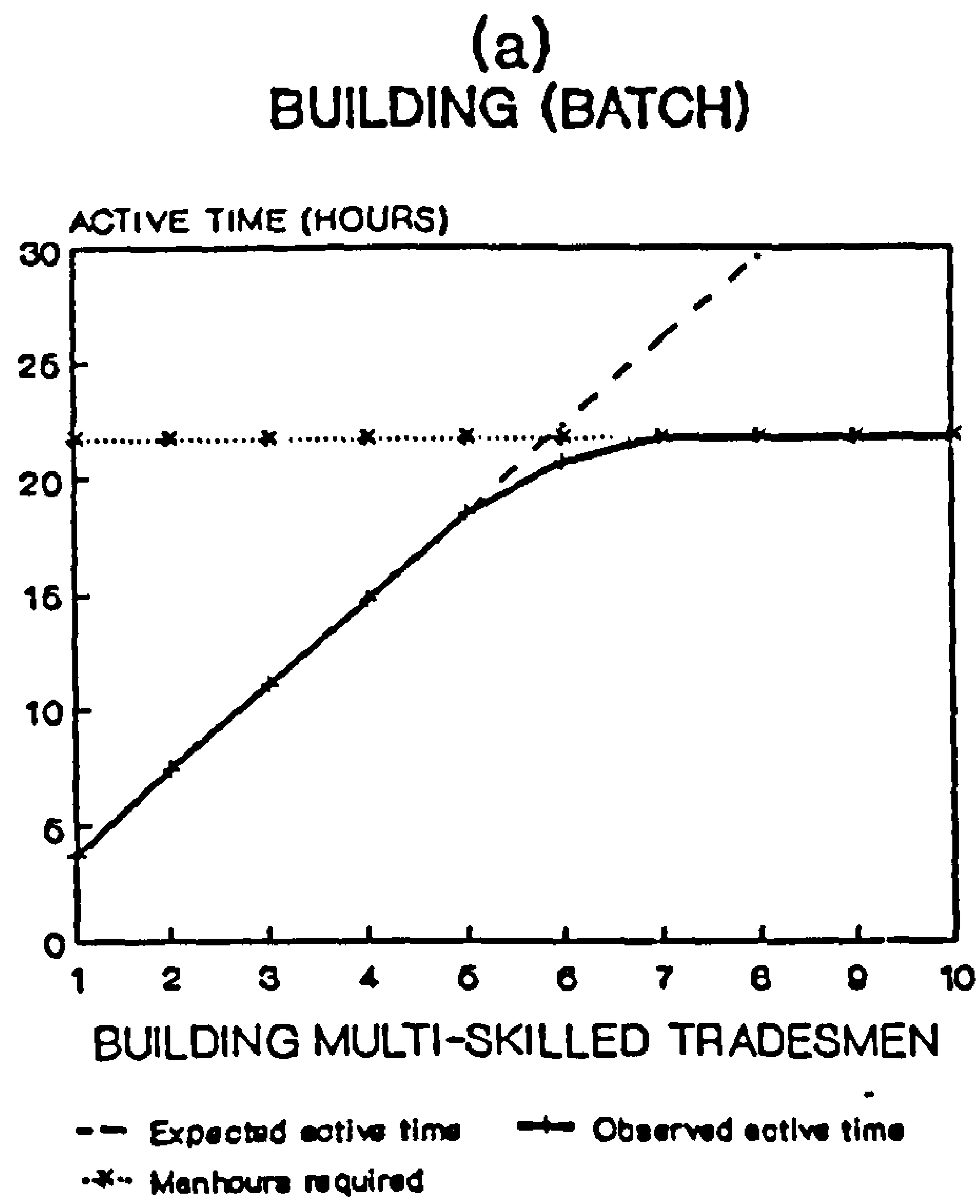


Figure 7.28: Assumed, observed total active time, and manhours limit, of plumbing and joinery single-skilled trades, using 'issuing a batch of jobs policy'; (a) Plumbing; (b) Joinery.

Thus, the minimum number of plumbers and joiners required to meet the building trades demand, when simulated separately, equals 6.321 single-skilled tradesmen, requiring 23.48 manhours on average to accomplish the daily maintenance demand for both plumbing and joinery trades.

Simulating the employment of multi-skilled building tradesmen by 'collecting a batch of jobs policy (3)' figure 7.29(a), has shown that the minimum number of 'multi-skilled building tradesmen', equals 5.864 tradesmen compared to 6.321 in the separate trades models, that is a reduction of 7.23% of the minimum workforce required.
The manhours limit required to meet the daily building demand for maintenance equals 21.7 manhours compared to 23.48 manhours in the separate trades models. That is, the possible gain from implementing 'multi-skilled policy (8)' is 1.78 manhours on average which is around 7.58% gain from the single trades policy the 'collecting a batch of jobs policy (3)'.
As far as the number of remaining jobs and the service time per jobs are concerned, when 'issuing a batch of jobs', figure 7.30(a) & 7.30(b) respectively, the employment of 6 or more tradesmen can bring the maintenance activities under control, whereas employing less than 6 building tradesmen increases the remaining jobs and the delay of jobs reported.

Another experiment on the plumbing and joinery trades, this time simulated using 'delaying non-urgent jobs and grouping them in time model (4)', has shown that the minimum number of plumbers and joiners when simulated as separate trades equal 2.506 and 2.87, see figures 7.31(a) and 7.31(b) respectively. Thus the sum of single skilled tradesmen is 5.18, requiring 20.78 manhours on average to meet the daily building trades demand for maintenance.



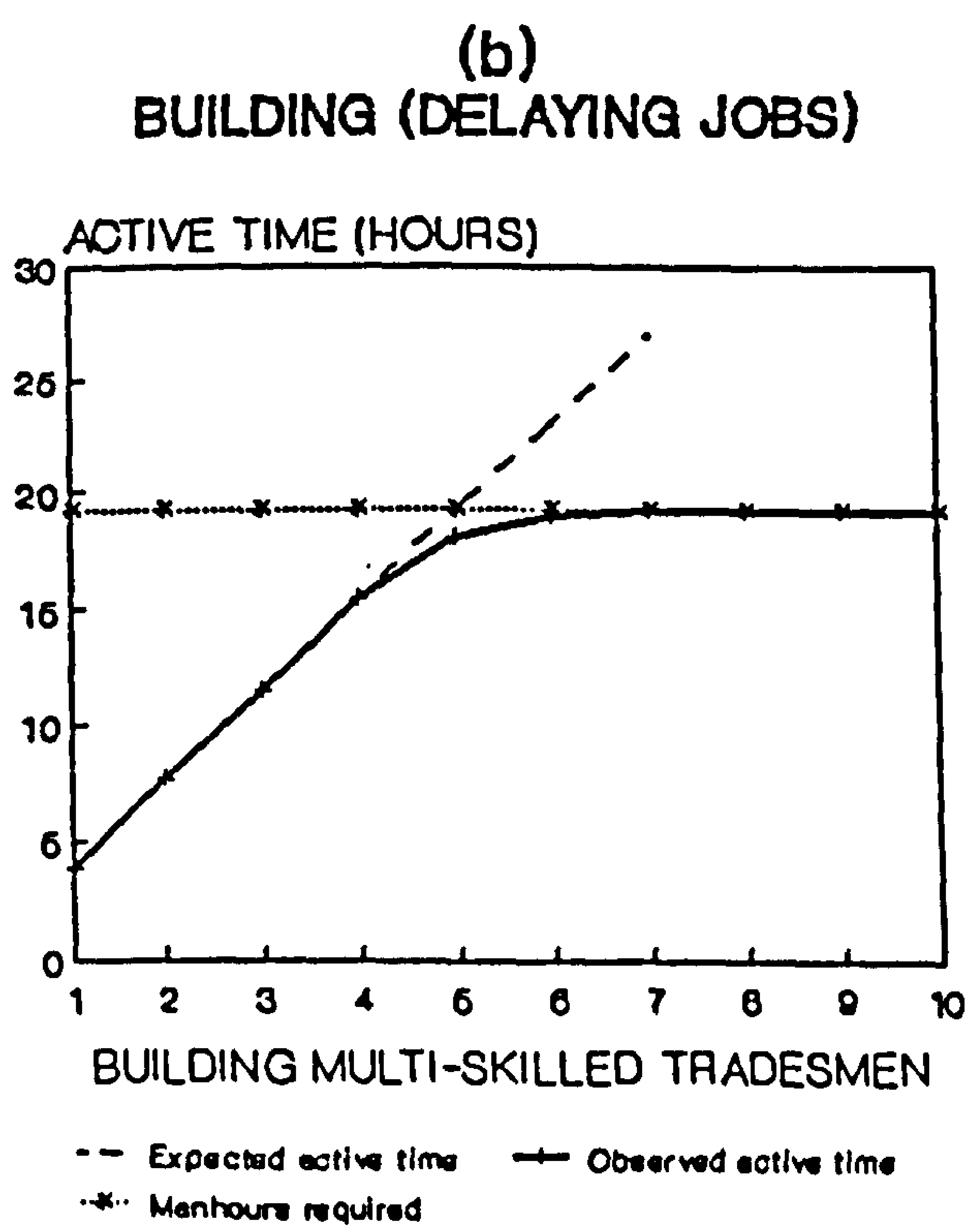


Figure 7.29: Assumed, observed total active time, and manhours limit, of building multi-skilled trade, using (a) Issuing a batch of jobs policy; (b) Delaying non-urgent jobs policy.

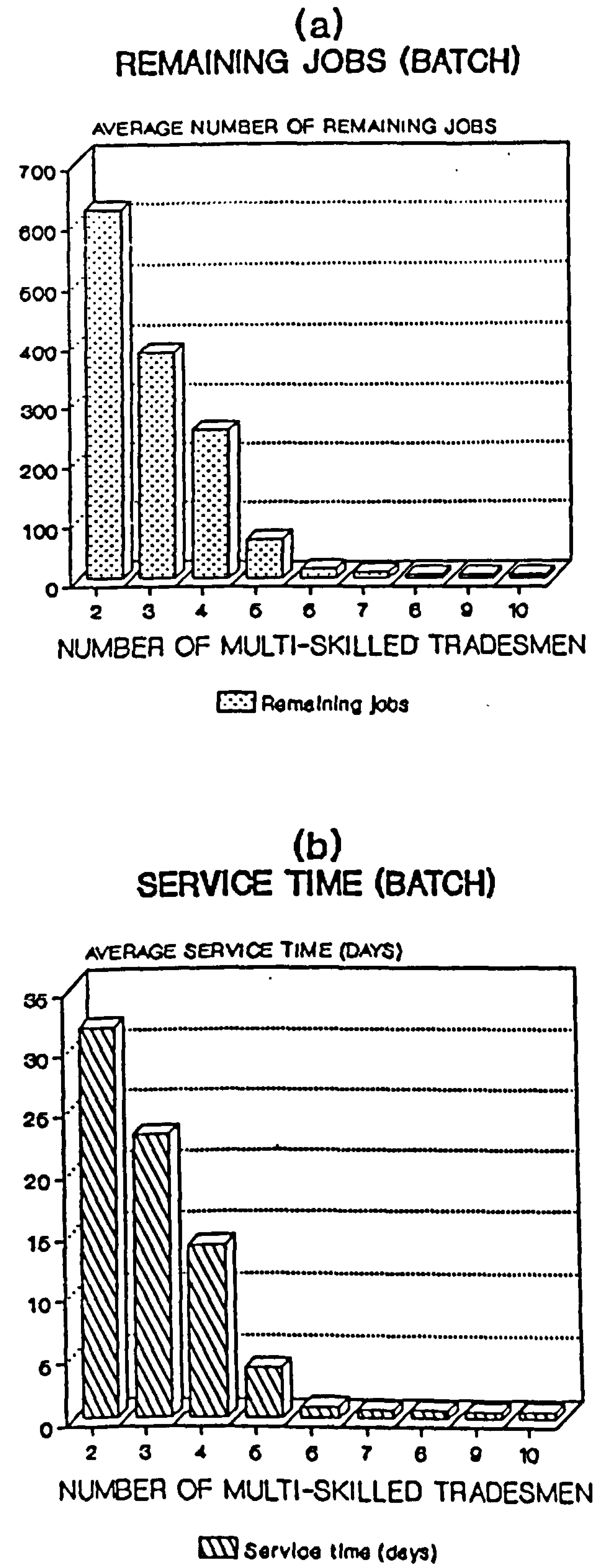
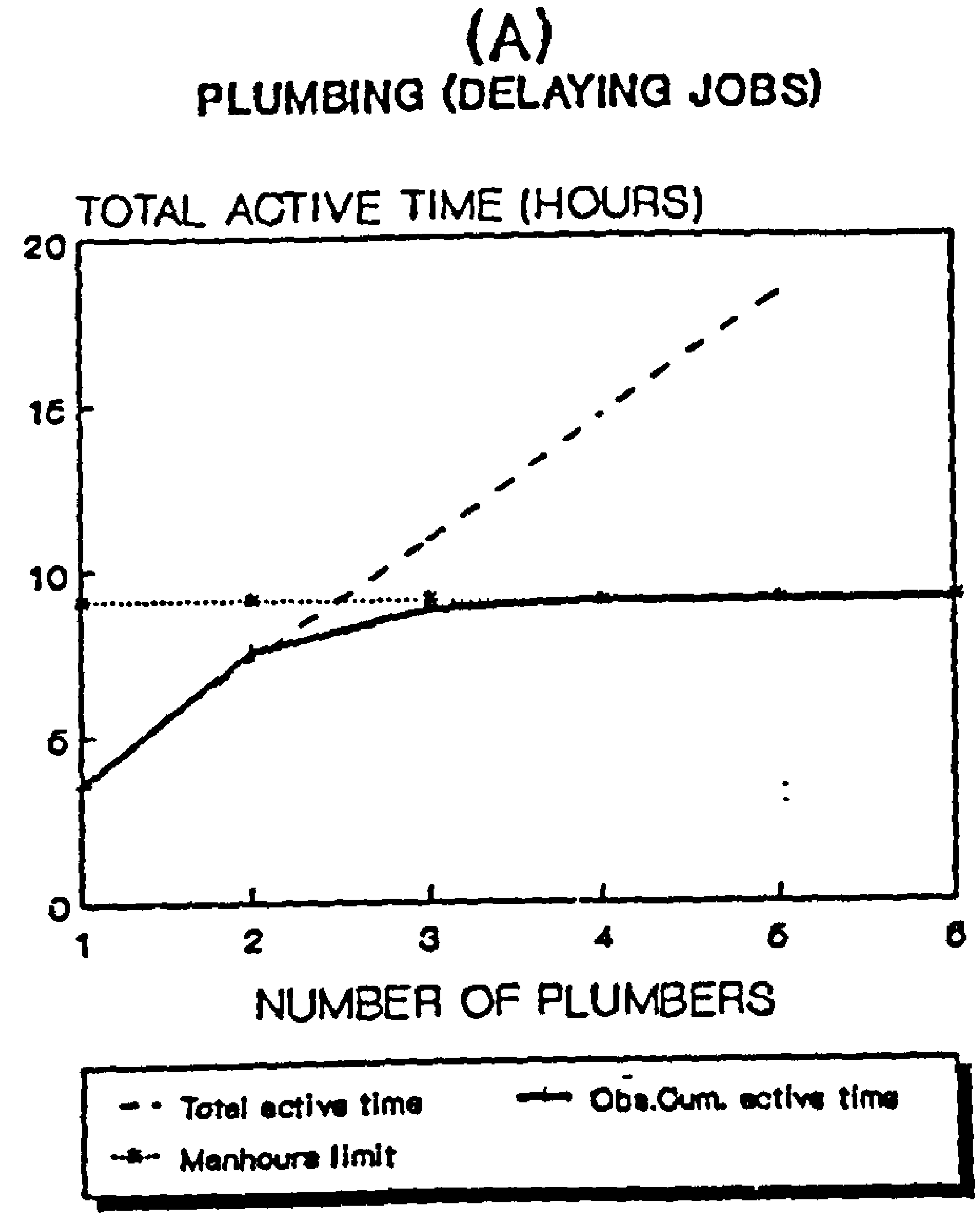


Figure 7.30: Shows the average of remaining jobs and service time of building multi-skilled trade using 'issuing a batch of jobs'; (a) Remaining jobs; (b) Service time.



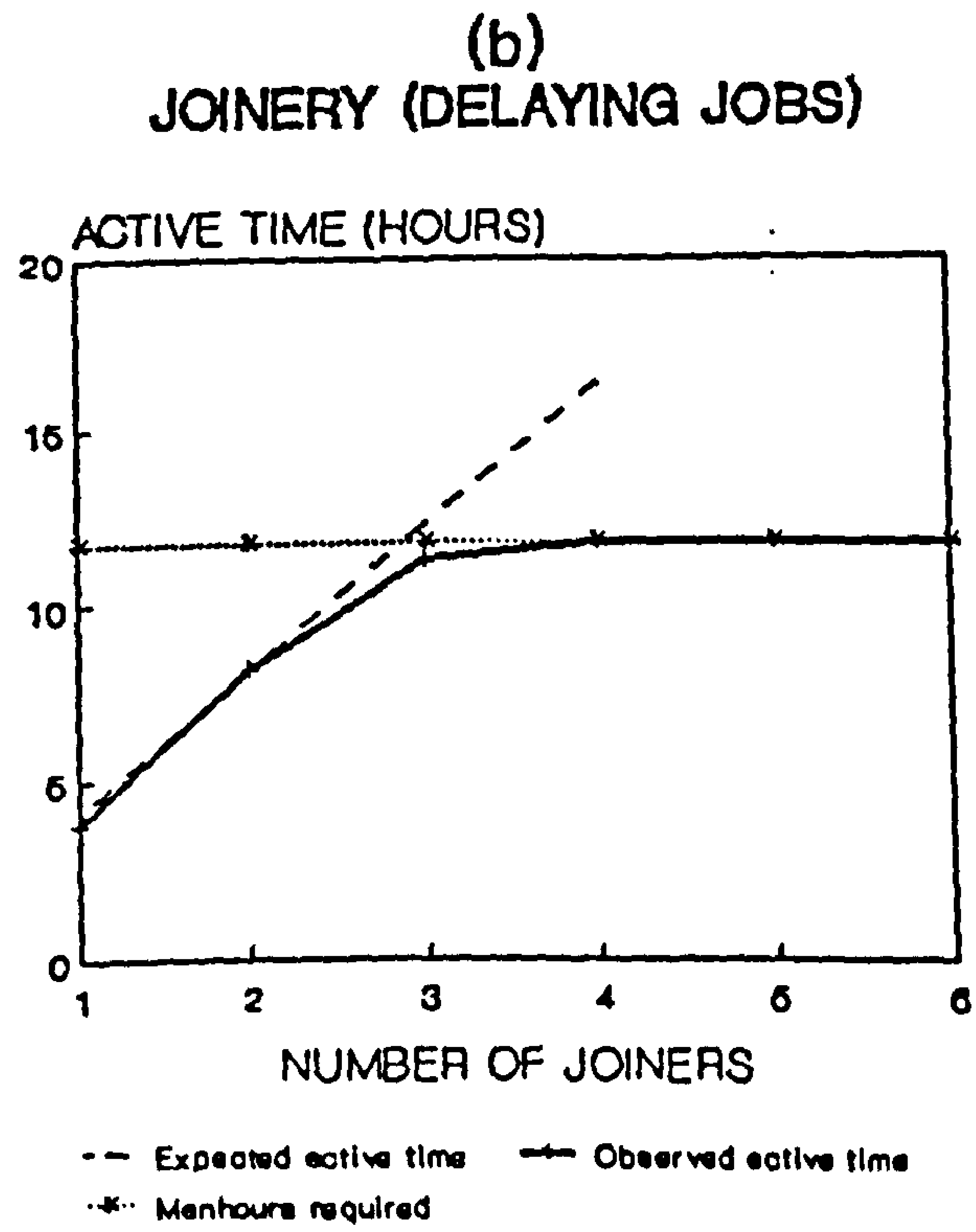


Figure 7.31: Assumed, observed total active time, and manhours limit, of plumbing and joinery single-skilled trades, using 'delaying non-urgent jobs policy'; (a) Plumbing; (b) Joinery.

Simulating the employment of multi-skilled building tradesmen by the same policy that is, 'delaying non-urgent jobs and grouping them in time model (4)' figure 7.29(b), has shown that the minimum number of multi-skilled building tradesmen equals 5 tradesmen, compared to 5.18 single skilled tradesmen, when running the plumbing and joinery trades separately, see figures 7.28(a) and 7.28(b). Multi-skilled tradesmen required 19.2 manhours to meet the building trade demand for daily maintenance compared to 20.78 manhours separate skills (plumber and joiner) assuming the same method of deployment. That is, there is an average gain of 1.58 manhours per day, that is, 7.6% of the manhours limit per day.

Examining the average number of remaining jobs outstanding at the end of the simulated working day and the average service time per completed job, is shown in figures 7.32(a) and 7.32(b) respectively, assuming the "delaying non-urgent jobs model (4)". As the number of multi-skilled building tradesmen increases to 6 tradesmen or more, little change in the output measures is observed, which can be interpreted as, as the number of tradesmen increases and satisfies the daily demand for maintenance in the building trade, then the level of backlog of jobs becomes insensitive to the increase in the number of tradesmen. As the number of tradesmen decreases, i.e. less than 5 tradesmen, the backlog of remaining jobs becomes more responsive, that is, the backlog of jobs, and therefore the average service, time increases as the number of tradesmen decreases.

To conclude this work, employing multi-skilled tradesmen policy which allows for 'not previewing' practice to take place for urgent jobs, depending on the supervisors knowledge, and 'delaying the non-urgent jobs and grouping them in time' appears the most promising for Withington hospital. This policy, which is a combination of a number of proposed policies has performance advantage over the single skilled trades when adopting 'issuing a batch of jobs policy (3)' and is associated with an estimated 20.9% reduction in the minimum workforce required, which represents an estimated gain 18.23% in the manhours limit. Another experiment has been conducted and has shown that this policy has performance advantage over the single skilled trades when adopting 'previewing all defects before repair policy (1)', and is associated with an estimated 39.17% reduction in the minimum workforce required, which represents an estimated gain of around 46.11% in the manhours limit.

The introduction of multi-skilled tradesmen has to extend the skills of tradesmen through training to the same level of skills expected of single-skilled tradesmen. This may require that inducements and incentives be offered to the workforce. There is, of course, the possibility of having some objection to this policy from the trade unions, if the outcome of it means losing more jobs.

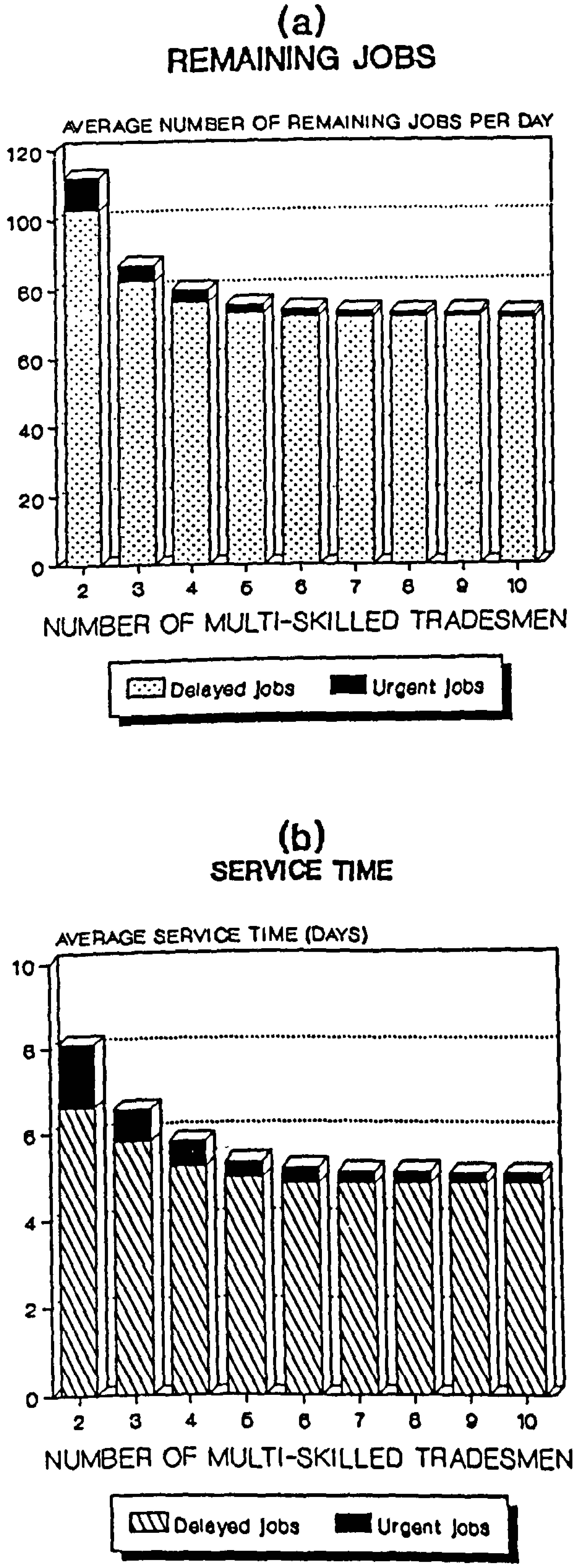


Figure 7.32: Shows two performance measures when using 'delaying non-urgent jobs and grouping them in time policy' for multi-skilled building trade, these are; (a) Average number remaining jobs; (b) Service time per completed job.

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Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1. Introduction

Previous chapters have considered the demand for maintenance and the possibility of reducing it, the data and information system at Withigton hospital, and the proposed maintenance management actions presented by alternative methods of deployment and policies. This research presents detailed discussion on the outcome of various maintenance management policies and their consequences in terms of the performance measures. Performance measures include the manhours limit, and the minimum number of tradesmen required to meet the daily demand for maintenance in plumbing trade using the proposed maintenance management policies. Other performance measures, which are equally important, are the active time, travelling time, average number of jobs completed per day, average number of incompleted or remaining jobs outstanding at the end of the simulated working day, and the average service time per completed job. The purpose of these detailed studies has been to clarify what potentially could be possible and beneficial by way of managing the maintenance activity of a major hospital complex, through adopting a different method of deployment.

In the analysis of simulation output, chapter seven, it is mainly the analysis of the plumbing trade is presented. This was not selected because of an overriding concern for this trade as such, but was selected as representative of trades involved in the maintenance of the hospital in general. For this reason, a listing of salient observations and conclusions of the research study is presented in section 8.2. Section 8.3 lists recommended future action thought necessary to avoid some of the difficulties which faced this study and to achieve better utilization of the maintenance workforce within a major hospital.

8.2. General observations

1 - The increases in sophistication and complexity of medical services within the health service are reflected in the sophistication and complexity of building, their finishes, fittings, contents and services. Not only do the building and their contents comprise of increasingly complex technical systems with interrelating parts or elements, but there are now considerable financial, legal and orgnisational constraints affecting maintenance activities which pose management and logistic problems.

2 - Nicholson (1990) study has assessed the priority of technical systems in The Edith Cavell Hospital at Peterbourogh health care. The highest priority was not medical, as one might expected, but a washing

machine. That suggests the building users should have input to or control in setting up priorities for the servicing and repair of facilities in their departments, which is not current practice at Withington Hospital.

3 - Three separate categories of hospital building maintenance work has been identified by The Local Government Operational Research Unit, Report 144 (1972), in their analysis of one year of data in The Royal Berkshire Hospital. These categories are the fabric maintenance, improvement and modification, and day-to-day repairs.

4 - A large backlog of maintenance work has built up during the last three decades due to the surge of new hospital buildings in the 1960's. This has led to an emergency cover only policy for maintenance of older hospital buildings, partly to conserve scarce resources of much needed medical staff and equipment, and also because of a belief that these buildings would probably be replaced in the foreseeable future (National Economics Development Office 1985). The cost of work required to bring properties in England up to the level regarded by health authorities as the minimum acceptable standard has been estimated as of the order of £2bn (Davies 1983).

5 - The data gathered in this study were collected by different means, from different sources, which were setup for different purposes such as budget control or accounting. Each source has collected data in different level of details for different designed usage. The history data, which were collected by the maintenance department are divided into *building group* and *engneering group*. Data of the *engineering group* covered the whole pavilion (building) without being broken down into its components

(individual wards). This contrast to the *building group* data which covered each individual ward within the pavilion. This lack of consistency and detail is an obstacle hindering further analysis to identify the source of a ward's demand for maintenance, and the effects of medical specialities upon maintenance demand. It was felt by the maintenance management at Withington hospital, and commented on in The Local Government Operational Research Report 144 (1972), that medical speciality may influence the demand for maintenance. It is recommended that thought be given to occasionally constructing a snap-shot model of maintenance activity by collecting data which can facilitate the identification of the demand for maintenance in terms of size, nature, cost of maintenance work, equipment, ward and speciality. This will provide information to aid the maintenance management, identifying problems, and perhaps be used in subsequent maintenance modelling.

6 - The history data, which was stored in a computer system, was unreliable since it has included many duplicated records caused either by a computer or an operator error. Also very few jobs were stored in the computer system due to a shortage in staff time (secretarial time).

7 - Day-to-day jobs data was collected after the failure to persuade the tradesmen and the trades union to cooperate with this study, see section 4.5.2., by collecting data through the snap-shot model. Day-to-day jobs data were then collected in simple form, with the help of maintenance department secretary. This was considerably less than that planned to be collected to identify the size and the nature of the maintenance problem, as well as the possible use of snap-shot data in maintenance

modelling. A comparison of the history data and day-to-day jobs data has shown that the percentage of jobs reported in each trade are relatively close except for plumbing percentages where there is a noticeable difference, which may be due to unreliable history data, (table 3.1). Clearly the computerised history data can only give lower estimates of the real volume of maintenance activities which were undertaking during the period studied.

8 - The material cost was not included in the full history, but is accounted for as a variable by the maintenance department in a weekly report to the Works Office. This report does not refer to the actual job or the trades involved. Recording information about materials used per job per trade can help the maintenance department to ensure that materials and spares are available when required for the emergency or urgent jobs and to purchase materials and spares in economic quantities.

9 - In recent years, a substantial literature has grown around specific topics of industrial maintenance which may be termed collectively as maintenance models. These are concerned with the latter part of a solution process in that it is assumed the existence of a problem has been recognised and its nature defined. As yet, little in the literature addresses the task of problem recognition, or the broader question of how management within an orgnisation can identify how to improve upon the overall effectivness of current maintenance practice.

10- The most common approach to building maintenance is to wait until a defect is reported to the maintenance department, that is adopting a responsive model. A better approach could arguably be, for example, to adopt a policy of replacement or inspection of selective elements or facilities of the property and subsequent rectification of observed defects. Observing and rectifing a defect at an early stage is likely to reduce the defect consequences and therefore the repair cost.

11- In many large building complexes the majority of maintenance repairs are single trade repairs, such as plumbing or electrical. If a sufficiently large proportion of the maintenance work which is identified and reported to the maintenance department, it can be grouped at discrete points in time, and maintenance management can allocate its resources and rectify the defects in a more efficient manner. This case has been investigated.

12- If the hospital facilities are not in an acceptable condition, there is not necessarily a maintenance problem. A high breakdown rate can arise as a consequence of human error or misuse. In this case, the problem is one of training and supervision, and no amount of maintenance will provide a real solution.

13- Any improvement in maintenance has to rely to a large extent upon the level and quality of back up data and records. A number of studies have shown that the fundamental problem common to virtually all orgnisations studied, regardless of size and nature, is that the maintenance management has to cope with an information system in which there is mis-match between the data collected and that which is necessary for effective maintenance control. There is an even greater mis-match between available data and that which is capable of defining the nature of the problem, (not simply its size), and enabling modelling.

14- In a large number of cases the information system has been designed primarily for another use, such as financial control, monitoring and reporting. Relatively little attention has been given in the development to the requirements of maintenance management. That may explain the mis-match between data collected and that which is necessary for effective maintenance control.

15- Maintenance personnel are unclear as to what data should be collected, and what analysis to undertake to provide quantified guidance in the management of their equipment. In general, building maintenance management remain relatively inexperienced in the analysis and utilization of data as a management tool. There apears to be a recognised need for guidance.

16- In setting up a maintenance information system, the basic aim should be clearly identified and procedures and techniques identified and developed for the processing, analysing and utilizing of the relevant data.

17- At a breakdown, a considerable amount of data is potentially available. This data split naturally into three main areas, namely cause of fault, consequences of fault and means of prevention. Collecting this data by means of a snap-shot survey has helped in identifying the nature of the maintenance problem within the industrial context, and there is every reason to suppose the same could apply in building maintenance.

18- It is vital for the design process to include a better utilization of feedback information to assess the performance of equipments. The ability to create a satisfactory and workable design, and therefore to minimise maintenance, derives from knowledge and experience which can be fedback to the decision-making and the incentive for the maintainer and designer to keep learning.

19- The data required for this study was to be collected by means of questionaires to be completed by the operative who performs the repair. The form was designed to be simple and to meet the needs of the maintenance management. In particular, it was to collect the data necessary to estimate the delay times of faults in order to investigate the possibility of applying the delay-time analysis.

20- Data collection exercise had faced a lot of difficulties and reluctance from the trade unions despite the considerable effort by the Works Office/maintenance management at Withington hospital and the Centre for Operational Research and Applied Statistics at the University of Salford. Attempts to convince the tradesmen to co-operate with the study which can help in developing methods enhancing the maintenance management performance and the productivity of the tradesmen were unsuccessful.

21- Large unions are generally less likely to oppose reforms or technological change than are individuals or particular groups of workers who fear that their own position in the labour process will be adversely affected. It is important therefore to distinguish between the position of such individuals or groups and that of the unions as a collective orgnisation.

22- The no co-operation policy adpoted by the maintenance trade unions at

Withington hospital might have occured because: (a) the tradesmen belief that the results of the study and the subsequent changes will have serious consequences for them; (b) problems associated with the existing morale of NHS staff and the unfortunate timing of the data collection exercise; (c) the suspicion of the tradesmen about the objective of the study and that it might be connected directly with the Government proposed White Paper for Health Service reform " Working for Patients" (1989); (d) problem associated with the questionaire form.

23- Simulation model formulation consists of developing a model describing the system behaviour. This model transforms a set of input random variables into a set of output random variables, also known as the response variables.

24- Building a realistic maintenance management simulation model, requires the collection and analysis of the input data which provide the driving force for the simulation model. Determining appropriate distributions for input data is a major task in simulation from the stand point of time and resources.

25- The observed standard repair time of the electrical, mechanical, plumbing and joinery trades, which are used to fit a theoretical distribution or as an input to the simulation model, were calculated back from the the standard labour cost taking into account the cost of labour per hour during the time of the data collection.

26- The distribution of the standard repair time of the joinery, plumbing, and mechanical trades have been fitted by Erlang distributions. The empirical distribution of the standard repair time of electrical trade has been used in the simulation.

27- No standard statistical distribution fits the expected travelling time from the maintenance department to the job locations. A cumulative distribution of the travelling time has been used in the sampling process.

28- A number of important parameters have needed to be subjectively estimated based upon the experience of the maintenance manager and the supervisors. These include the expected time required to schedule and allocate the necessary resources and requisition of spares; the expected time required to collect a job from the maintenance department; the percentage of emergency, urgent and non-urgent jobs; the expected time spent attempting to gain access to a job location; the probability that a tradesman collect wrong spares; and the probability that required spares are not available in stock and have to be ordered.

29- The demand for maintenance is usually met by a limited number of tradesmen. The downtime waiting for repair is sometimes associated with the safety of, or the inconvenience to, patients and staff. This waiting time might be reduced by increasing the number of tradesmen. The optimum number of tradesmen can be found by minimising a measure of the labour cost and the inconvenience to patient and staff. Within the overall context of the hospital, such a measure is not easy to find and is avoided here by presenting consequences of maintenance action to aid management choice. Of chief interest is modelling the manpower requirements under different operating circumstances.

30- Real life problems in the area of maintenance manpower requirements and gang size are normally too complex for using analytical methods. The development of simulation models has shown that discrete-event simulation is a very useful tool for analysing problems in the area of maintenance. By using this technique, it is possible to model systems of a complex nature in a rather realistic and intelligent fashion such as: representing the maintenance activities on a daily basis starting from 8.30am until 4.30pm; identifying the day of the week and the month of the year in order to sample from an appropriate distribution; sampling the sickness according to the monthly trend and following the rules of holiday allocations; computing the daily workforce available for a fresh start in every simulated day; imitates the real system behaviour of tackling emergency jobs; and keeping required records of all the necessary details about time and data of job arrivals.

31- Simulation models of the maintenance activities and proposed maintenance management policies at Withington hospital have been developed to assess the manpower requirements and any changes in the operating procedures. The advantage of modelling is that the magnitude and nature of changes can be assessed and contemplated prior to any actual change in operating procedures. This is generally recognised as being most valuable.

32- New version of ECSLPLUS simulation software has been used to model the maintenance activities of a hospital. However, ECSLPLUS programs are slow in execution, CAPS 'Computer Aided Programming System' can, sometimes, produce unexecutable basic programs due to logic errors, and the documentation is not user friendly.

33- Hospital maintenance management procedures have been simulated by developing three specific simulation models, these are:

(1) Collecting one job at a time;

(2) Collecting a batch of jobs at a time;

(3) Delaying non-urgent jobs and grouping them in time.

Each simulation model is capable, through some changes, to simulate the following maintenance management policies for the four key trades, namely: 'Previewing' and 'not previewing' a defect before repair; 'employing part-time tradesmen during peak days (Mondays and Tuesdays)'; 'working seven days a week instead of five days a week'; 'no sickness model'; and 'employing a multi-skilled tradesmen policy'.

34- It has been recognised that the variability of simulation results is a significant problem in itself. Since the simulation model is an input-output transformation, it follows that in general the model output variables are random variables. This may require long and complex simulation analysis in order to draw meaningful conclusions from the simulation.

35- Two types of simulations with regard to analysis of the output has been identified in the literature namely *terminating* simulation and *steady-state* simulation. The proposed simulation models of the maintenance activities at Withington hospital are considered to be terminating type simulations, because, (1) there are two events that start and stop the simulation runs; (2) The input distributions, such as the interarrival time of jobs, changes over the working days of the week, and the distributions of sickness and holiday change over the months of the year. Therefore steady-state simulations are not appropriate for these terminating models.

36- The average active time per tradesman per day, recorded in every replication or simulation run, has been considered as a prime measure in determining the consequences of maintenance staff level, since repairing a defect (job) requires, beside the repairing and diagnosing time, other necessary activities such as, travelling time, gaining access to job locations, requesting and collecting spares.

37- The point and interval estimates of the difference between the mean performance measures of compared policies is important in answering two questions: (1) how large is the mean difference, and how accurate is the estimator of the mean difference? (2) Is there a significant difference between the two policies?

38- The statistical technique used to construct a two sided confidence interval of the mean difference between the two compared policies assumes that the basic data are approximately normally distributed. This assumption is reasonable since each response variable is itself a sample mean of observations from the observed replication. Computing the confidence interval is based on the correlated sampling and antithetic random numbers in order to achieve a variance reduction in the point estimator of mean difference.

8.3. Conclusions

1 - The majority of maintenance jobs, more than 80% are, or can be considered to be, single trade jobs such as plumbing or joinery in the *building group*, and electrical or mechanical in the *engineering group*. These trades operate virtually as autonoumous groups 90% within the parent maintenance department.

2 - Most frequent jobs are usually small jobs such as replace a light bulb, which represent about 55.9% of the total electrical jobs, and repair a nurse call buzzer 7.1% of the total electrical jobs; repair bed 20.6% of the total mechanical jobs; sink blocked and rewasher a tap, 15.5% and 15.2% of the total plumbing jobs, and repair door handle or fit or move shelves, 31.4% and 14.9% of the total joinery jobs. These types of defects might be reduced by implementing the appropriate and effective maintenance action such as a block replacement to light bulbs, or by introducing a periodic inspection policy.

3 - The demand for maintenance may be assumed to be random. Given the current state and condition of the hospital, maintenance demand is not influenced by the age of the building or the level of activities which were taking place within it during the period studied (i.e. the patient throughput), or by the both measures. In forming this judgement, it must be remembered that it is based upon the use of unreliable data available for the study, which underestimated the correct level of maintenance demand. Also the age of buildings studied was between 75-100 years old, and may be thought of as representing the same age

group of buildings. Finally, it was not possible to establish eitherway if the medical speciality has an influence on the demand for maintenance. For instance, the day-to-day demand for maintenance in psychiatric wards was thought by the maintenance management to be higher than the demand in other medical specialities.

4 - No obvious relationship has been established between the average number of jobs arriving per working day and the average of those arriving on the next, or the previous working days.

5 - There is a significant statistical evidence that the average number of jobs arriving on Mondays and Tuesdays are different of the mean of those arriving during Wednesdays, Thursdays and Fridays; but there is no significant statistical difference between the mean number of jobs arriving on Mondays and those arriving on Tuesdays, likewise there was no significant difference between jobs arriving during Wednesdays, Thursdays and Fridays. This can be explained as being due to the accumulation of non-emergency jobs during weekends which are noted and then reported on Mondays or Tuesdays. It is assumed that Mondays and Tuesdays averages have the same underlying distribution as Wednesday-Friday averages, but with the additional average jobs accumulated during weekends.

6 - It is thought by the maintenance management that there is no difference between the number of jobs arriving during morning working hours from those arriving during the afternoon hours. This suggests that there is no surge in the reporting of jobs in the morning hours, which have accumulated during the off working hours. Evidently, although defects

may be noted at a constant rate during a 24 hours period, the reporting of defects to the maintenance department during the working hours may be assumed to be at a constant rate.

7 - The expected number of jobs arriving per day per trade and the expected time between job arrivals during working hours can be assumed to be homogeneous. That is the time between job arrivals during the working hours of the day is exponentially distributed.

8 - The average of extra workload of reported jobs on Mondays and Tuesdays is representing 89% of the average workload during a steady state day. This suggests that the arrival pattern of jobs is different at weekend to midweek days.

9 - The average number of days of holiday per tradesman is at the lowest level during the months of February and April. The average increases during March, this is believed due to tradesmen wishing to complete their entitlement of holiday, which may otherwise be lost, before the end of the financial year. Summer and Autumn months, June-October, show higher average number of days of holiday than the rest of the year. There was no significant difference in the number of days of holiday during the months of the year. One or two days holiday is typical, even during the Summer months.

10- Virtually no work or trade related sickness has been reported. The average number of days of sickness per plumber or joiner was considerably less than the average number of observed days of sickness per electrcian and fitter. Analysis of the sickness data of electrician and fitter has shown that three tradesmen suffering from long term illness has caused a rise in the average number of days of sickness for electricians and fitters.

11- A bottleneck situation can appear when employing less than four plumbers with a 'previewing policy (1)', where jobs can arrive faster than they could be repaired or completed. Whilst this inbalance persists, it will cause a continually growing queue of jobs to form which have to wait increasingly longer times in order to be repaired.

12- Employing 4 plumbers in the 'previewing policy', which is the minimum viable number of tradesmen for this policy, shows that they are in control, for some time, but there are two peaks when jobs are piling day after day of simulation. These periods are identified as the peak time of sickness and the holiday seasons. It is recommended that the maintenance management seeks to employ a suitable number of tradesmen in this period of the year on temporary basis. Employing more than four plumbers, the peak periods are disappearing and the workforce are more than adequate for the day-to-day work load to the extent that there will be some idle time per tradesman. The utilizations per tradesman will, therefore, have dropped significantly compared to the level when employing 1-4 plumbers.

13- As the number of tradesmen employed by the 'previewing simulation model (1)' increases to more than four, no increase in the total active time can be observed. Therefore the total active time observed in the simulation is at the asymptotic level, for the demand and service statistics given, and has been utilized to represent the manhours level necessary to meet the daily demand for maintenance per trade per simulated policy.

14- Adopting 'not previewing most of the defects before repair (2)' instead of 'previewing all the defect policy (1)' can significantly reduce the total manhours limit required to meet the daily maintenance requirements of the plumbing trade by 3.6 manhours per day, saving 24.3% of the manhours limit, and an estimated 21.07% of the minimum workforce required in 'previewing policy (1)'. Therefore, the maintenance department should be encouraged to develop the skills of the supervisors or by introducing a data base computer system to help in identifying the required resources and spares needed for each job arriving.

15- 'Collecting a variable batch size of jobs policy (3)' by not previewing most of the defects can save an estimated 2.12% of the minimum workforce of 'not previewing policy (2)' and about 22.75% of the minimum workforce of the 'previewing policy (1)'. The corresponding gain in manhours limit estimated by 5.53% and 28.51% of the total manhours of 'not previewing (2)' and 'previewing (1)' policies respectively. The gain of the 'collecting a batch of jobs policy (3)' increases as the number of jobs arriving increases, or as the number of tradesmen employed decreases, which allows the maximization of the batch size of jobs. It is expected that this policy may give better performance when it is used in a large housing estate which covers tens of square miles.

16- There is a significant and an obvious improvement in the maintenance management performance measures when adopting a policy of 'delaying non-urgent jobs and grouping them in time (4)'. It is estimated that 16.6% reduction in the minimum workforce and 13.98% reduction in the manhours limit, required to meet the same demand for plumbing trade, can be achieved when switching from 'collecting a batch of jobs policy (3)' to 'delaying non-urgent jobs policy (4)'. Also, there is a significant improvement when it is compared with a 'previewing policy (1)' estimated as a 35.57% reduction in the minimum maintenance staff and 38.51% reduction in the manhours limit.

17- There is 15.8% gain in the minimum workforce if the sickness factor is eliminated, policy (5). No significant reduction in the manhours limit required to meet the demand for maintenance has been observed. The compared policies are simulated assuming the same method of deployment, that is the 'delaying non-urgent jobs and grouping them in time policy (4)'. The average number of remaining jobs, when employing 2, and 3 plumbers, is less than those for the 'delaying non-urgent jobs policy (4)'. This is due to the increase in the manhours available for maintenance work when the sickness factor is eliminated. The effect of sickness factor diminished as the number of tradesmen increases, when they will be in control.

18- 'Employing extra part-time tradesmen (6)' during the busy days, Mondays and Tuesdays, using 'delaying non-urgent jobs policy (4)' required on average 0.314 more tradesmen to achieve the minimum number of tradesmen required to meet the same demand for maintenance. This policy has been proposed as a result of observing a high rate of job arrivals in the current mode of practice at Withington Hospital. Introducing the 'delaying non-urgent jobs policy (4)' has contributed considerably in the ability to distribute the arriving jobs geographically according to their location within the hospital. Therefore, there is no obvious need to employ an extra part-time tradesman during the busy days since there are no such busy or peak days any more, and it may increase the minimum workforce by 16.5% compared to the minimum workforce in 'delaying non urgent jobs policy (4)'.

19- The influence of 'working 7 days a week instead of 5 days a week policy (7)' can be compared with the previous policy of 'employing extra part-time tradesman policy (6)', since it was proposed, partly, to eliminate the fluctuation in the job arrivals during the days of the week. Even if this policy can give a higher average number of jobs completed per day the decision to consider this policy has to be studied carefully by the maintenance management because it has other implications. For example, the need to employ extra tradesman, perhaps, part-time tradesman, to help in circulating the off days per tradesman per week, and some consideration of the social implication of working during the weekends.

20- Simulating the employment of 'multi-skilled tradesmen (8)' using "collecting a batch of jobs policy (3)" and comparing the results with the employment of single-skilled tradesmen such as, plumbers and joiners, has reduced the minimum workforce by an estimate of 7.23%, and 7.58% in the manhours limit required to meet the same demand for building maintenance.

Simulating the employment of 'multi-skilled tradesmen policy (8)' using 'delaying non-urgent jobs policy (4)' and comparing them with the single-skilled trades, plumbing and joinery, has reduced the minimum workforce required by 3.47% and 7.6% in the manhours limit required to meet the multi-skilled demand for building trade.

The 3.47% reduction in the minimum workforce using the 'delaying non-urgent jobs policy (4)' from the single-skilled to multi-skilled is less than the, 7.23% of the corresponding reduction in the minimum workforce using 'collecting a batch of jobs policy (3)'. This result highlights the possibility for an improvement in the performance over the single-skilled trades when using the 'delaying non-urgent jobs' policy.

8.4. Recommendation

The following recommendations have been compiled to assist those contemplating to conduct similar studies. Much of the literature concerning the development of maintenance modelling assumes the availability of the necessary data for modelling and proper problem definition. This study has shown that the process of collecting the required data for modelling is not always an easy task and certainly cannot be taken for granted. There are a number of points might be suggested to reduce the chances of the reoccurrence of some of the problems encountered:

1. Determine the objective of the study and, therefore, the required data collection. Discuss the problem with for the workforce involved at the earliest appropriate time.

2. A reliable sample of data collection exercise by the maintenance management on a daily basis can be a good supplementary data source

to evaluate the level and size of the maintenance problem. Currently, historic data is either not reliable or does not exist. It is recommended to collect basic data such as, part one of the survey form (for office use only) in figure 4.2, for a limited period of time via a snap-shot, without involving the tradesmen in the data colection. This data can facilitate the prototype analysis.

3. Prepare a general questionaire to collect all necessary data such as the nature and the cause of defects and the mean of prevention (if there is any), as well as data necessay for the proposed modelling.

4. It is recommended that the researcher should collect the required data by him/her self in the first week or so, by requesting to accompany the tradesmen, and record and clarify the required data during the repair through conversation with the tradesmen. This method may remove any misconception as to the objective and of questionaire or its meaning, and will build a good and trusted relationship between the researcher and the tradesmen.

5. The researcher should present his findings at interim stages to the tradesmen who helped in the data collection exercise. Other tradesmen may also be invited to the presentation and discuss the results. Through these means, one hopes that trust and understanding can be further developed and unwarranted fears controlled. If the response was good enough there may be a possibility of expanding the data collection exercise to cover other equipments or collecting sample data over a larger period.

APPENDIX

SUMMARY OF THE MINIMUM WORKFORCE AND THE MANHOURS LIMITS PER POLICY

POLICY	PERFORMANCE MEASURES AND THEIR PERCENTAGE DIFFERENCE			
	minimum workforce	% difference from preceeding policy	manhours limit	% difference from preceeding policy
Previewing policy	3.89		14.8	
Not previewing policy	3.07	21.08%	11.2	24.32%
Issuing a batch of jobs	3.005	2.11%	10.58	5.53%
Delaying non-urgent jobs	2.506	16.6%	9.10	13.98%
The following policies are compared with delaying non-urgent jobs policy				
No sickness	2.11	15.8%	9.07	
Employing part-time tradesman	2.82	-16.5%	9.09	
Working 7 days a week	3.34	-33.5%	9.08	

Table 7.4: Shows the calculated minimum number of tradesmen required to meet the demand for plumbing trade, the manhours limit per simulated policy, and the percentage difference in both measures with the preceeding policy.

AVERAGE ACTIVE TIME (HOURS)

POLICY		NUMBER OF TRADESMEN 1	2	3	4	5	6
Previewing all jobs	: mean	3.67	3.73	3.80	3.50	2.96	2.48
	standev.	2.86	2.50	1.93	1.74	1.60	1.41
Not previewing most of: the jobs	mean	3.64	3.68	3.67	2.80	2.26	1.91
	standev.	3.56	3.16	2.57	1.77	1.46	1.23
Issuing a batch of jobs	: mean	3.52	3.58	3.24	2.64	2.12	1.77
	standev.	4.60	3.08	2.32	2.09	1.69	1.27
Delaying non-urgent jobs	: mean	3.54	3.75	2.93	2.28	1.81	1.54
	standev	3.85	3.13	2.26	1.48	1.32	0.98
No sickness	: mean	4.26	4.14	3.06	2.27	1.81	1.53
	standev.	3.99	3.16	1.98	1.47	1.32	0.97
Employing part-time tradesman	: mean	3.63	3.77	2.97	2.32	1.84	1.54
	standev.	3.53	2.75	1.73	1.39	1.11	1.03
Working 7 days a week:	mean	3.73	3.75	2.98	2.30	1.83	1.52
	standev.	3.92	2.97	2.01	1.33	1.09	0.81

Table 7.5: shows the average and the standard deviation of the active time per tradesman per day in the simulated maintenance management policies.

AVERAGE NUMBER OF REMAINING JOBS PER DAY

POLICY		NUMBER OF TRADESMEN 1	2	3	4	5	6
Previewing all jobs	: mean	449.0	218.9	42.87	16.5	2.22	0.8
	: standev.	186.9	133.5	18.53	4.4	2.61	1.99
Not previewing most	: mean	464.6	170.5	17.25	3.15	1.09	0.51
of the jobs	: standev	232.4	143.7	18.24	5.85	2.089	1.39
Issuing a batch of	: mean	211.4	49.9	3.93	2.27	1.26	0.81
jobs	: standev.	143.4	9.6	4.72	3.03	2.41	1.77
Delaying non-urgent jobs							
* Emergency & Urgent	: mean		1.51	0.63	0.84	0.17	0.15
jobs	: standev.		2.05	1.27	1.13	0.59	0.5
* Non-urgent jobs	: mean		61.56	42.15	37.25	35.26	35.1
	: standev.		32.05	12.96	7.84	6.6	6.5
No sickness							
* Emergency & urgent	: mean		1.56	0.69	0.57	0.1	0.1
jobs	: standev.		2.07	1.31	1.18	0.62	0.5
* Non-urgent jobs	: mean		56.07	38.97	37.18	35.26	35.15
	: standev.		35.66	9.96	7.58	6.67	6.62
Employing part-time tradesman							
* Emergency & urgent	: mean		1.25	0.599	0.177	0.164	0.08
jobs	: standev.		1.45	1.15	0.59	0.618	0.39
* Non-urgent jobs	: mean		57.17	38.97	36.18	35.25	35.20
	: standev.		13.4	8.30	6.60	6.60	6.08
Working 7 days a week							
* Emergency & urgent	: mean		1.15	0.69	0.67	0.21	0.11
jobs	: standev.		1.73	1.20	1.14	0.77	0.62
* Non-urgent jobs	: mean		53.49	37.60	35.90	35.70	35.50
	: standev.		34.70	11.33	8.13	6.38	5.92

Table 7.6: The average and the standard deviation of the remaining jobs per simulated day in the simulated maintenance management policies.

AVERAGE SERVICE TIME (IN DAYS) PER COMPLETED JOB

POLICY		NUMBER OF TRADESMEN 1	2	3	4	5	6
Previewing all jobs	: mean	66.52	22.71	4.61	1.48	0.36	0.32
	: standev.	43.33	23.93	2.23	0.715	0.254	0.223
Not previewing most	: mean	20.01	16.73	1.88	0.48	0.31	0.24
of the jobs	: standev	28.13	16.41	1.90	0.55	0.28	0.208
Issuing a batch of	: mean	19.67	3.89	0.59	0.405	0.30	0.25
jobs	: standev.	21.71	1.10	0.47	0.29	0.25	0.204
Delaying non-urgent jobs							
* Emergency & Urgent	: mean		0.583	0.29	0.252	0.178	0.16
jobs	: standev.		0.59	0.38	0.362	0.278	0.26
* Non-urgent jobs	: mean		5.83	5.09	5.00	4.80	4.80
	: standev.		4.88	4.17	3.58	3.50	3.30
No sickness							
* Emergency & urgent	: mean		0.50	0.31	0.24	0.177	0.169
jobs	: standev.		0.63	0.403	0.37	0.27	0.26
* Non-urgent jobs	: mean		5.30	5.02	5.01	4.9	4.8
	: standev.		5.80	4.20	3.96	3.55	3.34
Employing part-time tradesman							
* Emergency & urgent	: mean		0.331	0.298	0.170	0.17	0.16
jobs	: standev.		0.417	0.37	0.27	0.27	0.26
* Non-urgent jobs	: mean		5.22	5.035	4.93	4.80	4.80
	: standev.		4.47	3.84	3.50	3.55	3.40
Working 7 days a week							
* Emergency & urgent	: mean		0.35	0.30	0.23	0.20	0.15
jobs	: standev.		0.45	0.36	0.33	0.31	0.28
* Non-urgent jobs	: mean		5.15	5.01	4.90	4.80	4.80
	: standev.						

Table 7.7: Average service time and the standard deviation, in days, per completed job in the simulated maintenance management policies.

AVERAGE NUMBER OF PLUMBING JOBS COMPLETED PER DAY

POLICY		NUMBER OF TRADESMEN 1	2	3	4	5	6
Previewing all jobs	: mean	2.47	5.00	7.46	9.00	9.50	9.55
	: standev.	2.24	3.08	4.18	4.39	4.54	4.64
Not previewing most	: mean	2.75	5.52	8.55	9.5	9.55	9.55
of the jobs	: standev	3.02	4.48	4.59	4.24	3.89	3.60
Issuing a batch of	: mean	3.09	6.05	8.90	9.54	9.55	9.54
jobs	: standev.	4.54	4.79	4.32	3.82	3.65	3.44
Delaying non-urgent jobs							
* Emergency & Urgent	: mean		2.41	2.85	2.85	2.847	2.85
jobs	: standev.		1.94	1.75	1.72	1.65	1.70
* Non-urgent jobs	: mean		5.00	6.40	6.69	6.68	6.691
	: standev.		5.6	4.5	3.96	3.90	3.85
No sickness							
* Emergency & urgent	: mean		2.49	2.84	2.845	2.85	2.85
jobs	: standev.		1.93	1.70	1.70	1.66	1.64
* Non-urgent jobs	: mean		5.17	6.65	6.69	6.70	6.70
	: standev.		5.47	4.12	3.89	3.83	3.8
Employing part-time tradesman							
* Emergency & urgent	: mean		2.405	2.86	2.85	2.86	2.87
jobs	: standev.		1.75	1.76	1.65	1.66	1.66
* Non-urgent jobs	: mean		5.56	6.45	6.66	6.68	6.69
	: standev.		4.9	3.97	3.90	3.90	4.00
Working 7 days a week							
* Emergency & urgent	: mean		2.75	2.84	2.82	2.80	2.79
jobs	: standev.		2.07	1.8	1.78	1.78	1.74
* Non-urgent jobs	: mean		6.05	6.71	6.70	6.74	6.79
	: standev.		5.90	4.40	3.77	3.34	3.25

Table 7.8: Average number of plumbing jobs completed per day, in the simulated maintenance management policies.

AVERAGE TRAVELLING TIME (IN MINUTES) PER TRADESMAN PER DAY

		NUMBER OF TRADESMEN				
POLICY		2	3	4	5	6
Previewing all jobs	: mean	98.24	82.93	62.03	50.45	41.9
	: standev.	42.62	38.44	29.05	24.99	20.88
Not previewing most of the jobs	: mean	54.71	50.60	35.34	30.75	21.26
	: standev	44.82	40.29	31.48	21.84	15.53
Issuing a batch of jobs	: mean	41.44	37.0	28.97	25.11	21.35
	: standev.	39.01	25.95	20.51	19.90	17.41
Delaying non-urgent jobs	: mean	28.09	21.98	17.00	13.9	11.7
	: standev.	16.57	14.07	10.7	9.90	7.40
No sickness	: mean	28.78	21.84	17.009	13.90	11.77
	: standev.	16.41	14.90	10.60	9.64	7.39
Employing part-time tradesman	: mean	25.92	19.78	15.50	12.83	10.84
	: standev.	18.24	11.53	10.70	7.90	7.40
Working 7 days a week	: mean	29.20	22.80	19.90	16.36	13.60
	: standev.	17.62	13.80	8.50	7.87	5.90

Table 7.9: Average of travelling time, in minutes, per tradesman per day in the simulated maintenance management policies.

AVERAGE ACTIVE TIME (HOURS) 'EMPLOYING MULTI-SKILLED TRADESMEN' EXPERIMENTS

POLICY		NUMBER OF TRADESMEN 1	2	3	4	5	6
ACTIVE TIME							
(1) Issuing a batch of jobs policy;							
* Joinery trade	: mean	3.89	3.90	3.83	3.22	2.59	2.16
	: standev.	3.93	3.59	2.73	2.19	2.09	1.703
* Plumbing trade	: mean	3.52	3.58	3.24	2.64	2.12	1.77
	: standev	4.60	3.08	2.32	2.09	1.69	1.27
* Building muli-skilled trade	: mean		3.72	3.73	3.725	3.71	3.45
	: standev.		2.32	3.22	2.49	2.44	2.14
(2) Delaying non-urgent jobs;							
* Joinery trade	: mean	3.76	4.07	3.73	2.92	2.34	1.95
	: standev.	3.90	3.57	2.73	1.84	1.52	1.204
* Plumbing trade	: mean	3.54	3.75	2.93	2.28	1.81	1.54
	: standev.	3.85	3.13	2.26	1.48	1.32	0.98
* building multi-skilled trade	: mean		3.84	3.85	3.84	3.6	3.15
	: standev.		4.38	3.55	2.67	2.404	1.838

Table 7.10: Average and standard deviation of the active time per tradesman per day in the simulated maintenance management policies.

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