A MODEL TO OPTIMIZE SINGLE TOWER CRANE LOCATION WITHIN A CONSTRUCTION SITE

by

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ABSTRACT

This thesis describes the development of a descriptive mathematical model to determine the optimum position of a single tower crane. The objective function of the model is that of minimization of total travel time necessary to complete all movements from the installation of the crane until it is dismantled and removed.

Previous models which have been developed to determine optimum crane selection and location are categorized as simulation models, expert systems and mathematical models and three particular models are credited as making contributions to the problem of tower crane location. However, the model developed here overcomes many of the deficiencies exhibited by these models.

In developing a model to determine optimum tower crane location, the characteristics of the construction site in which it will be placed and those of the crane itself must be considered separately. The most challenging and significant problem is in determining the total number of movements which will occur during the time when a particular crane is installed on a particular site. The method adopted was the application of a linear programming technique, the Simplex Method.

Once the (computer) model had been developed a wide range of simulations were carried out to see if any general truth concerning the optimum layout could be evinced. The result of these simulations demonstrated that there are potentially significant savings to be made, in terms of the time to complete all movements, by locating the crane in the optimum position rather than in one where the maximum time to complete all movements occurs. Typical savings were in the order of 30% but situations where the time savings were in excess of 100% and even 200% were not uncommon. The layout configuration was shown to have very little influence on the magnitude of the minimum time to complete all movements. And these optimum positions were found to consistently occur at the site perimeter, very often at the corners, whilst the positions associated with the maximum times were consistently located internally. However, when the cost implications of locating the crane at the perimeter, which necessitates the use of a crane with a longer jib than would be necessary were the crane located internally, were taken into account, it was shown that, in terms of cost benefits, the cheaper option is to use the crane with a short a jib as is viable for the purposes of reaching the points the crane is required to service, and locate the crane internally.

Finally, neural networks were shown to have potential as a tool to predict optimum crane location, but further work is needed to produce a working model.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

"Cranes have been fundamental tools since ancient times. In a modern urban setting, where construction heads upwards, the outstretched booms of tall construction cranes lace the sky line, virtual icons of development and telling gauges of the economic health of a city" (Shapiro and Shapiro 1988).

It is not an exaggeration to say, that anywhere in the world, the readily visible sight of numerous construction cranes across the sky line, not only excites those interested in construction, but confirms an economic upturn in the fluctuating fortunes of the construction industry (Economist 1993, International Cranes 1996c).

Many authors recognize the key role of materials handling and, in particular, vertical movement of materials, in the construction process, acknowledging that the crane, and most specifically the tower crane, is often the most important materials handling device on a construction site (Beliveau and Dal 1994, Burgess and White 1979, Chalabi and Yandow 1989, Everett and Slocum 1993, Golafshani and Aplevich 1995, Hammond 1962, Penn 1974, Vallings 1964, Warszawski 1990). Tower cranes are recognised as having a central role in determining the pace of construction (Gray and Little 1985, Tong 1995). Selection of the optimum number, type and location of tower cranes is, therefore, a focal issue in planning construction operations (Al-Hussein *et al.* 1995, Proctor 1995) and will considerably influence the cost and efficiency of construction (Warszawski 1990). However, the right choice is a complex matter (Al-Hussein *et al.* 1995, Construction Plant and Equipment 1975, Gray and Little 1985) influenced by many factors. The wrong choice can have disastrous consequences (Al-Hussein *et al.* 1995). On the other hand, a properly selected, placed and managed tower crane has a positive impact on the cost and schedule of a project (Chalabi and Yandow 1989).

The major advantage in using tower cranes as the primary lifting device arises from the fact that the jib or boom is supported at the top of a tall tower, allowing obstructions to be cleared (Harris 1994), and loads to be placed anywhere without interfering with the structure, whilst offering excellent operator view (Proctor 1995). Tower cranes are adaptable to buildings of all shapes and sizes, have a good range of both lifting capacity and working radii (Penn 1974) and can provide material movement in both the horizontal and vertical direction (Penn 1974, Vallings 1964). They can be raised to limitless heights (Shapiro and Shapiro 1988) whilst only utilizing a small work space on the ground (Chalabi and Yandow 1989) and can enable the use of far heavier building components than can be man-handled by their ability to place them in their final positions (Vallings 1964). Tower cranes may be used to lift multifarious building components, including concrete (British Cement Association 1993a, British Cement Association 1993b, Illingworth 1972, Ready Mixed Concrete Bureau 1994, Waddell 1975), structural steelwork (British Constructional Steelwork Association Ltd. 1989, British Constructional Steelwork Association Ltd. 1993) and reinforcement (Illingworth 1974). Finally, for many scenarios, they are believed to offer the most economical solution to the need for materials handling (Harris 1994).

Disadvantages associated with the use of tower cranes include the need to provide a suitable foundation (Construction Plant and Equipment 1974, Johnston 1981, Shapiro and Shapiro 1988) and this requirement delays the time in the construction schedule at which the crane can be utilized. A further problem is the need to dismantle the tower crane upon completion of the work (Shaprio and Shapiro 1988); for internally located cranes this may require some infilling of floor slabs where holes have been formed to allow the crane's tower to pass through. Cranes are prohibited from working in high wind speeds; if the manufacturer does not recommend an upper limit, 20 mph is considered to be the speed at which operations should stop (Shapiro *et al.* 1991).

They, in common with other items of large plant, may also be considered as dangerous, and appropriate safety measures concerning their use should be adopted. A further concern is the danger of electrocution (Trial 1985). Finally, as tower cranes are often dominant items of plant, whose use is vital to the successful completion of the contract, but where there may be inadequate provision of alternative material handling plant, it is essential that they are adequately maintained, as their breakdown could cause serious delays to the construction programme.

Many factors influence the selection and location of tower cranes. In the first instance it is necessary to decide if a tower crane (or cranes) offers the best solution to part, or all, of the demand for materials handling. Alternative solutions such as hoists, fork-lift trucks, concrete pumps and other types of cranes, such as mobile cranes, should be considered and their appropriateness for the situation assessed. As a general rule of thumb, in the United Kingdom, tower cranes are unlikely to be considered for projects of less than six months duration and for buildings less than three storeys high (Wimpey 1985). An alternative rule of thumb, suggested by Gray and Little (1985) is that tower cranes should be seriously considered when the unit weight to be lifted exceeds one tonne and the load needs to be placed more than two metres from an accessible edge. Further, tower cranes on a fixed base are also more suitable for buildings of a compact plan shape, rather than those spread over a large area.

Decisions are also required about the type of tower crane. The principal choice is between a saddle (or horizontal) jib or a luffing jib (which are described in more detail in Chapter 3). Further, it must be decided whether the tower crane remains in one position, either by being fixed to a static base, or by climbing (at that fixed position) as the building height increases, or whether the crane is mounted on tracks. However, this decision is outside the scope of this thesis, as, in the model to be developed, it is assumed that the crane remains fixed in position.

Assuming that the decision to use a tower crane has been made, the factors influencing its selection may be considered as technical, contractual or economical (Al-Hussein *et al.* 1995). Technical factors include those such as the shape of the building and the weight and size of material to be lifted, in addition to any constraints the site itself may impose on the use of the crane, such as access, terrain, topography and the layout of the site. Contractual factors comprise those related to the construction schedule and method and also include frequency and speed of lifts. Economical factors are those concerned with aspects such as running costs and the decision between hiring and purchasing, and are determined by crane availability, which will also influence the size and number of cranes used on a particular site.

Previous researchers have developed models which attempt to facilitate the problem of both crane selection and location. A simple classification of these models produces three model types, namely expert systems, simulation models and mathematical models; existing models are described in further detail in the following chapter. However, at this point it is worth highlighting the characteristic of expert systems, namely that they attempt to capture the knowledge held by experts in a particular field, in this case in respect of crane selection and more specifically, as far as this thesis is concerned, crane location, so that knowledge can be shared by others faced with similar problems. However, it is argued that the knowledge held by these experts is based on 'rules of thumb' and anecdotal evidence and not on a rigorous analysis of the problem. This is not meant to say that such knowledge should be disregarded, but that the model which is proposed here can act as a supplement to such knowledge.

In determining crane position (assuming the crane is fixed to a base), there are three broad alternatives (Proctor 1995).

- Position the crane within the building footprint. Temporary holes through the floor system must be provided or stairwells, lift shafts or internal courtyards can be used.

- Place the crane outside the building, but close enough so that the mast can be tied into the building. This method may impede the use of self-climbing wall forms or flying deck forms.

- Locate the crane completely outside the building. A large radius crane is required and separate foundations will be needed.

To facilitate delivery of materials and other building components to the crane, Gray and Little (1985) argue that the ideal location is "one outside the building footprint ....". Christian (1981), Forster (1978) and Vallings (1964) support the proposal that the crane is placed outside the building, but close to the structure. According to Harris (1994) and Penn (1974), it is preferable to site cranes outside the building if at all possible, with the advantages of cheaper and easier erection and dismantling and which avoids the cost of leaving out and subsequently making good parts of the structure. Chabali and Yandow (1989) state that, barring unusual circumstances, cranes should not be placed in the building. It is hard to find any documented advice to place a tower crane internally. However, circumstances exist when this position is the only solution (such as when the building footprint occupies all of the construction site) and Pollock (1996a) provides an example of two internally climbing tower cranes which were used in the construction of the Commerzbank building in Frankfurt. Of the ten cranes used to construct the Berjaya Star City complex in Kuala Lumpur, eight were located internally (Cranes Today 1997b), whilst Penn (1974) also provides photographic evidence of tower cranes being erected inside the building footprint. Therefore, it can be seen that, even though "rules of thumb" may have evolved, and may be postulated in relevant literature, they are not necessarily reflected in practice. This anomaly was also reflected in the results of a survey carried out by the author (see Section 1.3.2 and Section 8.4 for more details). Practitioners were asked to rank their preferred strategy in respect of crane location. Statistical tests carried out on the results obtained from 29 respondents showed that there was no statistically significant difference in the rankings given to "place inside the structure in a lift shaft, court yard or other opening", "place outside the structure but sufficiently close that it can be tied to the structure" and "place away from the structure". However, the option of "place inside the structure where 'making good' later is required" was statistically significantly less favoured than the other options.

1.2 The interaction of site layout planning and optimization of crane location

The consideration of construction site layouts are an integral part of construction site planning, since the physical factors of a site will influence, either negatively or positively, method, sequence and duration of every construction activity (Calvert, 1986). It is obvious that the question of tower crane location cannot be considered in isolation from the wider problem of site layout; indeed crane location is a sub-problem of the overall site layout problem.

Site layout planning is recognized as being an important activity (Hamiani and Popescu 1988, Philip *et al.* 1997, Rad and James 1983, Tommelein *et al.* 1987, Tommelein *et al.* 1992b, Yeh 1995). Further, the benefits of a good layout are generally acknowledged, but deficiencies are hard to measure and it is difficult to attribute their impact to a poor layout (Cheng and O'Connor 1994, Tommelein *et al.* 1987). Models which have been developed to assist in site layout planning may be simply classified as product models or process models (Tommelein *et al.* 1992a and 1992b); existing models are described in further detail in the following chapter.

Considering the optimum crane position will only offer a partial solution to the site layout problem. However, as mentioned earlier, the tower crane, if selected, is a vital component in the materials handling system, and therefore warrants specific individual attention. Furthermore, the especial characteristic of a crane, which potentially offers movement in three directions simultaneously, demands particular consideration. However, whilst this is not a specific objective of the model to be developed, the model has the potential to allow the effects of moving other facilities, while the tower crane position remains fixed, to be assessed; although the impact of doing so will only be measured in the same terms as that used to establish the optimum crane position.

1.3 Aim and objectives

1.3.1 Aim

As mentioned in Section 1.1, tower cranes are widely acknowledged as the most important materials handling device on a construction site, and their selection and location is a focal issue in planning construction operations. The fact that cranes offer movement (of materials) in three dimensions simultaneously means that it is difficult to envisage any other item of plant replacing them in the near and even distant future, especially with the predicted increase in use of pre-fabricated components, whose size and weight demand the use of tower cranes to enable them to be lifted into position. There is also a growing increase in time-pressure on project completion, with the associated commercial implications if projects are not completed on time. Consequently, as the crane is the only item of plant which can move all construction materials in three dimensions as part of the same operation, they have a significant role to play in ensuring timely completion of projects. In addition, crane location was rated by twenty-eight of the twenty-nine respondents, in a survey carried out by the author (see Section 1.3.2 and Section 8.4 for more details), as being of "great importance". Therefore, aim of this thesis is to develop a model to optimize the location of a single tower crane within a construction site. Specifically, the model to be developed attempts to optimize crane location by computing the travel time associated with potential crane locations in order that the (viable) position associated with the minimum time can be selected.

The model will be a mathematical symbolic model which is prescriptive and deterministic. An objective function will be set and certain constraints or restrictions will exist; these matters are described in more detail in Chapter 5. The model may be thought of a decision support tool, as it is a model which can aid the decision maker in determining the optimum crane location.

The philosophy of this model may be based on procedures which could be carried out manually, but, because of the large amount of computation required, it is necessary that such a model, if it is to be of any practical use, becomes a computer-based model.

Development of such a model may be viewed as only offering a partial solution to the wider problem of construction site layout. However, one virtue of such a model is that it offers potential to be used to examine construction site layout in the wider context, as it may be used to examine the effect of moving individual facilities (i.e. those points served by the crane) whilst the crane position remains static.

1.3.2 Objectives

In order to achieve this aim, and as a result of developing such a model, the following objectives may be identified.

- *Review previous research in respect of the general problem of site layout and the more specific sub-problem of tower crane location.*

- *Develop a means of assessing optimum crane location in relation to the facilities which that crane must serve, and hence define the objective function of the model, which is a quantified measure of the effect of altering any of the decision variables (such as the crane location).* The optimum selection of the decision variables will be that which minimizes, or, in some instances, maximizes, the objective function. Although the objective function is, of necessity, of a quantitative nature, it is emphasized that the use of a quantitative model is not intended to replace qualitative experience, but is intended to act as a supplement to such knowledge. This discussion is carried out in Chapter 2.

- *Examine the features of a construction site which impinge upon the location of a tower crane on such a construction site.* Such features contribute to the constraints which the solution proposed by the model must satisfy. This examination is carried out in Chapter 3.

- *Assess global crane movement from the time of installation of the crane until its dismantlement and removal.* Global crane movement may be defined as the total number of movements which will take place from the moment of installation to the moment when the crane is dismantled. A model to optimize crane location can only be based on global crane movement, as it is not possible to move the crane once it is erected. It is inevitable that this may mean that, on a given day, the crane is not in its optimum position if that day is considered in isolation. Global crane movement may also be considered as a constraint which the solution proposed by the model must satisfy. This topic is also discussed in Chapter 3.

- *Examine the features of a tower crane which impinge upon the location of such a crane on a construction site.* This may be considered as the final constraints in the model. In particular, the question of load capacity must be addressed and formulae to calculate the load capacity at any radius developed. This examination and subsequent development is carried out in Chapter 4.

- *Develop a model to consider the interaction of construction site and tower crane characteristics.* Such a model, having verified that the proposed crane position is feasible in respect of reach and lifting capacity, will compute the time taken to complete all movements for a given crane placed on a given site.

- *Develop user friendly computer software, to enable the model to be used by people with no knowledge of the model philosophy.* This development is described in Chapter 5.

- *Assess other models developed for the same purpose.* Three other such models have been highlighted and they are examined in Chapter 6.

- *Examine a wide range of construction site scenarios to see if any general truths about optimum crane location can be evinced.* This has been carried out through a series of simulations, which are described in Chapter 7.

- *Examine the issue of crane cost, related to the length of the jib, versus the benefits from using jibs or varying lengths.* This is discussed in Chapter 8.

- *Develop a prototype neural network to illustrate the potential of neural networks as a possible tool to address the issue of crane location.* This is also described in Chapter 8.

- *Validate the use of the model and its output by seeking the view of practitioners.* This was achieved through the use of a questionnaire, supplemented with some brief interviews, which is also described in Chapter 8, although reference is made to some of the results at appropriate places in the thesis.

The interaction of these twelve objectives are shown in Figure 1.1, highlighting the sequence of activities which must be followed to satisfy these objectives and showing which activities may be carried out in parallel.

1.4 Hypothesis

Therefore, the hypothesis postulated in this thesis is:

"The efficiency of the construction process will be improved by the development and application of a model to consider the quantitative factors, namely travel time, associated with the location of a single tower crane within a construction site."

Specifically, the model to be developed optimizes crane location by computing the travel time associated with potential crane positions in order that the (viable) position associated with the minimum time can be identified.

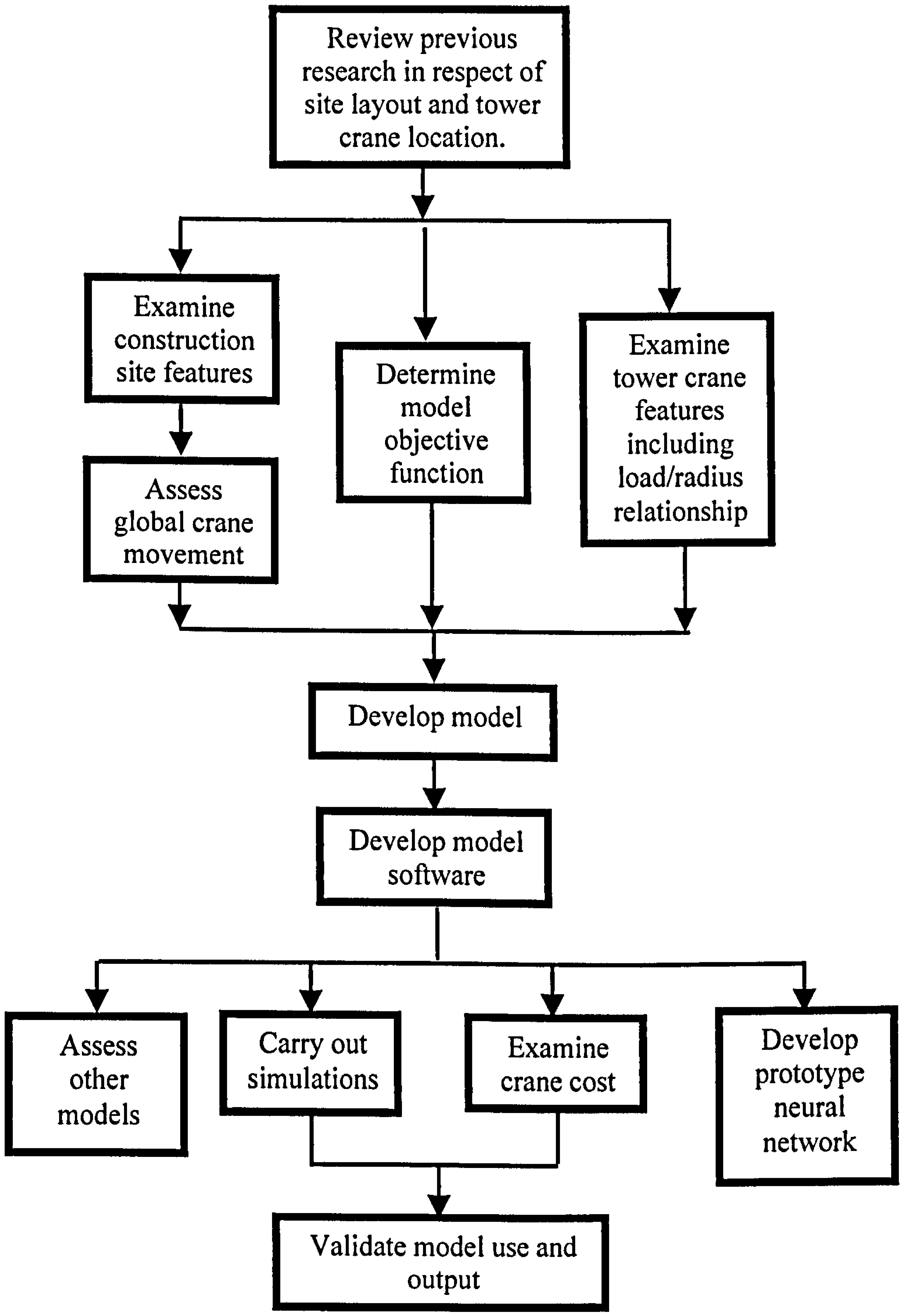


Figure 1.1 **Sequence of activities to satisfy the objectives**

It should be emphasized that time is the parameter optimized by the model. Time and cost are, of course, inter-related and any time savings have potential to reduce costs. The justification for this approach is discussed in detail in Section 2.6. It should also be stressed that the influence of other parameters, such as operator visibility and the suitability of location in respect of the need to provide a foundation, have been disregarded in the ensuing analysis, as it is assumed that only crane locations which satisfy such criteria will be investigated by the model.

1.5 Scope and limitations

The scope of this thesis is limited to attempting to optimize the location of a single tower crane within a construction site. There is no attempt to consider multiple cranes. Furthermore, the crane is considered to be static and the opportunity to utilize rails along which the crane can move is disregarded.

The model is a descriptive, deterministic model and it may be argued that a prescriptive, stochastic model would be preferred. However, the fact that the model is descriptive rather than prescriptive is not a serious limitation, as a prescriptive model may well suggest a solution which is not practically feasible (that is a crane location which cannot be used for functional reasons). In any event, it is anticipated that the number of feasible locations will be quite small and, by using the model, it will be a relatively quick process to pinpoint the optimum feasible location. Ideally, a stochastic model would be preferred to a deterministic one. On the other hand, it could be argued that there is an element of uncertainty in the model in respect of the anticipated number of movements to and from facilities and that there is little point in incorporating another element of chance in the form of stochastic modelling techniques.

Although mention is made, in reviewing the literature, of qualitative factors that should be taken into account when deciding on crane location, the model which has been developed is a quantitative one and its output is given in entirely quantitative terms. It should be stressed that the model, which may be thought of as decision support tool, is not an attempt to replace judgement based on experience and a consideration of the qualitative factors, but provides supplementary information, expressed in quantitative terms, of the effect of a proposed crane position, and so aids the decision maker. It is also assumed that the decision to use a tower crane has been taken, and no judgement is made as to whether the use of a tower crane is the optimum one in terms of the need to provide materials handling.

In developing the model, no reference to purported experts has been made, although practitioners (considered to be the experts in this case) were consulted, via a questionnaire, to ascertain their opinion of the main outcome of the research. The reason for this, as has been demonstrated, is that there are fundamental differences of opinion that make over reliance on experts' opinions dubious (see page 5). Furthermore, it is believed that the experience acquired by experts in this field is not based on any rigorous consideration of the quantitative factors. The fundamental premise of the model provided here is quite simple and is based on consideration of the global movement of the crane, or more specifically the crane hook, during its time on a given construction site. Although it is difficult to predict such movement accurately, particularly in advance, it is argued that the use of a model which attempts to predict such movement will lead to an improvement in the advice given in respect of crane location.

1.6 Methodology

The stimulus for this thesis was a model developed by Rodriguez-Ramos and Francis (1983), which claimed to determine the optimum position of a tower crane on a construction site. However, studying the description of the model in detail revealed that this assertion was misleading and that the model did not do as claimed, but rather that it attempted to determine the optimum position of the crane hook whilst waiting between movements; by implication the crane position must be pre-determined to enable the position of the crane hook to be ascertained. From this, the idea of developing a model to do what was claimed by Rodriguez-Ramos and Francis, that is determine the optimum position of a tower crane on a construction site, was conceived and the conceptual model developed.

A literature search revealed two important aspects of this problem. Firstly, tower cranes play a key role in the provision of materials handling on construction sites. Therefore, their selection and location are important factors in construction planning. Secondly, despite this observation, very little attention is actually given to this matter, especially crane location, and there is a dearth of models or methods to guide practitioners.

Some expert systems have been developed but, for the most part, they concentrate on the selection rather than the location of cranes and, in any event, the expert data-base of these systems is limited and there is little or no evidence that they are based on a fundamental consideration of the problem, but rather rely on possibly limited past experience and rules of thumb. Therefore, at an early stage, the broad aim of this research, to develop a model to optimize the location of tower crane within a construction site, was established; the focus on a single crane, which has already been acknowledged as a limitation, was only determined later, when it was realized that to investigate multiple cranes would, at this stage, be too complex.

The next question to be addressed is to determine precisely how to this aim may be achieved. Research strategy or characteristics may be classified in many ways, but one distinct division is between quantitative and qualitative research (Coolican 1990, Fellows and Liu 1997, Holt 1998, Naoum 1998). Quantitative research is based on testing a hypothesis or a theory, composed of variables measured with numbers, and analysed with statistical procedures to see if the hypothesis or theory hold true (Creswell 1994). On the other hand, qualitative research utilizes subjective methods very often based on personal opinion, perception or feeling (Holt 1998). Coolican (1990) asserts that the characteristics of quantitative research are that the information is objective and narrow, the setting is artificial, the design is structured, reliability is high but validity is low and these characteristics also apply to this research. However, Fellows and Liu (1997) claim that research classification can not be precise because most research occurs within a continuum, and that often combining approaches can be beneficial; for example, qualitative and quantitative approaches may often be complementary.

Holt (1998) defines nine research methodologies, which may be summarized into five groups.

- Process observation and measurement: this involves, in the first instance, observation of whatever is being studied, and, secondly, if appropriate, some measurement of that which is observed. A classic example is method study (observation) and work measurement (measurement).

- Open and structured surveys: open surveys involve utilizing questionnaires to ask questions which may be seeking opinions without any pre-determined response, whilst structured surveys utilize closed questions which require respondents to select an answer from a pre-determined list. In the latter case the questions may seek to elicit factual information (such as type of work) or subjective information (such as strength of opinion on a given matter).

- Unstructured and structured interviews: these are similar to surveys, except that they are carried out orally in a face-to face context. Unstructured interviews utilize open questions with no pre-defined format, whilst structured interviews utilize a standard set of questions for all interviewees.

- Symbolic and physical experiments: symbolic experiments often utilize mathematical models, but other examples could include regression analysis, where the relationship between independent and dependent variables is determined. On the other hand, physical experiments, which may be carried out either in a laboratory or in 'the field', involve the building of samples (such as concrete cubes) and equipment (such as a machine to determine compressive strength).

- Mathematical models: such models use quantitative data and are based on the manipulation of formulae and equations. See Sections 5.2.1 and 5.2.2 for more detailed discussion about model definitions and types and Figure 5.1 for details about model development.

The research described here may be defined as being of a quantitative nature. The principal methodology adopted in this thesis is (symbolic) mathematical modelling. As tower cranes are readily visible, some process observation did, albeit informally, take place. Surveys and interviews have been used in order to obtain factual information and to validate both the ease of use of the model and output generated by the model. Holt (1997) asserts that symbolic experiments and mathematical models are both appropriate methodologies at doctoral research level.

To achieve the research aim, twelve objectives have been specified, and the activities to satisfy these objectives identified (see Figure 1.1). Many of these activities involve literature research, which has been carried out in the usual manner, by searching such sources of information as text-books, journals, conference proceedings and British Standards, using both manual and electronic means and utilizing appropriate key words. The aspects of the literature search associated with each activity are summarized in Table 1.1.

Two of the activities identified in Table 1.1, *Review previous work in respect of site layout and tower crane location* and *Examine construction site features*, may be completed through literature search. The remaining ten activities require empirical research in order to be completed and fulfil the objectives outlined earlier in section 1.3.2. Table 1.2 summarizes the aspects of empirical research required in respect of these activities. Three of these activities (*Examine tower crane features including load/radius relationship, Develop prototype neural network* and *Validate model output*) have used industrial input, either by providing information or by responding to a questionnaire survey.

As mentioned above, the principal methodology adopted in this research is the development of a symbolic mathematical model. There is no standard modelling process; one version of model development is given in Figure 5.1 and a further example of the modelling process is given in Figure 1.2. However, there is agreement that model development is an iterative process. Using Figure 1.2 as a basis, the steps outlined will be examined and related to the model developed in this thesis.

Table 1.1 **Aspects of the literature search appropriate for each activity in order to satisfy the objectives**

Activity	Aspects included in literature search
Review previous work in respect of site layout and tower crane location	Review construction site layout planning and models, facility layout planning, tower crane developments and comparison with mobile cranes, procedures and models (expert systems, simulation and mathematical models) to select and locate cranes, tower crane utilization and behaviour modelling.
Determine model objective function	Review possible objective functions.
Examine construction site features	Review construction site layout characteristics.
Assess global crane movement	Review methods for assessing global crane movement.
Examine tower crane features including load/radius relationship	Review tower crane standards, codes of practice, safe use and regulations, types of tower crane (tower, jib and base), determination of crane lifting capacity and initial crane lifting capacity check.
Develop model	Review model definitions, types and development. Examine the type and influence of obstructions.
Develop model software	No substantial literature search element, apart from assessing most appropriate programming method.
Assess other models	Assess which other models have been developed to determine optimum crane location (this was carried out as part of "review previous work").
Carry out simulations	No literature search element.
Examine crane cost	No literature search element.
Develop prototype neural network	Review neural network methodology and construction management applications.
Validate model use and output	Review methodologies suitable for collecting data from practitioners

Table 1.2 **Aspects of empirical research appropriate for each activity in order to satisfy the objectives**

Activity	Aspects of empirical research
Determine model objective function	Provide an example to justify the approach.
Assess global crane movement	Define movement types. Select linear programming (Simplex method) as the most appropriate method and set up the objective function and set of constraints which exist.
Examine tower crane features including load/radius relationship	Consider load/radius formulae and find those commonly available to be inaccurate. Contact crane manufacturers to ascertain more accurate formulae.
Develop model	Develop the model in terms of equations to consider the interaction of the characteristics of the construction site and the tower crane.
Develop model software	Become familiar with programming and write programs.
Assess other models	Use the developed software to make comparisons with the results of the model developed here and those other models which have also been developed to determine optimum crane location.
Carry out simulations	Use the developed software to carry out a series of simulations to determine if any general principles concerning tower crane locations are apparent.
Examine crane cost	Collect information concerning crane hire/purchase rates from crane hire companies to enable comparison between hire/purchase cost and operating costs due to crane position to be made.
Develop prototype neural network	Select appropriate software (based on availability) and develop a prototype neural network, considering such aspects as input and output layers and network architecture.
Validate model use and output	Select questionnaire survey as most appropriate technique, design and distribute questionnaire and analyze results. Carry out brief interviews in respect of model use.

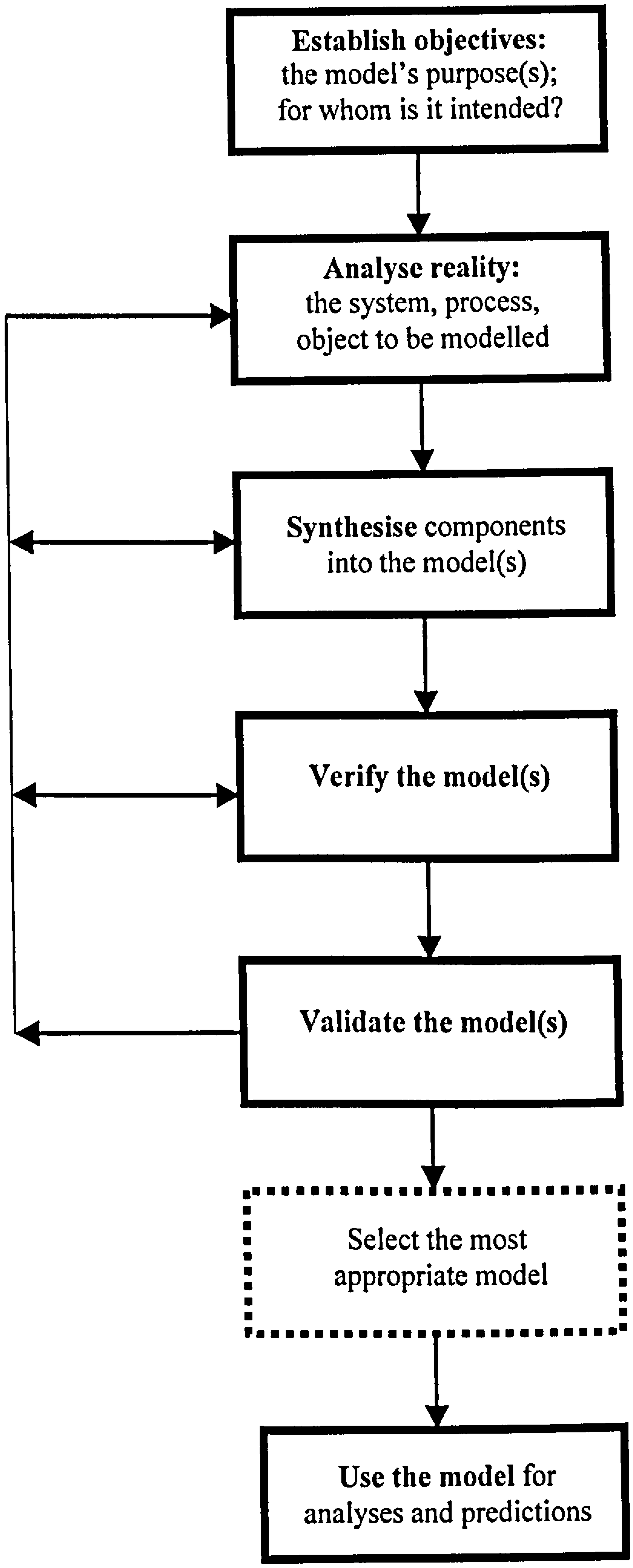


Figure 1.2 **The modelling process**
(Adapted from Fellows and Liu : 1997)

Establish objectives:

The objectives of the model should reflect its purpose and should be appropriate for use by the person for whom it is intended. The objective of the model is to consider the interaction of construction site and tower crane characteristics and, having verified that the proposed crane position is feasible in respect of reach and lifting capacity, compute the time taken to complete all movements for a given crane placed on a given site. The model considers global crane movement (from installation on site to removal from site) and is a prescriptive, deterministic model. That is, it in itself does not suggest an optimum solution, but requires the user to compare the times associated with feasible crane locations. The data used in the model are deterministic (fixed) and no account of data variability is considered. The software (suite of programs) which has been developed so that the model may be used, may be run as executable files in a MS-DOS environment; they are menu-driven and no knowledge of the programming environment (Turbo-Basic) is required. The software has also been used to carry out a series of simulations, described in Chapter 7.

Analyse reality:

Analysing reality involves identifying the relevant variables and their relationships as well as defining the boundary of the system to be modelled. It also includes an assessment of the availability of data. For example, the relationship between crane operating radius and load lifting capacity needs to be formulated in a way suitable for input into the model. Most manufacturers provide load lifting capacity at small frequent intervals between the minimum and maximum radii, but to be useful for the model this information needs to be expressed in terms of a formula which can predict the load at any radius, given that information such as the minimum and maximum loads and radii are first entered into the model. Some data, such as the physical boundary of the construction site, will be known, whilst others, such as the maximum weight of materials to be lifted at a given facility, may not be known with confidence, and a conservative "best guess" will have to be used; this does not negate the purpose of the model, as the requirement to consider these issues can only be an advantage in terms of overall planning. The boundaries of the problem have been addressed in section 1.5 with the most significant boundary being that the model only attempts to consider a single tower crane located in a fixed position.

Synthesise:

Synthesis requires the separate elements of the model to be combined into an entity. In this case it has been recognized that the two crucial entities in the model are the characteristics of the construction site and the characteristics of the tower crane and they and their associated variables are evaluated separately, prior to their input into the model, where their interaction is modelled.

Verify the model:

Verification of a model involves determining whether the structure of the model is correct, by examining the outputs from the model under a given set of conditions to see if they are what are expected. In this case, the model has been verified by examining several scenarios and ensuring the output is that which is anticipated.

Validate the model:

The validation process requires output from the model from known inputs to be compared to realizations of reality. Validation should demonstrate consistency of the model over a range of conditions. Bell (1993) and Coolican (1990) both assert that validity is concerned with whether an item, test or effect demonstrates or measures what the researcher thinks or claims it does. This is different from the verification procedure which is more concerned with the issue of reliability. Validity is a complex issue (Bell 1993) and a variety of ways in which validity can be measured have been evolved, such as face, content, criterion, concurrent, predictive and construct validities (Coolican 1990). However, many of these measures seek to compare what has been newly produced by the model with what is already accepted as valid. This is a problem in respect of the research proposed here, as there is no existing validated solution. Ideally, two construction sites, identical in all aspects except crane location, should be set up, one with the crane located in the optimum position as indicted by the model, and one with the crane located in the position selected in the normal way, and then suitable comparison can be made to either prove or disprove the validity of the model. Obviously this is not a viable option. Furthermore, the objective of the model is to seek to embody a feature of applied research bias, that is "an improvement in traditional thinking" (Holt 1998), as it is contended that there is, in fact, very little fundamental thought given to the crane location problem. This makes a rigorous validation process difficult, if not impossible. However, the model is validated, albeit in a imprecise way, firstly, by comparing the model proposed here, and its output, with models proposed by three other authors (see Chapter 6), secondly, by carrying out a series of simulations to see if general truths concerning tower crane locations can be evinced (see Chapter 7) and, thirdly, by ascertaining the views of practitioners in respect of the data requirements of the model and the main conclusion of the research.

Select the most appropriate model:

This stage is only relevant if more than one model has been formulated; in this case there is only one model and so it is not relevant.

Use the model:

As mentioned above, the software which has been developed may be used by someone without computing knowledge. Ideally the model should be used to examine the influence of crane location at the pre-planning stage and determine the overall optimum position within the practical constraints that exist.

1.7 Overview of thesis structure

The purpose of this section is to provide an overview of each of the nine chapters of the thesis.

1.7.1 Chapter 1 – Introduction

Chapter 1 is the introductory chapter. It illustrates the importance of tower cranes to the construction of high rise buildings, and briefly explains that the location of a tower crane, or, indeed, tower cranes, on a construction site, is a sub-problem of the overall site layout problem. The aim and objectives are outlined and the scope and limitations of the research are established. Methodological issues are also discussed.

1.7.2 Chapter 2 – The tower crane location problem

Chapter 2 provides a brief history of cranes and, in particular, the use of tower cranes on construction sites. Previous research, both in respect of site layout and the sub-problem of tower crane location, is delineated. The chapter concludes by discussing the objectives by which site layouts in general, and locations of tower cranes in particular, may be assessed and attempts to justify the "minimization of travel time" approach.

1.7.3 Chapter 3 – Construction site characteristics

This chapter describes those construction site characteristics pertinent to the development of the optimization of crane location model, and which therefore need to be incorporated into the model. Specifically, the chapter investigates the ways in which global crane movement, from installation of the crane, until its dismantling and removal occur, may be assessed.

1.7.4 Chapter 4 – Tower crane characteristics

Chapter 4 describes the features of tower cranes which are pertinent to the development of the optimization of crane location model. There is a brief discussion of the types of tower cranes available and the relevant standards and regulations which govern their design and use. Of particular importance is the development of formulae which enable the load lifting capacity at any radius to be calculated.

1.7.5 Chapter 5 – Formulation and development of the optimization of crane location model

The purpose of this chapter is to describe the development and formulation of a model to optimize the location of a single tower crane within a construction site. Such development draws upon the discussion in the preceding two chapters, concerning construction site and tower crane characteristics, and describes the interaction of these two separate entities.

1.7.6 Chapter 6 - Comparison with other models

As mentioned earlier, other authors have attempted to develop models with a similar objective to that outlined in this thesis. This chapter examines these models developed by Rodriguez-Ramos and Francis (1983), Choi and Harris (1991) and Zhang *et al.* (1995 and 1996) and, in particular, highlights their deficiencies through presentation of a numerical example.

1.7.7 Chapter 7 – Model simulations

The model to be developed is primarily intended for use in individual situations where a particular tower crane is being located within a particular construction site. However, the model may also be used to examine a wide range of situations to see if any general principles concerning the location of tower cranes are apparent. In order to achieve this objective a series of simulations has been carried out; this chapter describes these simulations and discusses the results, which have been produced.

1.7.8 Chapter 8 – Discussion

In the light of the results arising from the previous chapter, this chapter discusses the issue of crane cost, related to the length of the jib, versus the benefits from using jibs of varying lengths. The results arising from the simulations in the previous chapter are eminently suitable to be used as input to a neural network model. Hence the development of such a model, and the results obtained, are briefly described, in order to demonstrate the potential of neural networks as a tool to address the issue of crane location. Finally, the results of some interviews carried out to confirm the requirements of the model and a survey carried out to validate the model output are described and analyzed.

1.7.9 Chapter 9 – Conclusions and recommendations

This final chapter draws conclusions from the previous chapters and demonstrates that the aim and objectives proposed earlier in this thesis have been met. Recommendations concerning crane location are made and suggestions for future research provided.

CHAPTER 2

THE TOWER CRANE LOCATION PROBLEM

2.1 Introduction

As long ago as the twelfth century, cranes of the shear leg type were erected at the ports to unload blocks of Caen stone used to re-build Canterbury Cathedral (Barber 1973). However, tower cranes, as we know them today, were only introduced into Britain by the Department of Scientific and Industrial Research in the 1950's (Barber 1973). In the intervening fifty or so years technological advances have enabled the production of cranes such as the Krøll K-10000, which has a 10,000 tonne metre capacity and which can lift 120 tonnes at a radius of 100 metres (Pollock 1996a). The capacity of mobile cranes has also increased dramatically in recent years, offering, in many situations, a viable alternative to tower cranes. This chapter briefly examines the history of cranes and compares and contrasts the use of mobile and tower cranes.

It is not possible to consider the problem of tower crane location without some reference to the overall problem of site layout, as the two problems are intrinsically linked. Any change in the selection or location of tower cranes will impinge upon the site layout and any change in the site layout will impinge upon the selection and location of the tower cranes. Therefore this chapter highlights and discusses previous research, both in respect of the general problem of site layout and the more specific sub-problem of tower crane location.

As the model to be developed attempts to embody tower crane behaviour, brief mention is also made of previous work done in the area of tower crane utilization and behaviour modelling.

Any optimization model must have an 'objective function' which measures, numerically, how well each solution fulfils the criterion set down in the objective function. Many criteria have been suggested, but the criterion for quantitative layout models is now frequently stated as the minimization of materials handling costs (Vollman and Buffa 1966). In the case of determining optimum tower crane location for a specific crane, there are no alternative costs to compare and it is assumed that cost is directly proportional to time. The chapter concludes by discussing the objectives by which site layouts in general, and locations of tower cranes in particular, may be assessed and attempts to justify the "minimization of travel time" approach.

2.2 Tower crane developments

The appearance and capabilities of cranes has changed dramatically over years, but their function has remained fundamentally the same, that is to use ropes and pulleys to raise and lower loads that would otherwise be too heavy to lift above ground (Shapiro and Shapiro 1988).

Weinreich (1989) suggests that one of the earliest depictions of crane technology dates back over 2000 years to a sculpture on the tomb of Quintus Haterius in Rome, where the so called "polyspaston" is simply a rudimentary tower crane making extensive use of pulley blocks and powered by a treadmill at ground level. Similarly, Shapiro and Shapiro (1988) suggest that one of the earliest examples of the application of cranes was in the first century AD when man-powered treadmills were used to raise and lower weights and Wislicki *et al.* (1997) claim that, at the same time, a mast crane was pictured on the family tombstone of the Roman master-builder Hateri. Glyn (1854), in his book entitled "Rudimentary treatise on the construction of cranes and machinery for raising heavy bodies for the erection of buildings, and for hoisting goods", suggests that the first form of crane made by man was a rope, of either bark or twisted thongs, which was thrown over the fork of an extended tree branch.

A later example of the use of cranes, namely those erected to unload blocks of stone for the re-construction of Canterbury Cathedral, has already been mentioned. Nevertheless, there is little to demonstrate any real development in the use of cranes until the advent of steam, apart from some elaborate designs which appeared towards the end of the 16^{th} century, during the period the Renaissance. One such crane, designed by Ramelli, had a hoisting mechanism which consisted of a spur and worm gear drive to two barrels coiling the primary ropes of a power wheel arrangement, and so multiplying the rope pull (Barber 1973). Another example of early cranes was that used in the construction of Cologne Cathedral (Wislicki *et al.* 1997). This crane had two treadwheels housed inside it, enabling it to traverse the entire working area. The crane remained in the building when work ceased in 1560, was struck by lightning in 1693, overhauled in 1819 and, finally, in 1842 ended its working life as it was used to raise and place a new stone for the completion of the Cologne Cathedral.

Early cranes relied upon the application of man-power. Glyn (1854) provides details of a series of experiments carried out by a certain Mr Field (late President of the Institution of Civil Engineers) to determine the strength of men working at a crane. Mr Field discovered, for example, that 1050 lbs. could be raised "easily by a stout Englishman" in 90 seconds, while 2100 lbs. could be raised "not easily by a sturdy Irishman" in 120 seconds. However, the introduction of vacuum, steam and water to provide the necessary power rendered the use of human strength obsolete.

Early cranes were of timber construction, and it was not until the industrial revolution that iron became the basic construction material, although large iron cranes did not appear until relatively late in the 19^{th} century. One of the earliest big iron cranes, a sensation in its day, was a tracked slew crane, nearly 100 feet tall, built by Bechem and Keetman for the Vulkan Vegesack shipyard in Bremen. Prior to the advent of tower cranes, wooden framed derricks were often used to erect high rise buildings; one such example was the construction of Liverpool Cathedral (Penn 1974). The first series tower crane was introduced by Julius Wolff, a Swabian crane manufacturer, in 1908. This was a luffing jib crane and it was not until 1930 that the same manufacturer introduced a horizontal boom crane, intended mainly for use on construction sites (Weinreich 1989). As mentioned earlier, tower cranes, as we know them today, were only introduced into Britain by the Department of Scientific and Industrial Research in the 1950's (Barber 1973) and it was not until about 1960 that tower cranes appeared in America (Waddell 1975).

Today the number of tower cranes in use, easily evident on the skyline, is quite striking (Harris 1994) and, as an indication of current commercial trends, companies are now even seeking to exploit their potential as advertising hoardings (Cranes Today 1997a). The capacity of cranes has increased to keep pace with the demands placed upon them to lift building components. One of the largest cranes is the Krøll K-10000 which has a 10,000 tonne metre capacity and can lift 120 tonnes at a radius of 100 metres (Pollock 1996a). Luffing jib cranes have significantly smaller capacities, with 30 tonnes being at the upper end of the range (Pollock 1996a), but offer the advantage of being able to operate in confined surroundings. Tower cranes, by virtue of their ability to climb, can also be used in the construction of extremely tall buildings, for example the 300m tall Commerzbank in Frankfurt (Pollock 1996a), the 237m tall Canary Wharf in London (Shepherd 1997), the 350m high Tehran Telecommunications Tower in Iran (International Cranes 1997), the 327m Sky Tower in Auckland, New Zealand (Green 1997) and 180m Shalom Centre, claimed to be the tallest building in Israel (Cranes Today 1998d). It also common to see multiple cranes on a construction site. For example, 20 tower cranes were used on the construction of the Chek Lap Kok airport in Hong Kong (Pollock 1996a), while the site for the Bauma exhibition in Germany had 24 tower cranes (International Cranes 1996a) and construction of the Garden Town in Istanbul in Turkey is using more than 20 tower cranes (Cranes Today 1998e).

Today, innovations such as computer chip-based detection systems, rather than mechanical load indicating devices, and hydraulic joysticks are expected. Meyer (1987) envisaged that the future tower cranes will be self-erecting tower cranes which combine the advantages of tower and mobile cranes, and this is confirmed by Cranes Today (1991) which states that a new generation of cranes is automatic self erecting mobile tower cranes, using the latest advances in computer and hydraulic technology. They have the advantages of reduced erection time, improved safety and greater mobility around site.

Tower cranes are often used in innovative situations. For example, a Liebherr 50 EC crane has been erected in upper reaches of the Orinoco River in Venezuela's tropical rain forest as part of a 5 year ecological project. The hook is set at a height of 36.3 metres with a jib length of 40 metres and is mounted on a 120 metre long track (Pollock 1996a). Schrader (1975) describes the use of a helicopter to erect a tower crane in the middle of a congested factory. A helicopter was also used to erect the Liebherr crane required for the extension to the Schiltorn Summit Tourist Facility 3000m high in the Swiss Alps, where anticipated problems due to metal fatigue and brittleness, because of the cold, meant that special modifications were required (Shepherd 1997). In the construction of Three Gorges Dam in China, two tower cranes have been adapted to accommodate a conveyor belt for pouring concrete. A conveyor belt feeds concrete from ground level to a point up the mast of the tower crane, from where the concrete passes on to a mast conveyor and then a jib conveyor, both of which are suspended from the jib of the crane (Bishop 1998b).

It is interesting to note different uses of tower cranes across the world. In mainland Europe, the use of mini-tower cranes, controlled at ground level, is common and in France, for example, almost every contractor with more than six men working on a site uses a mini-tower crane (Construction Plant and Equipment 1973). Self-erecting tower cranes are also popular in Europe. They claim to be the simplest, cheapest and most compact form of tower crane and have a maximum capacity of just over 12.0 tonnes (International Cranes 1996b). The use of cranes in America is dominated by mobile cranes (Pollock 1996a, Shapira and Glascock 1996) but there is some evidence that the use of tower cranes is becoming more popular (Meyer 1987); this is discussed in more detail in the following section. A growth area in respect of the use of cranes is Asia Pacific, where the luffing tower is becoming more popular, while the loader crane market is also exploding (Pollok 1996b).

2.2.1 Comparisons with mobile cranes

Tower cranes are traditionally associated with high-rise congested urban construction. Mobile cranes are associated with heavy civil and infra-structure construction where they are used for various other tasks, in addition to lifting. However, on jobs such as public, commercial, industrial and residential buildings, traditionally tower cranes are often used in Europe while, in America, mobile cranes will mostly be used. However, there is evidence that the tower crane market is declining in Europe. Tower crane exports fell by $19 million in Italy in 1997 (Aczel 1997), whilst the tower crane business in Germany has also suffered badly in the recent construction downturn (Bishop 1998a). This decline has also spread to South East Asia, which is experiencing a similar down-turn in the tower crane market (Cranes Today 1998b). This decline may be due in part to a period of recession but is also a reflection of an increasing market share for other forms of crane, most notably mobile cranes.

Shapira and Glascock (1996) investigated the culture of using mobile cranes for building construction in America and concluded that there may often be circumstances in which the use of a tower crane would be advantageous, but the culture of using mobile cranes means that tower cranes are often not even considered.

Shapira and Schexnayder (1999) investigated the factors affecting mobile crane selection and found that lifting assignments and structure dimensions were the key variables in the selection process; these are both variables which must also be considered when selecting a tower crane. Further, they discovered that equipment planning in respect of mobile cranes is a process carried out throughout the life of a project; this does not mirror the practice in respect of tower cranes, where the critical planning in respect of selection and location must be carried out at the early stages only.

On the other hand, Meyer (1987) describes the upsurge in use of tower cranes in America. Compared to mobile cranes they have the advantage of better reach and they do not block the road (in New York, mobile cranes are allowed on no more than 100 days per year on any site south of 69^{th} street). Meyer also found that tower cranes are replacing guy derricks.

The advantages of using mobile cranes include the following:

- there is no need to provide foundations (although a mobile crane must work on a firm surface);
- cranes may be brought onto site as and when needed, without the long term financial commitment associated with a tower crane;
- they can move around (subject to any constraints of the site) and so be positioned near to heavy loads; and
- different cranes may be hired for different jobs with differing lifting requirements.

However, mobile cranes need space to work in and are restricted in terms of the height at which they can operate. Tower cranes can reach greater vertical heights than mobile cranes while offering considerable horizontal working radii and only utilizing a small work space on the ground (Chalabi and Yandow 1989).

2.3 Construction site layout planning

Construction site layout planning is an essential activity (see Chapter 1) and while the benefits of a good layout are generally acknowledged, the effects of layouts, either good or bad, are difficult to quantify (Cheng and O'Connor 1994, Tommelein *et al.* 1987). Popescu (1981) estimated that the cost of temporary facilities on power plants amounts to 10 - 12 % of the direct cost of the project, although his definition of temporary facilities may be broader than that usually accepted. Handa and Lang

(1989) state that for every dollar spent on pre-planning, savings of 4 – 8 dollars are realized by the end of the job. Layout planning is only part of pre-planning and it is difficult to convince managers that such planning is an essential and indispensable task. On the other hand, Warszawski and Peer (1973) claim that by adopting a quantitative approach, namely the model they propose, direct savings of 0.5% of the total construction cost may be achieved.

Site layout planning requires a plan to be drawn up showing the relative positions of all facilities, accommodation and plant (Calvert 1986, Forster 1978, Tommelein *et al.* 1992a). This requires a list to be complied of the number, size and shape of all temporary facilities required to support construction (Oxley and Poskitt 1996). In arriving at the most suitable site layout, either a sheet of clear plastic can be used and laid over a scaled general arrangement drawing, or templates of all accommodation, plant and storage areas repositioned on the general arrangement drawing until a suitable layout is obtained (Oxley and Poskitt 1996). Mahoney and Tatum (1994) suggested that computer-aided design (CAD) can be used to plan construction site layouts; adoption of such a system allows easy and accurate visualization of the relationship between the permanent structures and temporary facilities on site.

There is usually no single point responsibility for designing site layout (Tommelein *et al.* 1987) and neither is there an industry standard method of laying out a site. Rad and James (1983) conducted a survey which revealed that layout designs are mostly based on experience, common sense and the adaptation of past layouts to present projects; very few companies use proprietary systematic approaches. This was also confirmed by a survey carried out by Marakomihelakis (1997) which found that "common sense" and adoption of past layouts to present projects were the two most popular methods used for planning layouts, while only 13% of the responding contractors used computer methods or expert systems to assist in the site layout planning task.

Site layouts need to meet multiple objectives, but, more often than not, these objectives cannot be met simultaneously (Tommelein *et al.* 1992a). Objectives may include maximization of efficiency or to provide for employee safety (Hamiani and Popescu 1998) or to provide the best conditions for optimum economy, continuity and safety during building operations (Calvert 1986). Choi and Flemming (1996) recognize the role that an efficient construction site layout plays in achieving high level objectives, such as project completion on schedule and budget, safety, operational efficiency, quality of construction and high employee morale. They also recognize measurable low level objectives, such as closeness to the work area, adequate space for work, elimination of obstacles to material flow and low ratio of material handling time to production time.

Site layout planning is a complex problem (Tommelein *et al.* 1987). The nature of the problem is such that no well defined method can guarantee a solution or be taught (Yeh 1995) and it is impossible to adopt any one set of standards for the manner in which to layout a site (Burgess and White 1979, Philip *et al.* 1997).

Models to layout sites have been developed, but, according to Tommelein (1992b) these models are rarely used in practice. The reasons given for this are:

- expertise is required to select an appropriate model;
- a large amount of data concerning material flow between facilities is required;
- "black box" systems do not inspire confidence; and
- too many simplifications are required.

Hamiani and Popescu (1988) concur that there is resistance to the use of quantitative models or techniques to assist in the task of site layout planning.

Tommelein provides two alternative classifications of layout models. In the first instance (Tommelein *et al.* 1992a) models are assessed against two criteria. Firstly, the classification is concerned with how general or domain-specific the described work is, which can range from any layout, to any construction site, to a power plant site and, finally, to a case study on a specific site. Secondly, the classification is concerned with whether the described method applies to manual guidelines or heuristics, checklists or specifications for evaluation, through to automated computerized satisfying or optimizing layout generation, at the artificial intelligence end of the spectrum. In the second instance (Tommelein *et al.* 1992b), models are either described as product models or process models. Broadly, product models are defined as cut out templates and modelling blocks, now often replaced by computer models, or anecdotal descriptions of specific site layouts, which are often too specific and therefore not re-usable. On the other hand, process models are defined as descriptive models which generate inputs without human assistance and which typically involve heuristic or improvement algorithms.

The earliest work on layout modelling was done under the auspices of facility layout modelling. Therefore, brief reference will be made to work in this area before some of the most relevant construction site layout models are described.

2.3.1 Facility layout planning

Facility layout and location problems have been the subject of analysis for centuries, although it was not until the emergence of the interest in Operations Research (OR) that much real progress was made. Between 1960 and 1974, over 500 papers were published in this area (Francis and White 1974).

One of the earliest examples of a systematic approach to facility layout, Systematic Layout Planning (SLP) which was developed by Muther (1961), received considerable publicity due to the success derived from its application in solving a large variety of layout problems (Francis and White 1974). SLP is concerned with combining the effects of quantitative movement of materials (flow intensity is recorded in a from-to chart and represented schematically in a materials movement diagram) with the qualitative relationship between activities (importance of closeness is recorded in an activity relationship (REL) chart and represented schematically in an activity relationship diagram). The importance of an activity relationship is rated according to a five-point scale that ranges from Absolutely necessary (A) to Unimportant (U). Finally, the two diagrams are combined to produce a schematic combined relationship diagram.

Developments in computers led to a radical change in conventional methods and allowed a number of alternatives to a layout problem to be readily generated (Francis and White 1974). Moore (1980) classifies computer models in to two main groups - construction heuristics and improvement heuristics.

Construction heuristics are those which start with an empty open floor space. The two best known examples are ALDEP (Automated Layout DEsign Program) and CORELAP (COmputerised RElationship LAyout Planning) (Francis and White 1974). ALDEP was developed within IBM and presented by Seehof and Evans (1967). The layout is developed by randomly selecting a department and placing it in the layout. The REL chart is then scanned and a department having a high closeness rating is then also placed in the layout. This process is continued until all departments are placed and a score to reflect the closeness ratings of adjacent departments calculated. The process is repeated a specific number of times and the layout with the highest score selected. CORELAP (Lee and Moore 1967) works on similar principles.

Improvement heuristics are those which require an initial existing layout. The best known example of an improvement heuristic is CRAFT (Computerised Relative Allocation of Facilities Technique) (Francis and White 1974). CRAFT was developed by Armour and Buffa (1963) and seeks an optimum design by making sequential improvements in the layout. A given layout is first evaluated and improvements are made by making pair-wise improvements until no further improvement can be made. The optimum layout is that associated with minimum cost to travel between facilities, which is assumed to be a function of material flow and distance.

Eilon and Deziel (1966) describe the use of a general purpose electronic analogue computer for locating a distribution centre by minimizing the network link-lengths. The approach is to develop iso-cost curves, which embody the co-ordinates of the points to be served, and appropriate weighting factors.

Zoller and Adendorff (1972) describe the development of a layout simulation program and conclude that the model gives similar results to those which would have been obtained by using CRAFT and suggests that future developments should have broader objectives, rather than the rather narrow handling cost criterion.

Mallette and Francis (1972) describe how facilities can be located so as to minimize the total costs by representing the problem as a general assignment problem.

Liggett and Mitchell (1981a) describe the development of a Space Planning System to locate a set of activities within a facility such that operating efficiency is maximized. The system employs a sophisticated initial placement strategy, based on an algorithm developed by Graves and Whiston, to create an initial arrangement, then applies a simple iterative improvement strategy. In a further development (Liggett and Mitchell 1981b) they describe an interactive graphic floor plan layout method, which is based on graphics which display the possible solutions to a problem and assess the optimum solution in terms of an expected value for the objective.

Foulds *et al.* (1985) describe the comparison of three theoretical graph heuristics that attempt to determine the optimal planar adjacency graph from a REL chart. It is suggested that the layout problem is best solved by splitting the problem into two phases - adjacency and design. Three algorithms were tested and it was found that that Improved Delta and Greedy algorithms were most successful and that the Improved Delta algorithm required less processing time for large samples.

2.3.2 Construction site layout models

Warszawski and Peer (1973) recognize that existing models of industrial plant layout are often of the quadratic assignment type. However, in view of the differing characteristics between the construction process and a typical manufacturing process, they suggest that a better approach would be to use a multi-level fixed-charge model. They continue to develop a general model and a series of models to deal with several sub-problems, ranging from a single supply centre in a single-stage project through to several supply centres in a multi-stage project. Although they claim considerable cost savings can be derived by adopting this model, the drawback is that the model requires considerable quantitative input, including, for example, the transportation costs per unit commodity from each location to each destination and the capital and maintenance costs for each supply centre for each commodity.

Srikhao (1997) produced a computer program to evaluate the proposed location of support facilities on a construction site. The program was based on a methodology proposed by Roe (1983) and was written using Visual Basic for Applications. The method evaluates each proposed layout by calculating a layout score based on a combination of distance between facilities and the 'closeness score'. The closeness score incorporates both the flow of operatives and the flow of material and embodies such aspects as the carrying method and necessity of having facilities close to each other, as used by Muther (1961).

Tommelein *et al.* (1987, 1991 and 1992b) describe the development of SightPlan, an expert system for the layout of temporary facilities on construction sites. The intention of the system is not to automate the human thought processes but to act as an intelligent checklist that contains site objects and activities and suggests locations of those objects. The system was developed using the LISP programming language and comprises of construction site layout knowledge, a language for spatial arrangements and a framework for planning and design. SightPlan lays out temporary facilities, represented as rectangles, on a construction site, represented as a two-dimensional space. An early commitment strategy and spatial constraint techniques are used to find unique positions for facilities amongst those already in place. Developments of the system combine the best attributes of a computer's storage and computational abilities and human cognitive strengths. The authors claim that SightPlan demonstrates that knowledge based systems can successfully address problems not adequately modelled previously.

Hamiani and Popescu (1988) recognize that the limitations, when designing a layout, are, firstly, that iconic models must be used, and, secondly, that only a small number of symbols can be manipulated at any one time, which forces decomposition of the problem into small manageable sub-problems. In order for a sub-problem to be addressed, a facility to enter the design must be selected and its position determined while satisfying all constraints. In an attempt to solve this problem, Consite, a knowledge-based expert system for site layout, has been developed. Experts' design knowledge, consisting of heuristics and rules and thumb acquired through years of experience, are embodied into Consite as a set of rules. In order to produce a layout, Consite uses a plan-generate-and-test strategy. Hamiani and Popescu (1988) believe that Consite has demonstrated the viability of a knowledge based expert system approach to the job site layout problem.

Tommelein and Zouein (1993) recognize that site layouts vary with time and so have developed MovePlan, a graphical and interactive decision support tool for constructing layouts to suit resource site space demands, as dictated by an activity schedule. This enables dynamic layouts, based on identifying the period with the greatest space demands, to be produced.

Cheng and O'Connor (1994 and 1996) have developed ArcSite, an automated site layout system for temporary construction facilities. The system comprises of a Geographic Information System (GIS), integrated with a data-base management system. The knowledge resources are regulations, rules of thumb and experts' knowledge and experience. Using the concept of Searching by Elimination, the system develops an algorithm for generating potential sites for each temporary facility. Considering the constraints and selection criteria, ArcSite identifies the spatial relationship between the data layers which represent the site geographies. The heuristic approach initiates searching the available space to locate temporary facilities and then eliminates the areas occupied by the permanent facility and the areas closed for safety considerations. A number of alternatives which satisfy the searching criteria are generated and assessed against the Proximity Index (PI), the objective function developed specifically for this model, and which incorporates both qualitative and quantitative factors.

Yeh (1995) has attempted to solve the problem of construction-site layout by using annealed neural networks, which merge many features of simulated annealing and Hopfield neural networks, offering rapid convergence and high solution quality. The method of measuring the achievement of a 'good' layout is by using the cost function, which is considered to have two components - construction cost and total interactive cost, although Yeh (1995) admits that determining these costs is difficult.

Choi and Flemming (1996) have built on the earlier work of Flemming and Woodbury (1995) and Flemming and Chien (1995) by adapting SEED (software environment to support early phases in building design) to the design of construction site layouts. To extend the existing model to site layouts requires a class library of specific functional units and a pre-processing module to generate the input and an appropriate evaluation procedure. Evaluation may be made on the basis of closeness to work area, adequate space to work or access between facilities. SEED can be used to provide alternative layouts at different phases of the work.

Philip *et al.* (1997) propose a genetic algorithm approach to optimize construction site layout. Ideally, a hybrid approach, combining heuristics to account for qualitative factors, and algorithms to account for quantitative factors, should be adopted. The use of genetic algorithms is an optimization technique which represents the decision variables in the form of a string representation and then generates new solutions by copying and swapping partial strings. The strings resulting from each generation are evaluated using a fitness function, and the components of the fittest strings are then used to generate new solutions. In addition, the technique also permits the chance of mutations and generation of new solutions based on random selection in order to model natural occurrences. Genetic algorithms have traditionally been used for non-graphical problems; in this case the problem is spatial related. Three options were evaluated for representing the layout of the site in a string format. The overall objective of planning the layout for the site is to minimize the travel effort between the various facilities. The travel frequency between the various facilities is represented as a frequency matrix and the travel effort for a given offspring is computed by determining the product between the facilities in the layout and the travel frequency. The fitness of an offspring is calculated as the inverse of the travel effort. Hence, the algorithm is coded to maximize the fitness of each generation. The program was implemented using C programming language. Philip *et al.* (1997) demonstrated that that this technique could be used to represent the spatial layout of facilities and to generate workable layouts.

As an extension of work done is this area, several authors (Bédard and Ravi 1991, Riley and Sanvido 1997, Shaw 1991) have examined the problem of space planning in respect of the overall completed building, with particular emphasis given to multi-storey buildings.

2.4 Procedures and models to select and locate cranes

In order to evaluate the most cost effective selection of the most suitable number, type and size of tower cranes, and the optimization of crane location, a planner, at the early stages of planning, must appreciate the full effect of crane choice and characteristics against the requirements imposed by the loads to be handled and the surroundings in which the crane will operate (Tong 1995). Planners should have an understanding of the needs and characteristics of tower cranes to enable them to be used properly (Proctor 1995) and also consider the constraints that the particular site will impose upon the use of an individual crane (Liu 1995). There is a wide variety of types, sizes and capacities of tower crane available and the project team should select numbers, types and capacity of cranes only after thoroughly planning the project's schedule, methods and materials (Proctor 1995).

It would be an imprudent contractor who selected a tower crane and positioned it on site without any thought as to whether the crane could reach the points (facilities) where it was required to lift loads and lift the weight of loads expected at each point. Calvert (1986) suggests that "cranes must be superimposed on the scaled plan to ensure that the required reach is available, and drawn to scale on vertical sections to check that obstructions are cleared." Gray (1987) states that "The primary need is to ensure that the crane can cover the whole plan area, plus the pick up zone, with enough capability to lift the required loads safely.". Grundy (1981) suggests that "Selection of cranes should be based on optimum site coverage with minimum down time.". Shapiro *et al.* (1991) propose a methodology to ensure that the crane can reach each facility and lift all the loads required at each facility - this is described in further detail in Chapter 4. It is also important to ensure that there is sufficient space to erect and dismantle the crane and that the crane can freely turn through 360 degrees when not working, to reduce wind resistance (Shapiro *et al.* 1991).

2.4.1 Systematic procedure to select and locate a tower crane

Gray and Little (1985) highlight the systematic procedure that must be followed to select and locate a tower crane. Their research is also concerned with assessing the potential use of a mobile crane as a viable alternative. However, the main steps in selecting a tower crane may be summarized as follows (Gray and Little 1985, Wimpey 1985).

- Determine whether a crane is needed.

  As mentioned in Chapter 1, as a general rule of thumb, in the United Kingdom, tower cranes are unlikely to be considered for projects of less than six months duration and for buildings less than three storeys high (Wimpey 1985). Gray and Little (1985) also suggest that tower cranes should be seriously considered when the unit weight to be lifted exceeds one tonne and the load needs to be placed more than two metres from an accessible edge. Further, tower cranes on a fixed base are also more suitable for buildings of a compact plan shape, rather than those spread over a large area.

- Determine the most suitable type of crane.

  Assuming that a tower crane has been selected, there still remains the choice of the type of crane, for example, whether the crane should have a luffing or saddle jib, or whether the crane should be a climbing crane or one with a fixed length tower. The types of tower crane available are described in more detail in Chapter 4.

- Calculate the required number of cranes.

  To determine the required number of cranes it is usual to calculate what is often referred to as the 'hook time', which may indicate that more than one crane is needed (Proctor 1995). Such calculation may only be carried out after familiarization with the drawings, inspection of the bill of quantities and determination of the construction programme (Wimpey 1985). Hook time calculation takes into account major elements of work and the number of operatives to be employed. Allowance should be made for sub-contractors and it is assumed that the efficiency (or utilization) of the crane is between 60% (Sir Robert McAlpine and Sons Ltd. 1985) and 70% to 75% (Wimpey 1985), although this may be less in areas prone to high winds. Some contractors have pro formas to enable the calculation of hook time to be easily carried out, utilizing historical data about crane usage (Sir Robert McAlpine and Sons Ltd. 1985). If one crane is used, the critical time for floors within the structure will be the same or less than the minimum crane days, in which case the crane will control the pace of the project. Assessment must be made of alternative forms of material movement and the implication of multiple cranes (Shapiro *et al*. 1991).

- Determine the optimum location for the crane.

  This was briefly discussed in the previous chapter, which outlined the three broad alternatives, and, highlighted that, although opinion usually indicates that a location outside the structure is preferable, there are examples of cranes being located internally. Gray and Little (1985) state that the problem is to minimize the maximum load moment over the set of all feasible locations and suggest a graphical method of analysis for determining the optimal location. In theory, this problem can be solved by using one of the optimization techniques (such as Powell's method) with a penalty function. However, this is not suited to buildings of irregular plan and there is also the possibility of detecting a local minima in some corner of the building, depending upon the starting point. It is therefore suggested to use a graphics package to evaluate a fine grid of locations to produce contours of equal function value.

2.4.2 Models to select and locate a tower crane

Many models to select and locate tower cranes have been developed, and these may be classified as (Tong 1995):

- expert systems;
- simulation models; and
- mathematical models

These three categories will now be discussed in more detail.

2.4.2.1 Expert systems

Several expert systems to advise on the selection and, to a much lesser extent, the location of tower cranes, have been developed, some of which are now described.

Gray (1987) describes the development of the expert system CRANES, devised using a Prolog based system for knowledge processing. The system employs a knowledge base of rules and includes a data base containing the pertinent characteristics of all crane types employed in the United Kingdom. It also has a graphical device which, when the user indicates the locations of the loads to be lifted, provides the necessary load/reach profile for the required crane. Although the need to ensure that the crane can cover the whole plan area is acknowledged, no other mention is made of crane location.

Warszawski and Peled (1987) describe the use of an expert system, LOCRANE, developed to give advice about the most suitable materials handling method, from a few limited options which are available, and then locate the crane. In the first stage, the user is requested to provide information about the site and nature of crane employment. In the second stage, the user is asked specific questions about the applicability of pertinent types of cranes to the specific case. In the third and final stage, the user is guided towards the rational selection of the most appropriate type of crane. There is no real mention of crane location.

Warszawski (1990) evaluated both CRANES and LOCRANE and concluded that the limitations of both systems were the use of strict rules which prevent other potential solutions from being considered (for example, the use of a mobile crane for a particularly heavy lift rather than using a large tower crane) and the lack of consideration of the dependence between the crane and other construction planning tasks.

Chalabi and Yandow (1989) describe the development of CRANE, an expert system for optimal tower crane selection and placement. The system has been developed (using the VP EXPERT shell), through interviews with construction industry experts, to carry out the following functions.

- Advise whether a tower crane is necessary. This decision takes into account the site and proposed building, its surroundings and potential material and storage points.
- Determine how many tower cranes should be used. This depends on two factors, the construction schedule (in terms of work load) and the geometry of the building (in terms of reach).
- Decide on the most efficient type of tower crane.
- Position the crane in the optimal location. This is usually done on a plan drawing of the site. A string line, scaled to the average working radius of the crane, is

used to find the best point(s) where the minimum amount of boom distance is required to reach all necessary points. This selection is based on the criterion that, barring unusual circumstances, the crane should not be placed in the building. The output is a list of locations for the mast and an appropriate boom radii. The final decision is made on non-geometric criteria, embodied in the expert system in the form of rules.

Hanna (1994) describes the development of SELECTCRANE, an expert system (developed using the EXSYS shell) to determine the most suitable crane for use on a construction site. Cranes are classified as mobile, tower or derrick cranes. The selection of tower cranes has cost implications. The information required includes expected weights, dimensions and lift radii of the heaviest loads, maximum lift height, lifting frequency, wind speed, site conditions, availability of space for erection and dismantling, obstructions and rental charges. However, it is not concerned exclusively with tower cranes or with the position of tower cranes.

2.4.2.2 Simulation models

Most of the examples of simulation models were not developed to be directly applicable to the issue of crane selection and location, but address wider issues concerned with construction planning and decision making. It is also observed that simulation models are usually developed as part of an integrated system with other model types, such as expert systems. However, the model proposed by Zhang *et al.* (1995 and 1996) specifically attempts to address the issue of tower crane location; this model is discussed in more detail in Chapter 6.

Tarricone (1992) describes the implementation of Computer Integrated Construction (CIC) and the development of a computerised method to organize the job site using visual simulation (a "what-if" visual thinking tool). One example given is the question of whether two cranes can operate safely in the same area without colliding.

Wijesundera and Harris (1989) and Wijesundera *et al.* (1991) describe the development of a dynamic interactive simulation model, CONPLANT, to assess the selection of material handling methods in construction. In the first stage, the most appropriate choice of materials handling plant is made by an expert system, which takes into account the physical characteristics of the particular project, such as ground conditions, structure shape and height, access conditions and the existence of obstructions, before making specific recommendations on the use of a relevant category of plant, such as the type of tower crane. In the second stage, the simulation model proceeds to evaluate all recommendations by considering such factors as the quantities of material to be handled, travel distances and machine performance. By changing variables, such as crane type, size and location, skip size, delivery system and construction crew size, the effect on utilization levels and costs can be evaluated and compared.

Liu (1995) acknowledges that "Cranes are among the most expensive and frequently shared resources on the construction site." Many of the characteristics that influence the selection and location of a tower crane are not deterministic and, therefore, Liu (1995) claims, simulation is an ideal method for allowing the alternatives to be examined and describes the development of COOPS, a graphical simulation system. Times (expressed in terms of mean and standard deviation) for various activities involving the crane are used to simulate that activity. No account is taken of the position of the crane and the purpose of the model is merely to examine the optimal crane use on a daily basis.

Of more direct relevance is the computer integrated system for crane selection, developed by Al-Hussein *et al.* (1995). The decision process is complicated and selection of the wrong crane can have disastrous consequences. Al-Hussein *et al.* (1995) claim that "On a construction site, normally, the final position of a selected crane is arrived at after many trials, which tend to be time consuming and expensive. Much of the knowledge is not available to the decision maker.". Therefore, Crane Advisor has been developed, which is an integrated system. The first module is a case based reasoning module containing information on various constructed buildings with pre-selected crane(s). The second module is a rule based module containing experts' knowledge, heuristics and rules of thumb related to crane selection. The modules share a data base containing information about many cranes and information associated with their selection on previously constructed buildings. Crane selection can effectively be carried out using computer simulations. These simulations require detailed data on crane working range, site restrictions, shape of the building and material specifications, including masses and sizes. Crane Advisor is capable of performing such simulations using a computer-aided design (CAD) package that is linked to its data base. Using the general domain knowledge that is stored in the system's knowledge base, and optimization techniques, relationships between the jib size, boom size, mast height, and building floor layout are automatically generated. During the process the user may modify the jib size and height of crane that is recommended by the system, by selecting other components using the system's pull down menu. The user may however choose to select a different crane from the data base or select his/her own crane. In this case the user will be assisted in identifying the crane's location using the graphical simulations. However, the system does not offer any advice in respect of crane location.

2.4.2.3 Mathematical models

Furusaka and Gray (1984) have developed a mathematical model to select the optimum crane for a construction site. The model considers both mobile and fixed tower cranes. The optimum crane is that associated with least cost (hire, assembly, dismantling, running costs and provision of base). It is assumed that total lifting time is not unduly effected by the variability of crane lifting and slewing speed and that the loads to be lifted, and maximum loads, are pre-determined. Firstly, it is necessary to determine whether one crane is sufficient to cover the whole area. Certain constraints may exist, such as two tower cranes cannot be set up at the same location. This model is very much concerned with the construction of individual floors of a high rise building and looks at different options for each floor while also considering assembly and dismantling costs between each floor. The durations for which a crane is required for each floor are given in days. In calculating the minimum crane cost, each combination to pass from the ground floor to floor *m* is considered. This seems to give an unrealistic scenario of the crane type changing frequently. It is not explicitly stated how the crane location is determined but it is assumed that it is the cheapest crane that can reach in such a position that enable all loads to be lifted.

Other mathematical models have been developed by Rodriguez-Ramos and Francis (1983) and Choi and Harris (1991). These models, along with the simulation model proposed by Zhang *et al.* (1995 and 1996) are of more relevance to this thesis as they are specifically concerned with tower crane location. They are discussed in more detail in Chapter 6, which compares the output from the model proposed in this thesis, with the output obtained by these three models.

Other more general models may also be of relevance. For example, Sprinivasan *et al.* (1994) developed a general purpose analytical model to compute the throughput capacity of a trip-based material handling system used in a manufacturing setting. The model is first developed for a single device system such as a crane. A trip-based material handling system consists of devices (such as a crane) which move materials from one point to another point. Each trip is concerned with empty travel and loaded travel (including pick up and put down). The model is concerned with developing a rule referred to as the MOD FCFS rule (modified first-come-first served rule). Essentially, when movement has occurred from one point to another, the device then serves any request at the put down point. If there are no such requests, it searches for the oldest unassigned move request in the system. By developing a series of equations it is possible to estimate the throughput capacity of the system; previous models have used simulation techniques which are time consuming and potentially costly in terms of computer hardware and software. Previous models are also based on modified queuing theory. However, this model is not directly applicable to the tower crane on a construction site scenario, where the total number of movements is considered to influence the crane position.

2.4.3 Models for other types of crane

Although not directly related to tower cranes it is worth mentioning two other model types which have been developed.

Firstly, some work has been done in the area of locating mobile cranes. Raynar and Smith (1993) describe the analysis of the number of moves made by a mobile crane in the erection of structural steel work. This has led to the development of a Prolog program, PRECISE, a computerized analysis method to minimize the number of moves required by a mobile crane for the erection of single storey structures. The program utilizes a production rule system which finds the optimum path for the crane and determines the steel erection sequence. Alkass *et al.* (1997) and Al-Hussein *et al.* (1998) describe a decision support system for crane selection and location on a construction site, which integrates knowledge-based algorithmic programs, data-base management systems, optimization techniques, speadsheet applications and graphics. The model is able to process complicated mathematical equations to determine the optimum crane configuration and provide instant evaluation to the constraints provided by the user. However, the model is restricted to single crane critical lifts in the construction of high rise buildings. More generally, Lin and Haas (1996) describe computer-aided methods to minimize the number of crane re-locations for each configuration in a lift layout phase.

A second area of interest is concerned with heavy lift planning. Williams and Bennett (1996) describe the development of ALPS (Automated Lift Planning System), which is a graphical crane and rigging system designed to simulate heavy lifts and to prepare lift plans, enabling the user to select an appropriate crane, design a rigging assembly to support the load, interactively simulate and animate the lift, and automatically determine potential interferences between the crane, the load and the surrounding environment. The library of manufacturers' data and load charts includes crawler, truck, hydraulic and tower cranes. Cranes may be selected which meet the specified lift criteria. Varghese and O'Connor (1997) describe the work done in developing a computerised heavy lift planning system. A visualization environment – Walkthru- was developed to include location to execute lift, lift path clearances and capacity during lift.

As such, it is more appropriate for manufacturing industry applications and is more concerned with the application of mobile cranes.

2.5 Tower crane utilization and behaviour modelling

Given the critical role played by tower cranes on construction sites, referred to in the previous chapter, there is surprisingly little evidence of the utilization of tower cranes on construction sites having been examined or their behaviour modelled.

Backhouse *et al.* (1994) investigated the application of overhead cranes to the construction industry. The aims of the project were to integrate advanced drives technology, a collision avoidance and diagnostic system and a control system to reduce load swing.

Beliveau and Dal (1994) describe the computer animation, through dynamic simulation, of certain materials handling components and provide a case study centering on a mobile crane. The research is concerned with kinetics, oscillation and acceleration/deceleration. The purpose is that, through modelling intended activities, the optimum process can be selected.

Golafshani and Aplevich (1995) attempt to compute time-optimal trajectories for tower cranes (under control and state constraints). Large load swings are observed and a sub-optimal control is then proposed to keep the load swings small. The Lagrangian method is used to the derive the equations of crane motion and subsequently the time-optimal trajectories are also derived. The minimum times for horizontal (trolleying), vertical (hoisting) and radial (slewing) movement are calculated, taking into account acceleration and velocity. Nevertheless, in the example given, these times approximate to that time which would be obtained by using velocity and distance only. The optimal time is then taken as the maximum of these three times. However, one problem with such a solution is the large load swings that occur.

Therefore, a sub-optimal trajectory is preferred. This gives a slight increase in travel time but reduces the magnitude of the load swing.

Leung and Tam (1999) have developed a regression model to predict the hoisting times for tower cranes used in public house building in Hong Kong, which, they assert, is a critical activity in high rise construction. Twelve factors influencing hoisting time, such as load weight, dimensions and position, were identified and a regression model developed, using work measurement to collect data for analysis. Other less quantifiable factors, such as the effects of weather and operator experience, were disregarded. An adjusted R-squared value greater than 0.7 was obtained for the model, which, the authors claim, indicates a high degree of fit.

On a more practical level, Barber (1973) claims that, on an average site, a tower crane can handle up to 160 individual loads in a nine hour day. Clapp and Mason (1966) monitored the movements of a rail-mounted tower crane, using a Creed recording machine, and found that the average cycle time was 6.4 minutes with a working time of 22.1 minutes per hour. It was also found that there was considerable variation in the distribution of weights lifted, although they have not stated what components the tower crane was being used to lift. Price (1986) conducted fourteen studies on tower cranes, in order to obtain data for cycle times for concreting operations. Time to taken to pour concrete into the skip was shown to have a linear relationship with the size of the skip and a similar relationship was developed for travel time and distance travelled, where the distance travelled was computed as the sum of horizontal and vertical distances. All these observations are too general to be of much specific use as far as the model to be developed is concerned.

More usefully, Mistry (1970) prepared a report for the British Ship Research Association, using systematic activity sampling to examine crane utilization in shipyards. The study included a tower crane but was not exclusively confined to tower cranes. The main findings were as follows.

- The elemental times for lifting and lowering were almost identical, but were not particularly significant. This would be expected as most cranes operated at the same speed for both lifting and lowering. However, it would be possible to adapt the cranes to achieve an improved lowering speed.
- The most significant elemental time was "idle time", which was 47.9% on average. It was realized that crane utilization would never exceed around 70%; this was achieved 3 times a day but could have been achieved more often if lifts had been planned.
- The "position" and "hold" elements accounted for 30.3% and 57.8% of the time respectively. Again, these could have been reduced with proper planning.

However, again they have not stated what components the cranes were being used to lift and it is assumed that the observations were related to the general duties of cranes in shipyards.

Wijesundera and Harris (1989) ascertained the shape of the cycle times distributions to mechanically handle unit quantities of particular materials from work study data obtained via observations taken at over 30 construction sites. The work concentrated on cranage operations, particularly the use of tower cranes on high rise structures. The cycle time distribution for handling concrete for example was found to be normal skewed to the right almost forming a log-normal curve.

2.6 Justification of approach

2.6.1 Overall layout objectives

As stated by Francis and White (1974), a plant layout study may be so wide as to:

1. minimize investment in equipment;
2. minimize overall production time;

3. utilize existing space most effectively;
4. provide for employees' convenience, safety and comfort;
5. maintain flexibility of arrangement and operation;
6. minimize material handling cost;
7. minimize variation in types of material handling equipment;
8. facilitate the manufacturing process; and
9. facilitate the organizational process.

Cullinane and Tompkins (1980) concur with these objectives and acknowledge that they will often be in conflict with one another and, for a particular project, weightings must be assigned to these objectives in order that the priorities can be ascertained. Although these objectives are intended to relate to the manufacturing process, it can readily be seen that they are all equally applicable to the construction site scenario, although there may be difficulty in measuring how effectively some of them have been achieved.

Further to this, it was mentioned by Vollman and Buffa (1966) that

> *"The criterion of quantitative layout models is now frequently stated as the minimization of material handling costs, which is assumed to be a linear function of the distance between components of the system under study."*

Movement of materials by crane is considered to comprise a significant proportion of the materials handling problem. Therefore the crane location optimization model is founded on the principle of minimizing the cost associated with tower crane's contribution to material handling operations. This is linked to two of the objectives listed above, that of minimizing material handling cost, and, as it is assumed that cost is directly related to time, that of minimizing overall production time. Again it is appreciated that, in both cases, the problem of location of a single tower crane is a sub-problem, contained within the larger context of the optimization of general construction site layout.

However, in respect of the minimization of material handling cost, it is not true, within the confines of this model, to state that cost (or time) is a linear function of the distance between components; the distance between components must be considered in three dimensions and the material handling costs therefore depend upon the ratio of movement in each of these dimensions. In these circumstances the model assumes properties of a dynamic non-linear nature. However, it is reasonable to assume that cost and time are directly related and that, in order to minimize cost, time must also be optimized. Therefore, the model to be developed here is based on minimization of crane (hook) travel time, which, without defining the precise relationship between time and cost, will contribute to the minimization of material handling cost.

2.6.2 Crane utilization characteristics

Initially it may appear that some direct measure of the crane's productivity would be of benefit in determining its optimum location. However, in this context crane productivity can only be equated to crane utilization (a measure of the time the crane is in use). This in itself is a meaningless parameter as the crane only serves as a tool to aid, and hopefully improve, the productivity of the site as a whole. Indeed, the introduction of tower cranes to construction sites can mean that the work is planned around them to the detriment of overall site productivity. However, it is important to acknowledge that tower cranes on sites are heavily utilized. Chan and Kumaraswamy (1995) reported utilization levels in excess of 80%, and therefore any model which can optimize the time a crane spends in use must be of overall benefit to the construction process.

By considering the potential behaviour of a tower crane, periods of activity and inactivity throughout the working day, with respect to the crane, may be subdivided into further categories. A schematic illustration of tower crane behaviour throughout the working day is given in Figure 2.1.

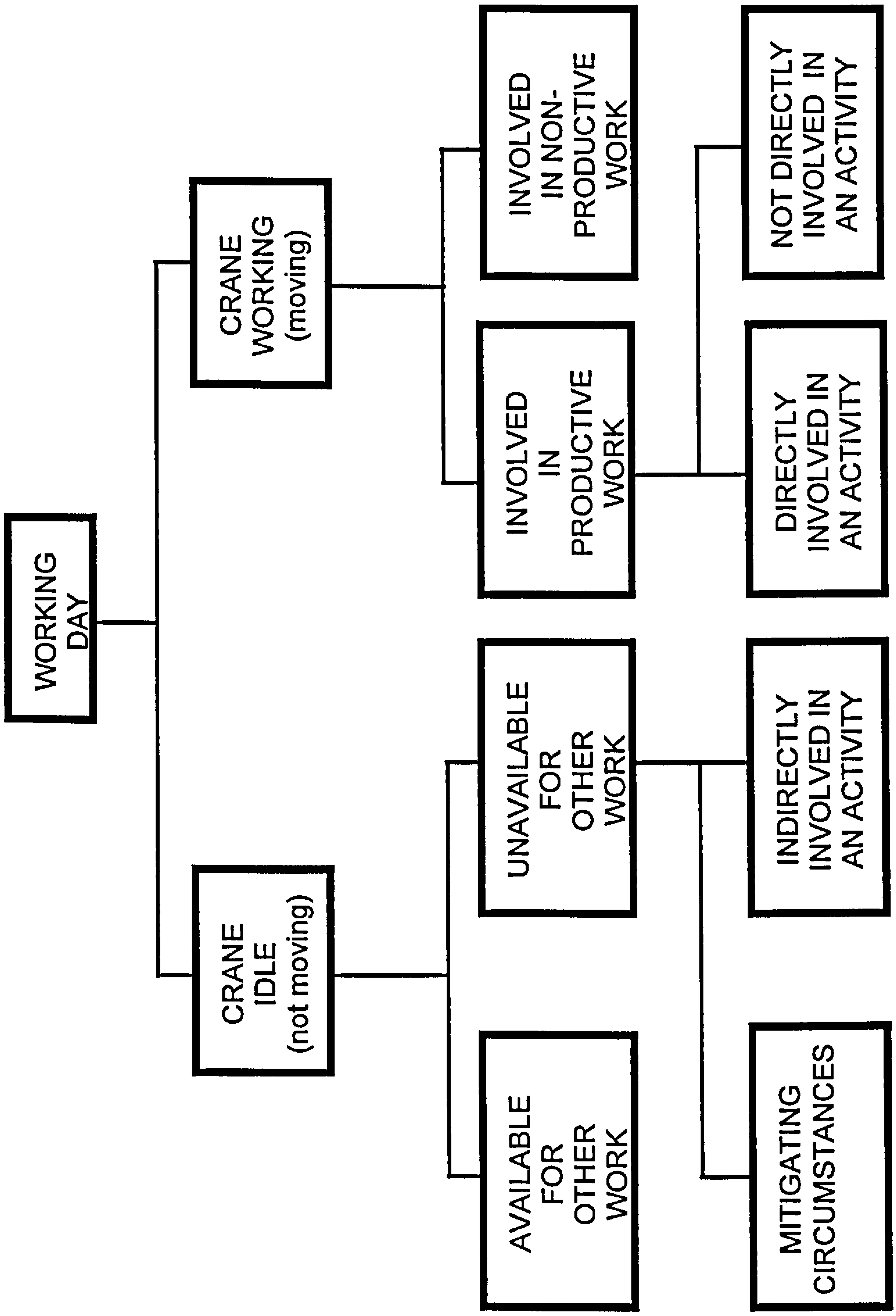


Figure 2.1 **Schematic illustration of tower crane behaviour throughout the working day**

The first hierarchical division of tower crane behaviour is the division of time into that time spent idle (i.e. not moving) and that time spent working (i.e. moving).

If the crane is idle it may be assumed that it is either available for work or unavailable for work. If the crane is unavailable for work this may be due to mitigating circumstances, such as necessary maintenance or adverse weather conditions. Alternatively the crane may unavailable for other work because it is indirectly involved in an activity. An example of this would be the crane waiting, with a skip attached, while concrete is discharged from the skip into a concrete pour.

If the crane is working (i.e. horizontal, vertical or radial movement is taking place) it may be involved in productive or non-productive work. Non-productive work may be defined as work which will almost inevitably occur, but which is not an intrinsic part of any activity, and will not have been included in any construction plan or programme. An example would be the use of the crane to double handle materials, an activity that could have been obviated by good planning and organization.

Productive work may be divided into two further categories.

- The crane may be directly involved in a productive work activity. This may be defined as the **transformation**, in the construction process, of the component involved. Examples of this include the placing of concrete and the fixing in position of cladding units. These activities will necessarily include periods of indirect involvement, when the crane will be idle but unavailable for other work.

- Secondly, although involved in productive work, the crane may not be directly involved in an activity. An example of this would include the lifting of pallets of bricks into position, prior to their placement (or transformation in the construction process) by bricklayers.

By consideration of the foregoing division of tower crane behaviour it can be deduced that there are two ways to assess the influence of tower crane performance, with respect to site productivity. Because of the nature of productivity data both of these measures are, by implication, concerned with that portion of time the tower crane spends in productive work.

Firstly, it is necessary to consider those productive activities in which the tower crane is directly involved. By implication the tower crane will also, for some period, during the execution of such an activity, be unavailable for other work while it is indirectly involved in this activity. Examples of this, stated previously, include the placing of concrete and the fixing in position of cladding units.

Secondly, it is necessary to consider those activities in which the tower crane, although involved in productive work, is not involved in the transformation, in the construction process, of the component involved. In these cases it may be considered that the crane is not directly involved in an activity, in so much that the productivity data, for such an activity, will not incorporate the contribution of the crane to the process. An example of this, stated previously, includes the lifting of pallets of bricks into position, prior to their placement by bricklayers.

However, in both cases, the actions of the tower crane represent the central element of the flow of material through a process. This process consists of three elements, despatch, delivery and reception, with, where appropriate, the tower crane providing the delivery element of this process. In some situations, the delivery element may be by-passed (where a concrete mixer discharges its load straight into foundations, for example) or may be provided by alternative means (for example, a hoist).

However, where delivery is provided by a tower crane, consideration must be given to the despatch and reception systems, as both will have a tangible effect on tower crane performance. If both the despatch and reception systems had infinite capacity, then variations in the flow of material through the process could be exclusively attributed to tower crane performance. In reality this will not be the case and the whole material flow process must be considered.

Considering those activities in which the crane is not directly involved, there are several reasons why the crane should be located in a position, which attempts to minimize the time required to move materials. Far more fundamental to the maximizing of productivity is the minimizing of unproductive time, of which waiting for materials is a not insignificant part (Thomas *et. al.* 1992). There may be situations where this is due to unavailability of materials. In the majority of cases, however, this will be due to inefficiencies or lack of capacity in the despatch, delivery and reception systems. Therefore, an improvement in the delivery system can only be beneficial, not only for individual elements, but for the overall effectiveness of material flow.

When considering activities in which the tower crane is directly involved the entire material flow process of despatch, delivery and reception must be considered, as it is only when the delivery component forms a bottleneck in the process that it becomes critical. Many activities have direct involvement with the crane, but concreting activities have been chosen to provide a brief example of the importance of the delivery system.

2.6.2.1 The crane delivery system: an example

If a crane and skip are being used to deliver concrete to a pour, the process, as far as the tower crane is concerned, can be simplistically divided into four elements.

- Fill (skip with concrete)
- Lift (skip to point of discharge)
- Discharge (concrete)
- Return (skip)

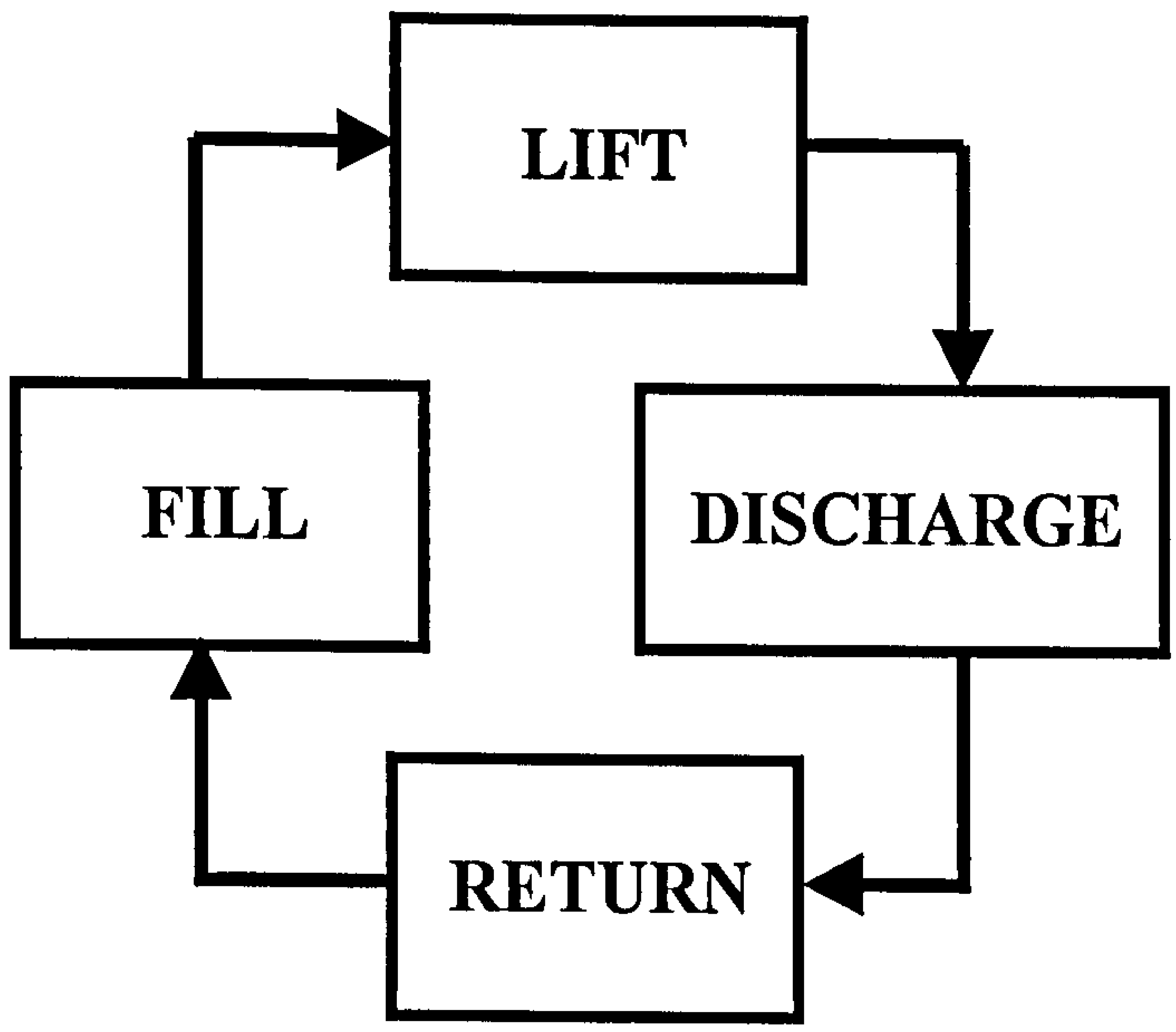
As far as the operatives placing the concrete are concerned, the process can be simplistically divided into two elements.

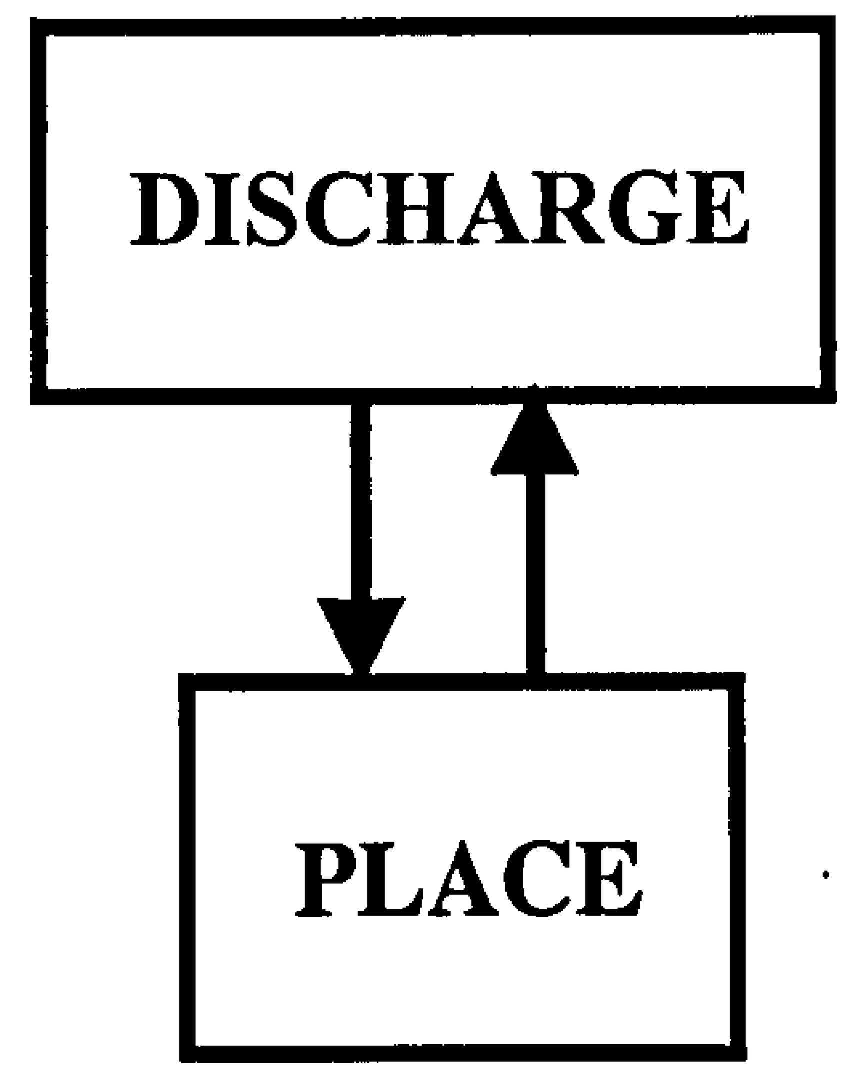
- Discharge (concrete)
- Place (concrete).

In both cases, these elements are cyclic, that is the first activity takes place again after the last activity has been completed. They are also sequential, that is the next element only begins after the previous one has ended. The point of interaction between the crane and the concrete placing operatives is the "Discharge (concrete)" element. This is displayed in Figure 2.2 which shows flow diagrams for each individual resource (the crane and skip and concrete placing gang) and the flow diagrams when the two resources are combined together at the point of interaction.

The system will be "balanced" if the despatch components (Fill, Lift and Return) take the same length of time as the reception component (Place). However, there will be delays to the operation if either of these two components do not take the same length of time. Obviously, there are many factors, such as the distance from the point of despatch to the point of reception and the size of the concreting gang, that influence the time associated with these components, but there is evidence to suggest that the delays to concreting operations are often caused by the despatch system rather than the reception system (Price, 1986). Further, when other crane related operations are considered, such as steel or pre-cast concrete erection, it is more likely that this will be the case, as the reception component (as distinct from the delivery component) is usually very short, and this assertion has been confirmed by work study which has identified that delays in these operations are due to delays in the despatch component (Emsley and Harris, 1990 and 1993).

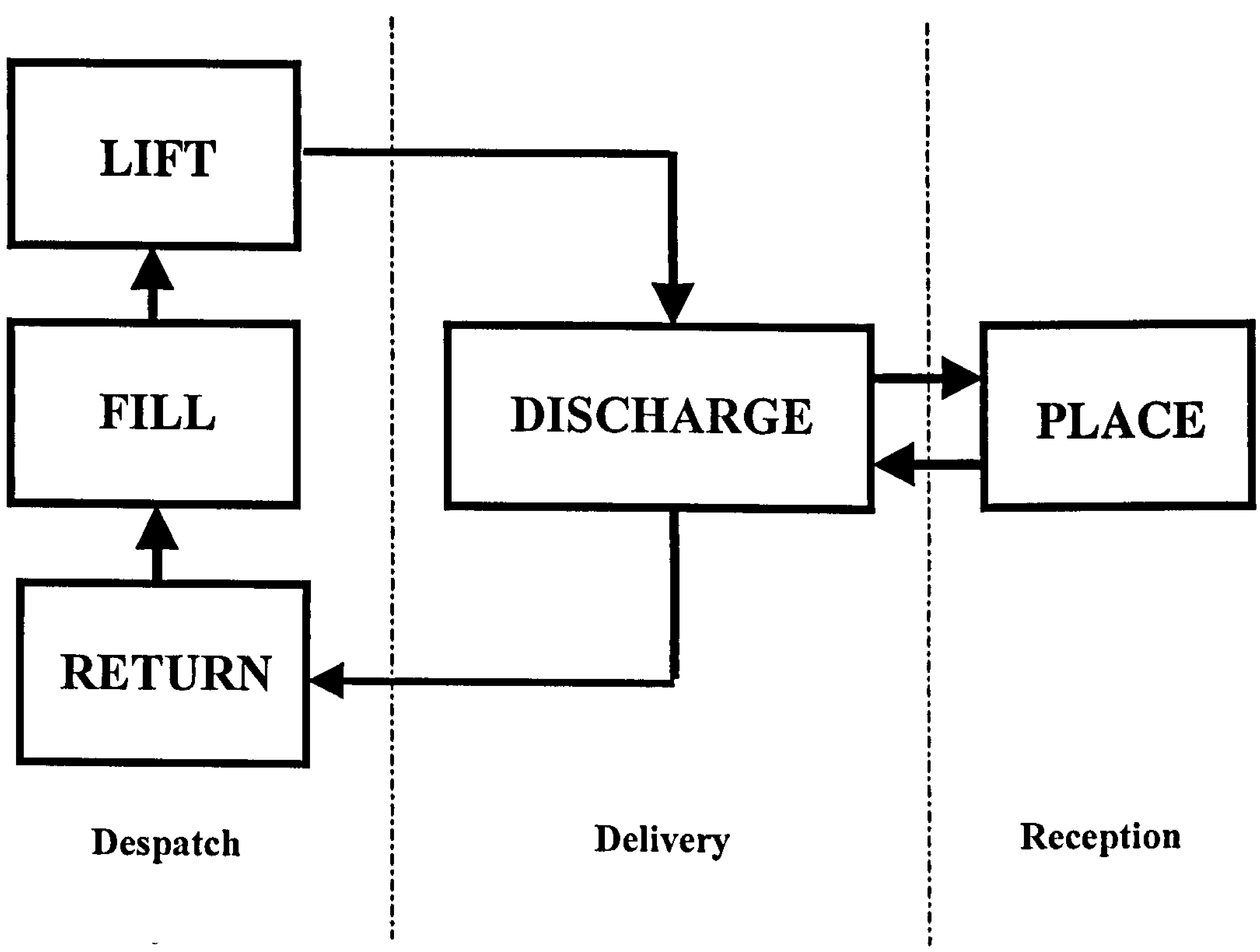
Therefore, it is reasonable to conclude that if the time taken to execute the delivery component of a material flow process involving a tower crane can be minimized, then this can only have benefits in facilitating an increase in productivity of crane related activities.





a) Flow diagram for Crane and skip

b) Flow diagram for Concrete placing gang



c) Combined flow diagram

Figure 2.2 **Examples of flow charts for a simple concreting operation**

2.7 Summary

The key role played by tower cranes in respect of materials handling is well recognised, and the central role played by tower cranes in determining the pace of construction is commonly accepted. Gray and Little (1995) specifically stated that "... the impact on the progress of work must be assessed because many of the critical operations will be crane dependent and, therefore, affected by the speed at which the crane can lift loads". Therefore, the selection of the optimum number, type and location of tower cranes is a focal issue in planning construction operations, but although it is acknowledged that the consequence of such decisions may have adverse or positive impact, there is very little, if any, irrefutable quantifiable evidence to endorse this supposition.

The problem of crane location cannot be considered in isolation from the more general problem of site layout planning and so may be regarded as a sub-problem of this wider problem. The site layout problem is a complex one, as no one method can guarantee a solution. Although various site layout models have been developed, these models have rarely been used in practice. However, whilst this is not the specific intention, the model developed in this thesis has potential to be used to assess the effects of different layouts, whilst the crane position remains static.

There is also little evidence of much research into the utilization and behaviour of tower cranes. Specifically as far as the use of tower cranes on construction sites is concerned, hoisting times have been shown to be critical in high rise construction and the cycle time distribution for handling concrete has been found to be skewed to the right, almost forming a log-normal curve.

The systematic procedure that should be adopted in crane selection and location embraces the need to determine whether a tower crane is needed, or more specifically whether there are other more viable alternatives, taking into account technical and economical factors, before moving on to consider the type, number and locations of such cranes. Models which have previously been developed to select and locate tower cranes may address the whole issue of crane selection and location, or merely one aspect of the overall problem. The types of such models may be broadly classified as expert systems, simulation models and mathematical models.

The expert systems which have been developed are mostly confined to providing advice on the selection of crane type, and may consider other types of crane and other materials handling methods, in addition to tower cranes. Any advice which is given in respect of crane location is confined to ensuring that from a suggested position the crane can reach all facilities and pick up all loads at these facilities.

Simulation models generally address wider issues concerned with construction planning, of which tower crane selection and location is a sub-problem. Simulation models have been used, amongst other applications, to examine whether two cranes can safely operate in the same area, to assess the selection of material handling methods, to examine the optimal use of cranes on a daily basis and to develop and integrated system where the features of structure to be built are also taken into account. However, one particular simulation model, developed by Zhang *et al.* (1995 and 1996) does address the issue of crane location; this is discussed in more detail in Chapter 6.

The quantitative nature of mathematical models is such that they are more likely to address the issue of crane selection and location, through the use of an objective function. Two specific mathematical models, developed by Rodriguez-Ramos (1983) Choi and Harris (1991), do attempt to optimize crane location in this way and they are also discussed in more detail in Chapter 6.

Apart from the three models referred to in the preceding paragraphs, it is believed that a search of the literature shows that no other models have been developed to seek to optimize the location of a tower crane within a construction site.

Many criteria for assessing layouts, and therefore, indirectly, the impact of crane location, have been proposed, but cost and time are the two mostly commonly cited, and indeed they may be considered in some ways as dependent. However, it may be considered that cost is fixed if it is considered in the context of the overall programme; the purchase or hire rate will be determined by the length of contract and is not significantly influenced by the cost associated with individual crane movements. And although it may be possible to determine the cost of individual crane movements, (although this maybe difficult as the three dimensional nature of crane movement renders a simple linear relationship inappropriate), there is really little purpose in attempting to minimize the cost of these individual movements. It may be maintained that the same argument could also be put forward in respect of time. However, the purpose of the model is not necessarily to reduce the length of time the crane is used but to optimize the time taken to carry out individual movements so that, where the crane is the bottleneck in the despatch and reception chain, this bottleneck may be eliminated.

Considering tower crane behaviour throughout the working day, the most significant components are when the crane is involved in productive work, either directly in the transformation of the component or materials involved, or in delivering materials. In either case the crane acts as the link between the despatch and reception systems. If the time to execute this delivery components can be minimized then this can only have benefits in facilitating an increase in productivity of crane related activities. Therefore, having demonstrated that the times associated with crane movement are potentially critical, the minimization of crane travel time has been selected as the criterion to be used by the model to determine the optimum crane location.

CHAPTER 3

CONSTRUCTION SITE CHARACTERISTICS

3.1 Introduction

Consideration must be given to the characteristics of construction site layout in order that these characteristics may be represented in the model. Construction site layout characteristics are briefly discussed, but the main objective of this chapter is to describe the data concerning construction site layout which are pertinent to the optimization of the crane location model.

For the most part, these data may easily be represented in the model as they simply describe the location of facilities served by the crane and the physical limits of the site.

Construction activities vary from day to day. On any given day the optimum crane position is likely to be different to that on another day. As the tower crane is installed at the beginning of the construction programme the optimum crane position is, of practical necessity, dependent upon total movement from time of installation to time of removal. Therefore it is also necessary to consider global crane movement. Such movement will consist of both direct movement, between facilities, and indirect movement, again between facilities but where the movement is not via the shortest route. This chapter investigates the ways in which global crane movement may be assessed, and the use of the Simplex Method, a linear programming technique, to evaluate global crane movement is described.

3.2 Construction site layout characteristics

It has been suggested that the layout of construction sites may be facilitated by the use of scaled templates, which are re-positioned on a plan of the site, until a satisfactory solution is found (Forster 1989). This implies that construction site layout is a two dimensional problem. However, when considering the use of tower cranes the problem is evidently one of three dimensions as the crane is used to transport materials horizontally, vertically and combinations of both.

Generally the boundaries of the site are known. Usually, crane overswing beyond the boundaries is not permitted (see Chapter 5). The site may be flat or vary in height across its bounds. Locations of facilities served by the crane must be pre-determined; it is not the intention of this model to optimize site layout generally, although the model may be used indirectly to assess the impact of moving a facility while the crane type and location remain fixed.

The quantity of material to be moved between facilities, by crane, is important, both in respect of providing a crane of adequate capacity, and also in respect of evaluating global crane movement. This is discussed in detail in Section 3.3.

3.2.1 Construction site layout data

With respect to the construction site layout data it is first necessary to define the site boundary. Once this boundary has been defined all facilities must be located within the boundary. The crane must also be positioned within the boundary and the user alerted if overswing beyond the boundary occurs (see Chapter 5). The boundary may be demarcated using Cartesian co-ordinates. For the purposes of the model, a maximum of 20 boundary points may be defined. One of the points may, if desired, be represented by the origin, but it is assumed that all co-ordinate values, along both the x and y axes, are positive.

In order that a check that facilities are located within the boundary may be made, it is necessary that the boundary points be entered in consecutive order, in either a clock-wise or an anticlockwise direction. For a polygon of n sides the sum of the internal angles = $180(n\text{-}2)$ degrees.

$$\textit{Sum of internal angles} = 180(n-2)\ \textit{degrees} \quad \ldots\ \textit{Equation 3.1}$$
$$\textit{(polygon of n sides)}$$

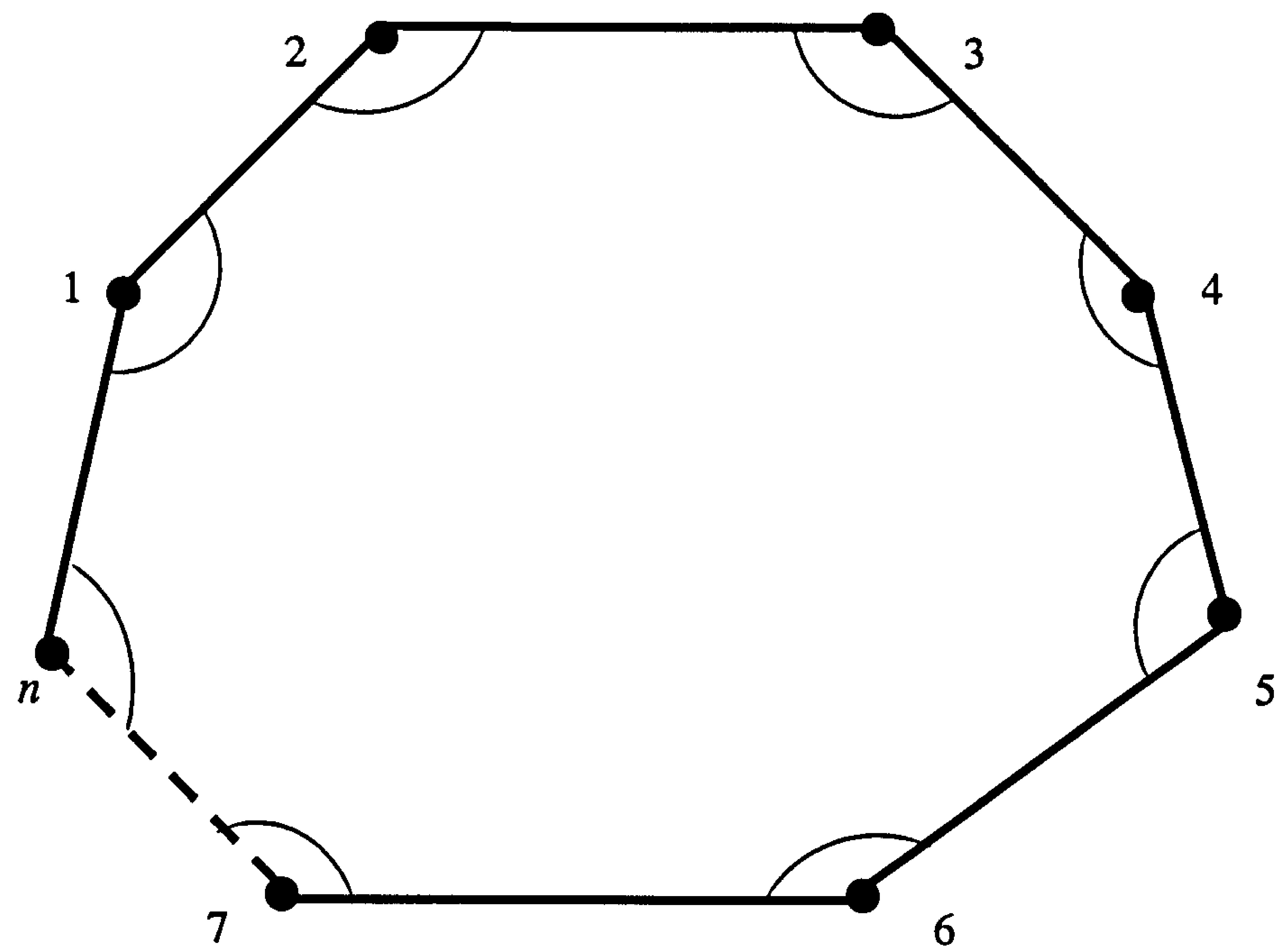
This equation is equally valid for both convex and concave polygons, and is illustrated in Figure 3.1.

By inspection, if the sum of the internal angles complies with equation 3.1, then the co-ordinates have been entered in consecutive order.

It is also necessary to enter the location of each facility to be serviced by the crane, using the same origin adopted in defining the site boundary. As explained previously, all facilities must be located within the site boundary. Visually this is simple to achieve but the model relies upon a computer program, which does not have this attribute. The program executes this check by utilizing the fact that if a facility lies within the boundary, the algebraic sum of the angles subtended between a point on the boundary, the facility and the next boundary point will be 360 degrees for the set of consecutive points that define the boundary. This is illustrated diagrammatically in Figure 3.2 for both convex and concave polygons. In the case of boundaries defined by concave polygons it is important that the effect of both positive and negative angles are taken into account in the algebraic summation of the subtended angles. This check must be repeated for each facility.

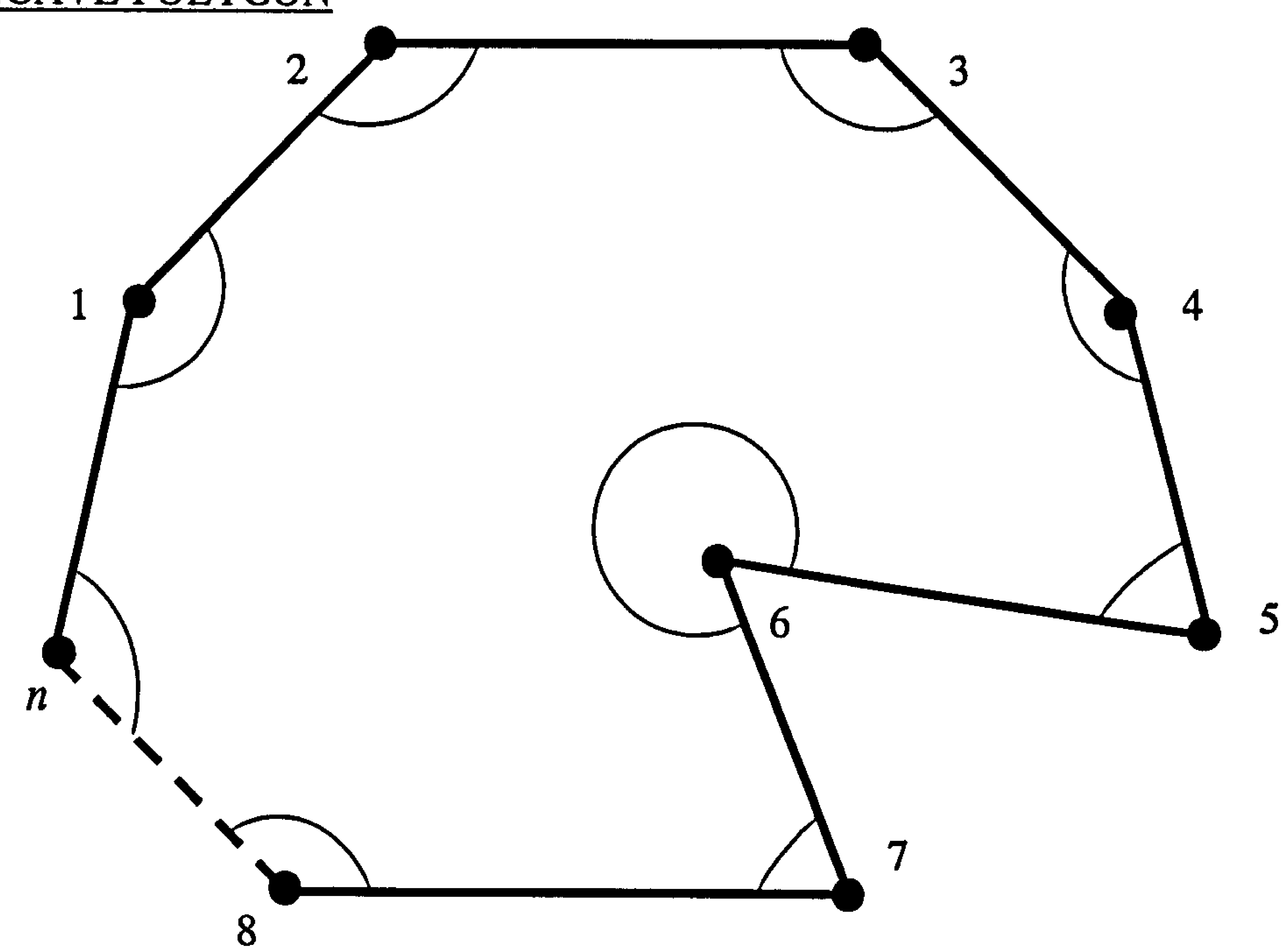
For a facility which lies on the boundary the same principle applies. For a facility outside the boundary the algebraic sum of the subtended angles is equal to zero. This is illustrated diagrammatically in Figure 3.3.

CONVEX POLYGON



Sum of of internal angles = 180 (n -2)

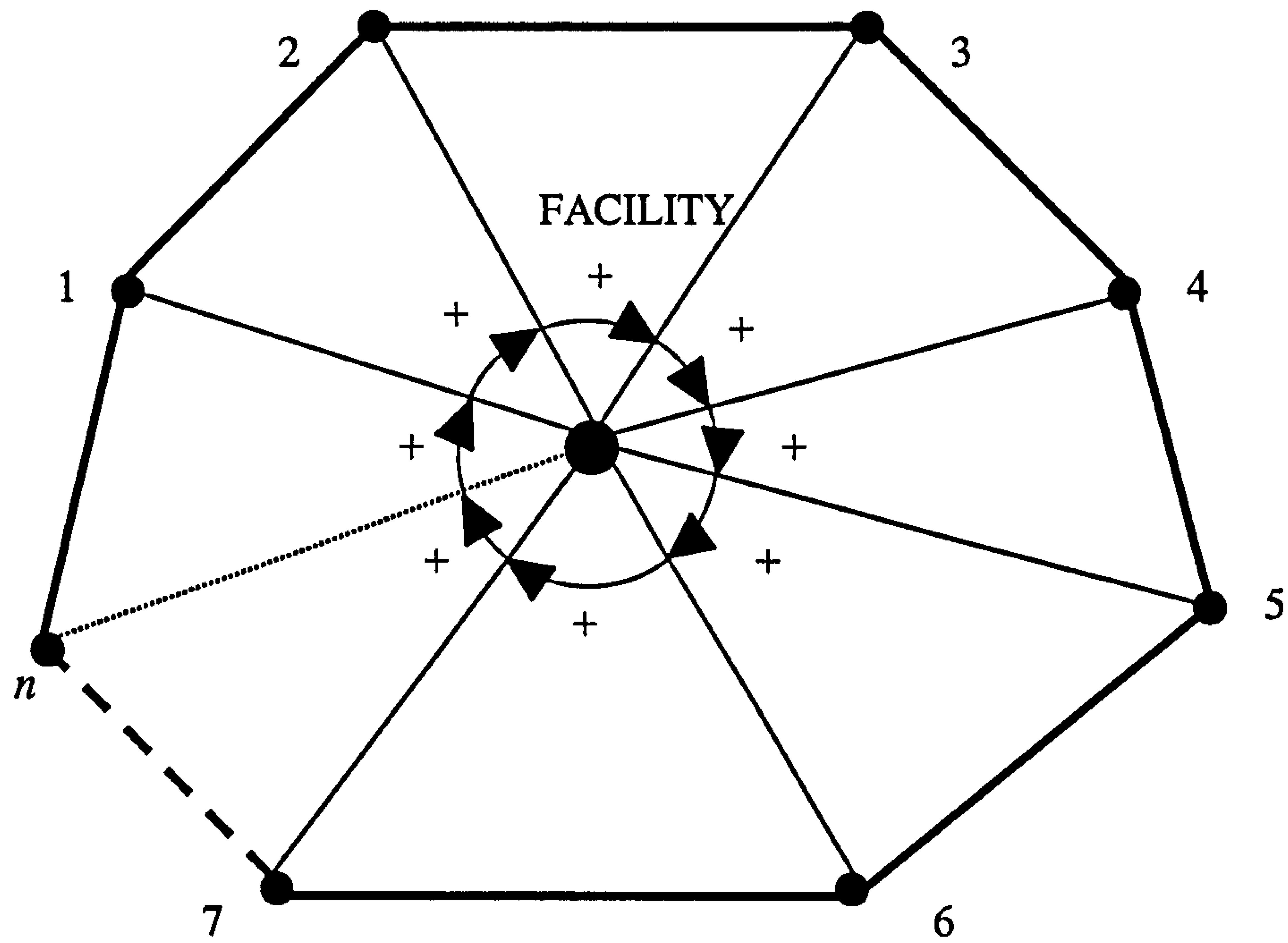
CONCAVE POLYGON



Sum of of internal angles = 180 (n -2)

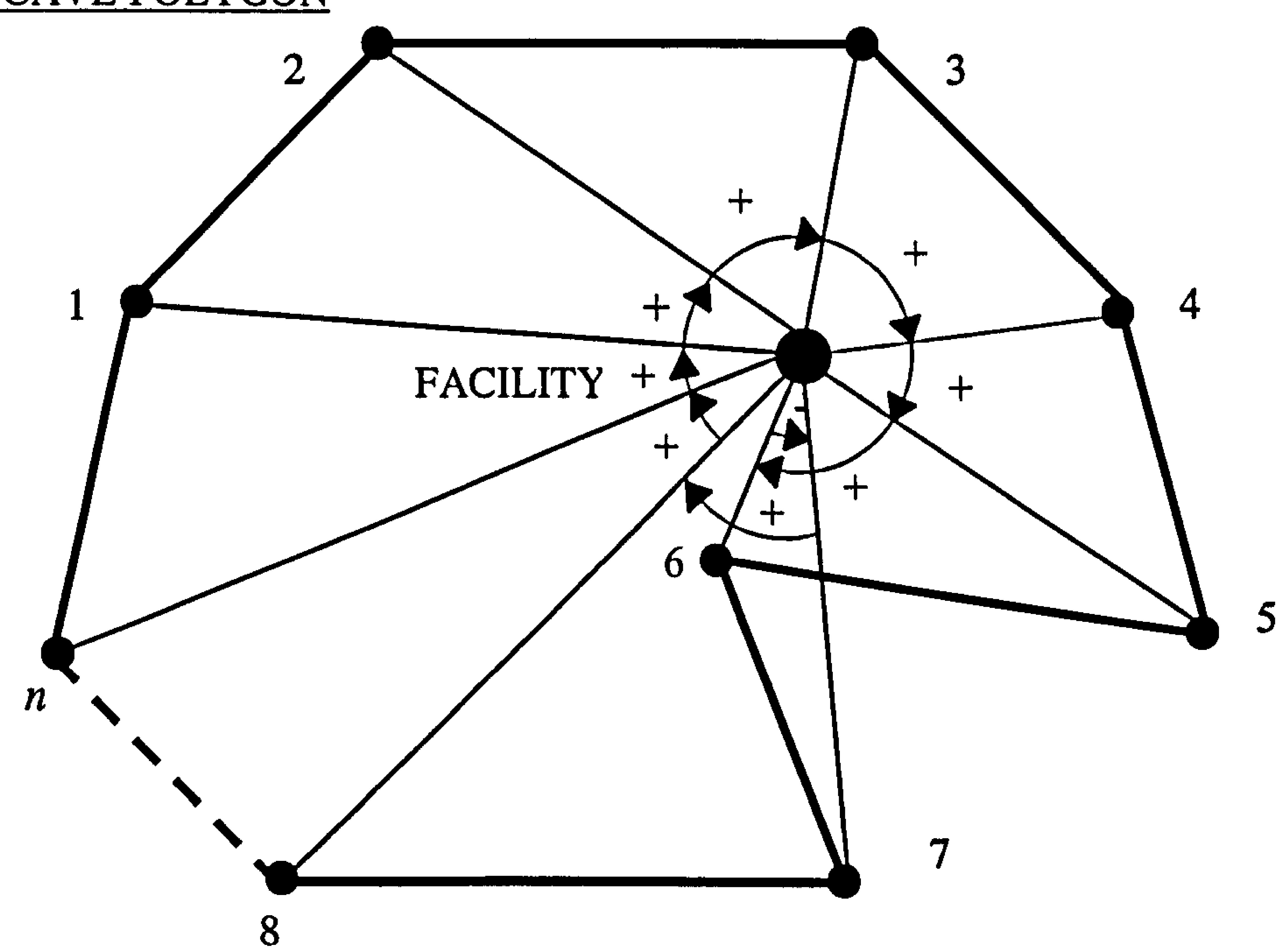
Figure 3.1 **Sum of internal angles of convex and concave polygons**

CONVEX POLYGON



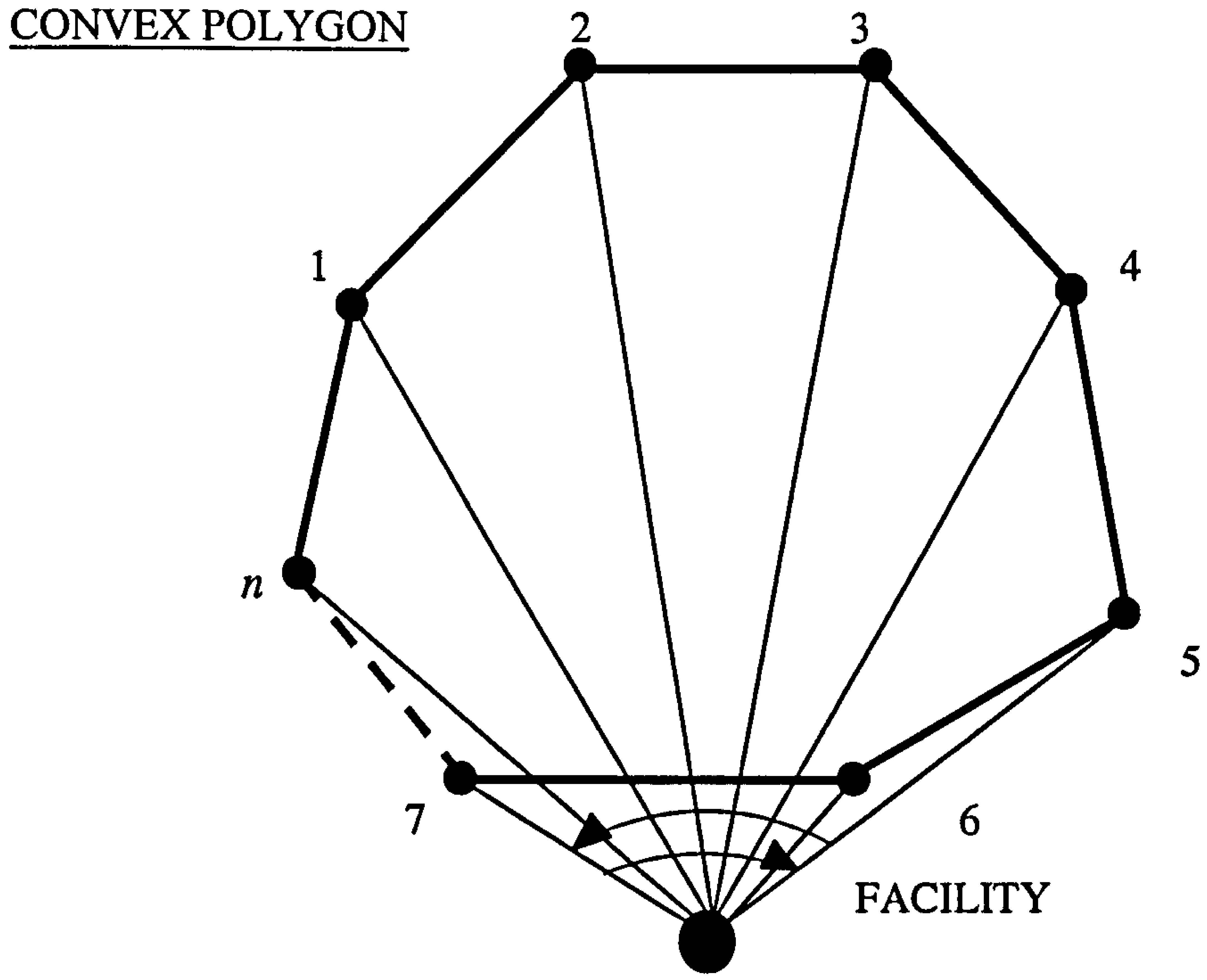
Sum of of internal angles = 360 °

CONCAVE POLYGON



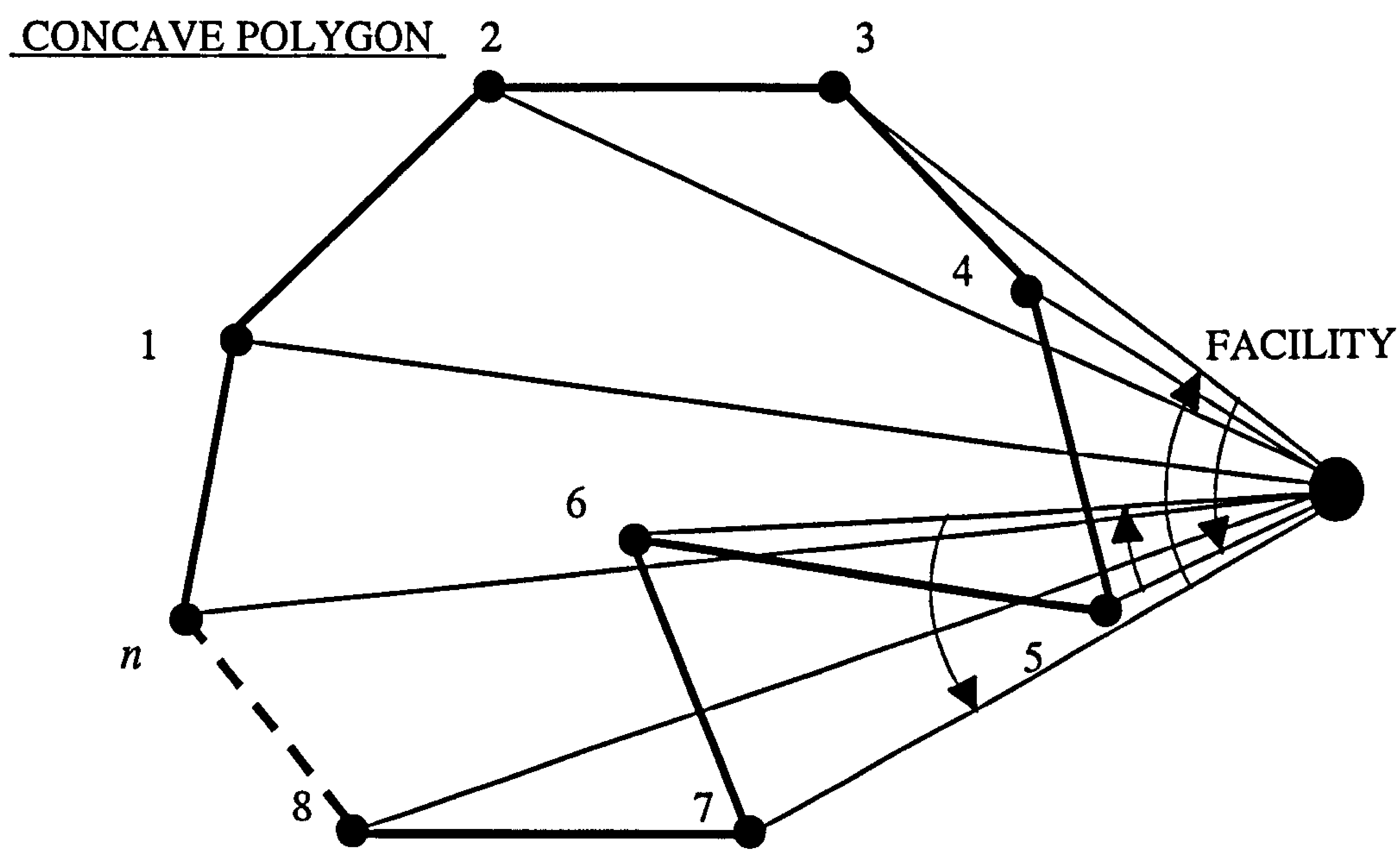
Sum of of internal angles = 360 °

Figure 3.2 **Facility located within the site boundary**



Angles 7-n, n-1, 1-2, 2-3, 3-4 and 4-5 are measured in one direction

Angles 5-6 and 6-7 are measured in the opposite direction and have the same total magnitude



Angles 7-8, 8-n, n-1, 1-2, 2-3 and 5-6 are measured in one direction

Angles 3-4, 4-5 and 6-7 are measured in the opposite direction and have the same total magnitude

Figure 3.3 **Facility located outside the site boundary**

Facilities may located at ground level or occur at any height, providing they are not above the maximum height at which the crane can lift.

Finally, it is necessary to enter data concerning the total, average and maximum load to be lifted, from one facility to another. Dividing the total load by the average load will enable the minimum number of movements between facilities to be computed. The value of the maximum load is necessary to serve as a check that the crane is of adequate capacity.

3.3 Evaluation of global crane movement

As previously mentioned, construction activities vary from day to day, and so the optimum crane position may also vary daily. However, this is not a practical solution and the optimum position of the crane, determined before construction commences, is based upon total construction activity (after crane installation).

In the model, construction activity is represented by the movements, between various locations, or facilities, which the crane is required to accomplish. The frequency of occurrence of such movements is independent of the location of the crane. However, each movement is comprised of three components - angular, radial and vertical movement. The magnitude of these three components depends upon the relative location of the crane to the facilities, and the time taken to execute any movement is a function of the angular, radial and vertical components of movement and the associated speeds. The optimum crane position will occur when the time associated with total movement of the crane hook is minimized. This concept is discussed in more detail in Chapter 5.

Travel of the crane hook between facilities may be considered as either direct movement, between facilities, or indirect movement, again between facilities, but where the movement is not via the shortest route. Direct movement between facilities may be computed with some certainty, depending upon reliability and comprehensiveness of the data available at the time when the decision of location of the tower crane takes place. Ideally indirect movement should not occur, and, because of the random nature of this type of movement, its occurrence cannot be computed with any degree of certainty. Neither is there any evidence to suggest that this type of movement will influence the crane location, as regardless of whether the movement is by the most direct route, which is the ideal, or by a more circuitous indirect route, movement will still take place from one point to another. Therefore, this type of movement has been disregarded.

It is important that crane movement is predicted as accurately as possible. However, the nature of construction operations means that an element of uncertainty will always be present; the model aims to minimize this uncertainty, and, once the model has been developed, the sensitivity of the input variables can be investigated.

For n facilities the number of movements occurring directly between facilities is:

$$
\begin{array}{ccccc}
 & 2 \Rightarrow 1 & 3 \Rightarrow 1 & \ldots\ldots & n \Rightarrow 1 \\
1 \Rightarrow 2 & & 3 \Rightarrow 2 & \ldots\ldots & n \Rightarrow 2 \\
1 \Rightarrow 3 & 2 \Rightarrow 3 & & \ldots\ldots & n \Rightarrow 3 \\
1 \Rightarrow 4 & 2 \Rightarrow 4 & 3 \Rightarrow 4 & \ldots\ldots & n \Rightarrow 4 \\
\cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & & \cdot \\
1 \Rightarrow n & 2 \Rightarrow n & 3 \Rightarrow n & (n-1) \Rightarrow n &
\end{array}
$$

$$= n\,(n\text{-}1)$$

For each of these movements a "trip value" needs to be assigned. This can be expressed either as an absolute value or as a percentage of the total movement (where then sum of all trip values = 100%).

The number of movements towards any facility must be matched by an equal number of movements away from that facility. Some movement between facilities must occur to expedite construction. For example, if a crane and skip are being used to pour concrete, movement must occur from the point of discharge of the concrete, into the skip, to the point of discharge of the concrete, into the pour. Such movement is distinctly stated and so may be described as "explicit" movement. However, if the crane is to continue to be used to place concrete, opposing movement from the location of the pour to the location of the point of discharge is required. Such movement is not distinctly stated but implied, and so may be described as "implicit" movement.

Further categories of movement must also be considered. Continuing with the previous example, once the concreting operation is completed the crane must, albeit not necessarily immediately, move to another facility and commence further activity. Such movement may be described as "linking" movement, as its purpose is to link one operation to another. A further category of movement may be defined to encompass any unnecessary movement, which will inevitably occur. This movement may be described as "wasting" movement as it does not contribute anything to the general construction activity.

As stated previously, the number of movements towards any facility must be matched by an equal number of movements away from that facility. Therefore the final category of movement may be described as "balancing" movement, as it is that movement required to ensure that a movement towards any facility is balanced by a movement away from that facility. This is essential to ensure continuing operation of the crane. Linking movement and balancing movement are not distinct, and the evaluation of one embodies the other; rather it is their concepts which are, albeit subtly, different. Linking movement, between facilities, is that which purposefully links one operation to another. Balancing movement, between facilities, is that which must occur, to ensure that, after movement towards a facility has been expedited, movement away from that facility follows.

The interaction of these five types of movement is illustrated in Figure 3.4, which shows that explicit, implicit, linking and wasting movement may interact freely with

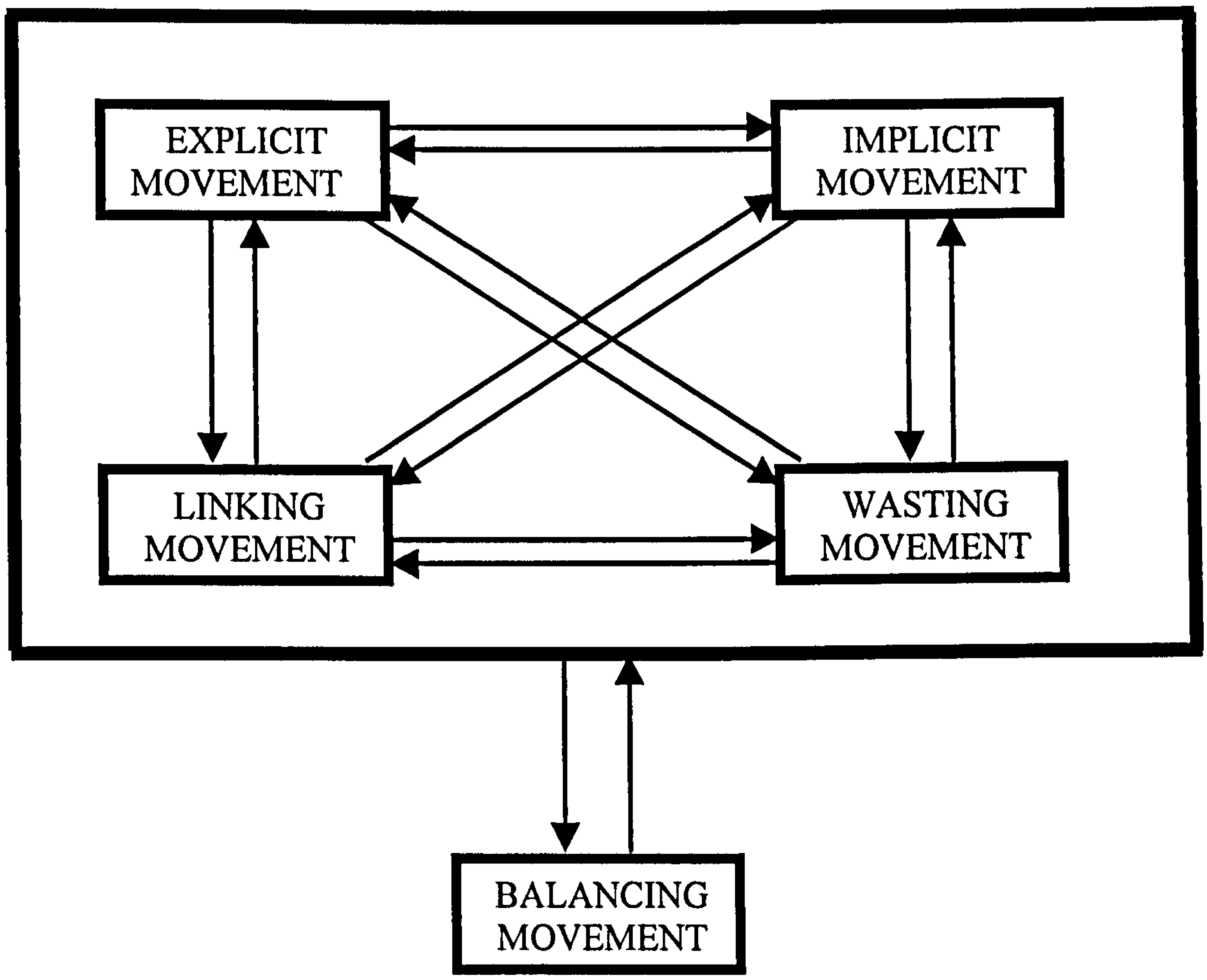


Figure 3.4 **Types of crane movement**

each other, while balancing movement is necessary to ensure that the number of movements (whether explicit, implicit, linking or wasting) are of the same magnitude to and from each facility.

The questions, which must be asked, are:

- With what confidence can the trip value of each of these categories of movement be evaluated?

- How important is the evaluation of each category of movement to the final outcome?

With respect to the evaluation of the trip value of each category of movement, it is possible to evaluate explicit movement by considering the total number of units to be moved from one facility to another, and the average number of units moved per movement. For example, if it is required to move 50 m^3 of concrete from the point of delivery to the point of discharge, using a 0.5m^3 skip, then the associated absolute trip value is 100.

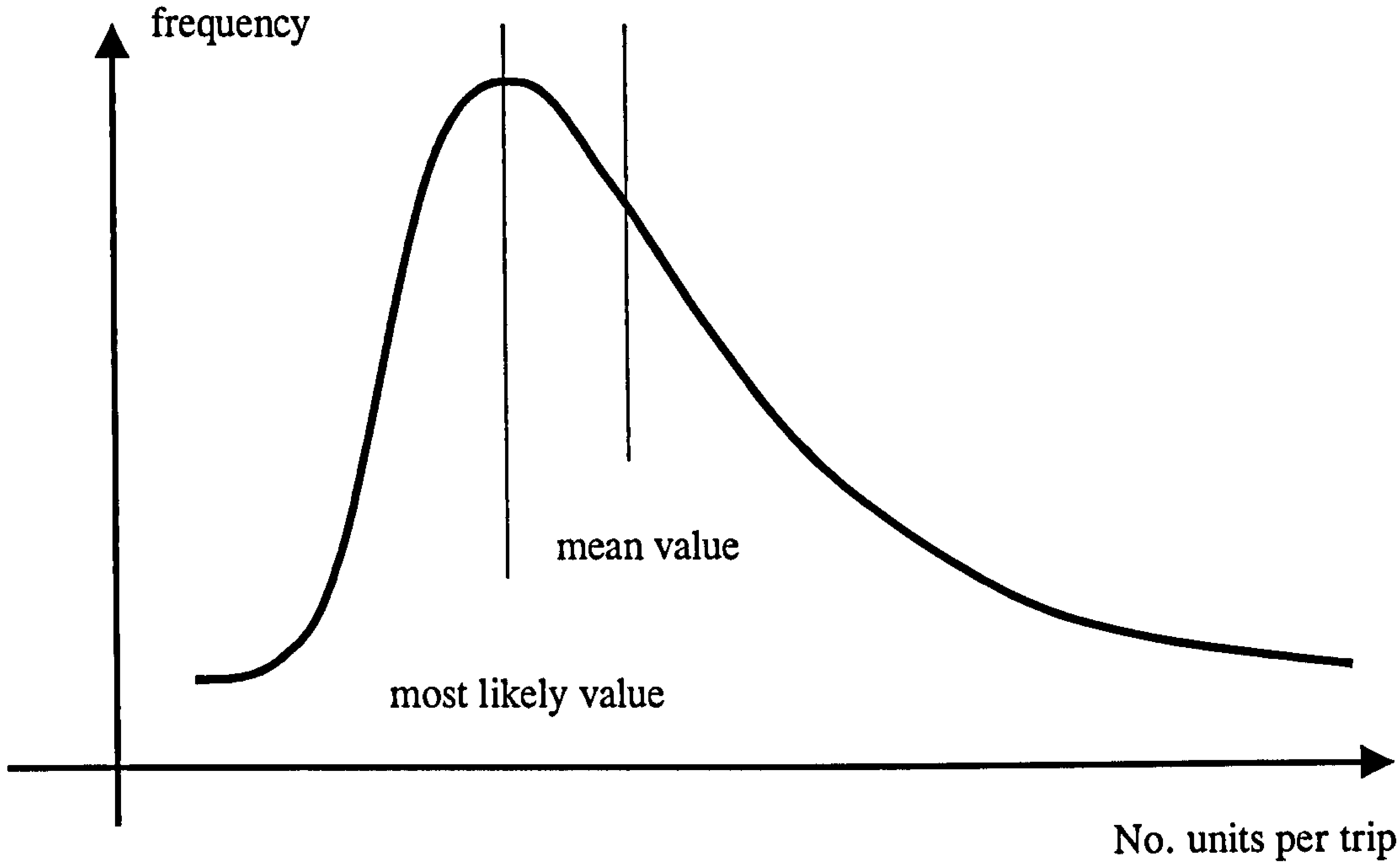
$$\textit{Absolute explicit trip value} = \frac{\textit{total number of units to be moved}}{\textit{mean (average) number of units per trip}}$$

.... *Equation 3.2*

Application of Equation 3.2 relies upon knowledge of the mean (average) number of units per trip. This can be predicted with more confidence in some cases than in others. For example, in the case of using a crane to place concrete, the mean (average) number of units per trip is reflected by the size of the skip. There is only a small number of skip sizes available and, generally, the skip size to be used is known.

However, in the case of using the crane to move reinforcement, the mean (average) number of units per trip is much more difficult to predict. At both ends of the scale urgency of demand may be the dominant factor; circumstances may demand the immediate delivery of a smaller number of units than average, tending to zero, or a larger number of units than average, governed by the maximum lifting capacity of the crane at the associated radius. A plot of frequency of occurrence against number of units per trip is likely to give a skew distribution, where the most likely value (the mode) differs from the mean (average) value. The most likely value may be less than or greater than the mean (average) value, resulting in positive and negative skewness respectively. This is illustrated diagrammatically in Figure 3.5.

POSITIVE SKEWNESS



NEGATIVE SKEWNESS

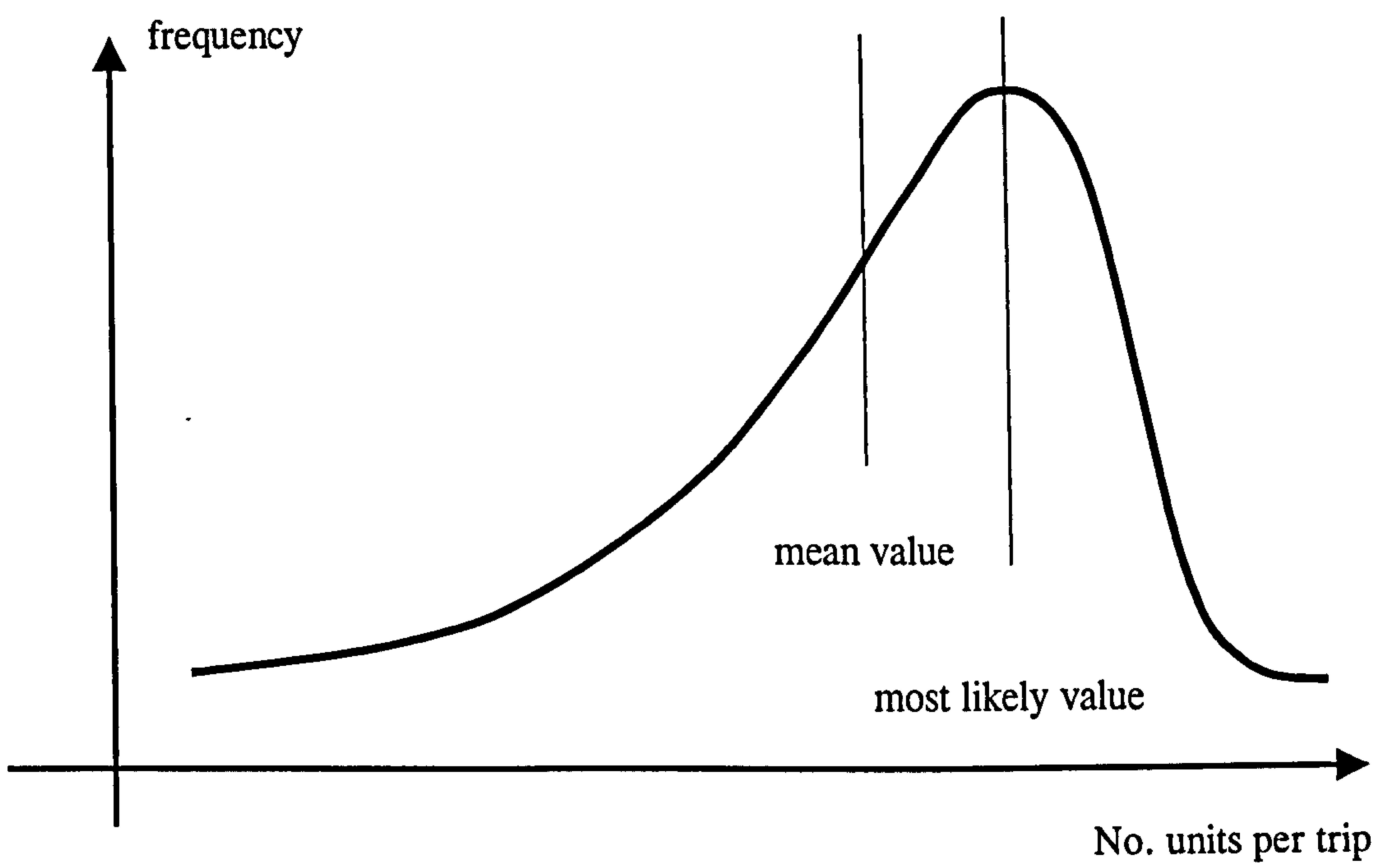


Figure 3.5 **Evaluation of trip value**
Positive and negative skewness

It can be appreciated that differing distributions, of number of units per trip, are likely to arise for differing materials. Such distributions will also be influenced by the characteristics of the individual site, and will reflect such factors as the efficiency of the material distribution system and the interaction of different gangs of operatives. Ideally the crane should be used to transport the maximum load possible, within the physical lifting constraints so imposed. However, the maximum number of units per trip is not likely to be an accurate reflection of the mean (average) number of units per trip, and so the model relies upon an estimate of the mean (average) value of the number of units per trip. It is not anticipated that it is possible for such an estimate to distinguish between the mean (average) value and the most likely value and so, for the purposes of the model, the average and most likely values (the mean and the mode) are assumed to be coincidental.

Explicit movement obviously occurs and must be evaluated and included in the analysis of crane movement. However, to rely on this type of movement alone would be misleading. The evaluation of movement between facilities is intended to achieve two purposes.

- To compute crane travel time. This depends upon the components of angular, radial and vertical movement and will vary according to the relative positions of the crane and facilities.

- To determine the relative weightings of each facility, which are a measure of the likelihood of the next movement being towards that facility. These weightings are independent of the relative positions of the crane and facilities.

If explicit movement alone was evaluated then movement towards some facilities would never be represented and the weighting of that facility would assume a zero value. This is clearly misleading. For example, considering movement of concrete from a point of delivery to a point of discharge, it is likely that movement towards the point of delivery will never occur, other than for the express purpose of subsequently moving more concrete to the point of discharge. Therefore, movement away from a facility must be matched by movement towards that facility. However, such movement is not necessarily direct and may be via a third facility, or indeed via more than one other facility.

Continuing with the example of using a crane to place concrete, it is likely that explicit movement, from the point of delivery to the point of discharge, will be matched by immediate opposing implicit movement, from the point of discharge to the point of delivery. Of course, there may be occasions when this pattern of movement is disrupted, and the crane is used for other purposes, in the middle of, for example, a given concreting operation, but, in certain situations such as this example, explicit movement is counteracted by implicit movement along the same direct route. However, in the case of using the crane to lift reinforcement, from its point of delivery, to its point of need, it is likely that such movement will not be part of a continuous process, but is an isolated incidence, albeit occurring several times during the working day, according to both demand and the availability of the crane. Therefore, in this example, explicit movement is not counteracted by immediate implicit movement along the same direct route.

Therefore, two types of explicit movement are defined. Firstly, that where it is reasonable to expect explicit movement to be counteracted by immediate implicit movement retracing the same route, and secondly, that where it is reasonable to expect that explicit movement will not be counteracted by immediate implicit movement retracing the same route. The definition of these two types of explicit movement embodies certain assumptions and simplifications. In the first case, although immediate implicit movement will occur during the operation, this pattern of movement will be disrupted at the end of the operation and begin again when the operation re-commences; this disruption is disregarded. In the second case, it is assumed that immediate implicit movement along the same route never occurs, although it may be that this does occur occasionally.

Considering the remaining categories of movement, which have been defined, wasting movement will inevitably occur. It is not possible to predict the extent of this movement. However, it will only influence the final outcome if it can be shown that such movement occurs in differing frequency between different facilities; if such movement is distributed evenly between each possible route, its omission will have no influence. Therefore wasting movement will be disregarded in the following analysis.

Linking movement will also inevitably occur, but it is not possible to predict the direction of such movement in advance; rather this movement will be of an *ad hoc* nature and will occur in response to the demands made upon the crane. Such is the nature of construction activity that although crane movement may be planned on a daily basis (and it is difficult to plan any further ahead than this) such plans will necessarily change to reflect the dynamic nature of construction. Therefore, linking movement will not be specifically evaluated, but will be embodied in the evaluation of balancing movement, which must be included in order that the number of movements towards any one facility is balanced by an equal number of movements away from that facility.

Balancing movement will be evaluated to ensure that the number of movements towards a facility is balanced by an equal number of movements away from that facility. Of course, it is not necessary that such movement be along the same route, but that total movement towards a facility equates to total movement away from that facility.

The evaluation of balancing movement will incorporate some of the linking movement, which will occur between facilities. However, the criterion for the evaluation of balancing movement will be the <u>minimum</u> movement that is required to ensure that the number of movements towards a facility is balanced by an equal number of movements away from that facility. This assessment of balancing movement then represents the <u>minimum</u> linking movement, which could occur. Linking movement, in excess of this, will inevitably occur, but may mostly be ascribed to inefficient use of the crane. Any additional linking movement which occurs will require compensating balancing movement and this will have a "knock on" effect on all other facilities contained within the site. As stated previously, it is not possible to predict the extent of linking movement, and so the model relies on the evaluation of minimum balancing movement, and hence linking movement, as this may be evaluated with more certainty.

For n facilities n equations of this type (number of movements towards a facility = number of movements away from that facility) can be generated. These n equations contain $n(n-1)$ variables (the number of movements occurring directly between facilities). For two facilities two equations can be generated (number of movements towards Facility 1 = number of movements away from Facility 1, and number of movements towards Facility 2 = number of movements away from Facility 2). These two equations contain two variables (number of movements from Facility 1 to Facility 2, and number of movements from Facility 2 to Facility 1). Therefore the equations can be solved and values assigned to each variable. However, when the number of facilities exceeds two, the number of variables exceeds the number of equations, and the traditional method of solution of simultaneous equations is not applicable.

In order to solve this problem three potential methods of solution were initially considered. These are briefly described below and the adoption of the final method chosen, that of a linear programming approach, justified.

3.3.1 Selection of evaluation method

The development of a specific algorithm to solve this problem was investigated in some detail. This was based on the principle of setting as many of the variables to zero as possible, while still maintaining the logic of the original equations. However, two significant problems arose which prevented the completion of the algorithm. Firstly, it was difficult to ensure that all eventualities had been incorporated into the algorithm, and, secondly, it was difficult to formalise the logic of some of the steps, which were executed manually by inspection, in order that these procedures could be incorporated into a computer program.

Secondly, the adoption of an appropriate "search method" was also considered. Many of these methods have been developed, for example, the Method of Hooke and Jeeves, the Complex Method and the Fibonacci Search (Adby and Dempster 1974, Bunday 1984). Some methods are suitable for functions of one variable and some for functions of n variables. In addition some methods are applicable to unconstrained optimization and some to constrained optimization.

However, all search methods commence with an estimation of the variable, or variables, involved and use some method to modify one variable at time in order to produce a new value of the function, until a minimum value of the function is produced. In this case the problem is one of constrained optimization (the minimum movement along some routes is already defined) with n variables. This type of problem "*... is a very hard problem. Indeed it is one to which there is no complete solution as yet.*" (Bunday 1984) and is further complicated by the fact that, in addition to n variables there also exist p functions (or equations). For this reason it was decided not to proceed with this line of investigation.

As it became evident that the previous two approaches to solving the problem were proving cumbersome, if not impossible, the adoption of a suitable linear programming technique, namely the Simplex Method, was considered. This method was first developed in 1947 by George B. Dantzig and has been subject to extensive refinement since its inception. It has the advantages of being well documented (Burley and O'Sullivan 1986, Gottfried and Weisman 1973, Kolman and Beck 1980, Krekó 1968, Lucey 1988, Rao 1984, Spivey and Thrall 1970) and, more importantly perhaps, producing a solution in a finite number of steps, *if* such a solution exists.

Adoption of the Simplex Method has been shown to be a suitable method for solving the problem in hand and its use is discussed in detail in the following section; the purpose of this section is not to provide a full discourse on the theory of the Simplex Method but to show how it may be applied to this particular problem.

3.4 The Simplex method

The general linear programming problem can be stated as (Kolman and Beck 1980):

Find the values of $x_1, x_2, \ldots, x_n$ which will
maximize or minimize $z = c_1x_1 + c_2x_2 + \ldots. + c_nx_n$ (1)

subject to the restrictions

$$\begin{array}{ccccccccl} a_{11}x_1 & + & a_{12}x_2 & + & \ldots. & + & a_{1n}x_n & \leq (\geq)\ (=)\ b_1 \\ a_{21}x_1 & + & a_{22}x_2 & + & \ldots. & + & a_{2n}x_n & \leq (\geq)\ (=)\ b_2 \\ . & & . & & & & . & \\ a_{m1}x_1 & + & a_{m2}x_2 & + & \ldots. & + & a_{mn}x_n & \leq (\geq)\ (=)\ b_m \end{array} \qquad (2)$$

All functions are linear and the linear function (1) is known as the **objective function.** The equalities or inequalities in (2) are known as **constraints** and only one type of constraint may exist in any one equation.

The general linear programming problem may be expressed in **standard** form as follows:

Find the values of $x_1, x_2, \ldots., x_n$ which will
maximize or minimize $z = c_1x_1 + c_2x_2 + \ldots. + c_nx_n$

subject to the restrictions

$$\begin{array}{ccccccccl} a_{11}x_1 & + & a_{12}x_2 & + & \ldots. & + & a_{1n}x_n & \leq b_1 \\ a_{21}x_1 & + & a_{22}x_2 & + & \ldots. & + & a_{2n}x_n & \leq b_2 \\ . & & . & & & & . & \\ a_{m1}x_1 & + & a_{m2}x_2 & + & \ldots. & + & a_{mn}x_n & \leq b_m \end{array}$$

$x_j \geq 0,\ j = 1, 2, \ldots., n$

Linear programming problems in this form have a set of feasible solutions, which satisfy the constraints, and one, or more, solutions that maximize the objective function.

Alternatively the general linear programming problem may be expressed in **canonical** form as follows:

Find the values of $x_1, x_2, \ldots, x_s$ which will
maximize or minimize $z = c_1x_1 + c_2x_2 + \ldots. + c_sx_s$

subject to the restrictions

$$
\begin{array}{ccccccccc}
a_{11}x_1 & + & a_{12}x_2 & + & \ldots. & + & a_{1s}x_s & = b_1 \\
a_{21}x_1 & + & a_{22}x_2 & + & \ldots. & + & a_{2s}x_s & = b_2 \\
\cdot & & \cdot & & & & \cdot & \\
a_{m1}x_1 & + & a_{m2}x_2 & + & \ldots. & + & a_{ms}x_s & = b_m
\end{array}
$$

$$x_j \geq 0,\ j = 1, 2, \ldots., s$$

A linear programming problem in this form may be solved by finding all the basic solutions (i.e. those containing dependent variables), discarding those which are not feasible, and finding an optimal solution among the remaining. It can be appreciated that the method is both lengthy and tedious and the Simplex Method is an algebraic algorithm, which has been developed to solve this type of problem more easily. At least two variations of the algorithm are available (Kolman and Beck 1980, Krekó 1968). The one that has been adopted, while producing a larger matrix, or tableau, than the other method, has been selected because its form is more appropriate for inclusion in a computer program.

3.4.1 Application of the Simplex method to the determination of global crane movement

As discussed previously for n facilities n equations of the type

movement towards a facility = movement away from that facility

may be generated and these n equations will contain $n(n-1)$ variables. For n facilities these equations may be expressed as:

$$
\begin{array}{lcl}
m_{12} + m_{13} + \ldots + m_{1n} & = & m_{21} + m_{31} + \ldots m_{n1} \\
m_{21} + m_{23} + \ldots + m_{2n} & = & m_{12} + m_{32} + \ldots m_{n2} \\
\cdot \quad \cdot \quad \cdot & \cdot & \cdot \quad \cdot \quad \cdot \\
m_{n1} + m_{n2} + \ldots + m_{n(n-1)} & = & m_{1n} + m_{2n} + \ldots m_{(n-1)n}
\end{array}
$$

where m_{12} represents movement **from** Facility 1 **to** Facility 2.

Alternatively, to make the equations compatible with the canonical form:

$$
\begin{array}{lcl}
m_{12} + m_{13} + \ldots + m_{1n} & - & m_{21} + m_{31} + \ldots m_{n1} = 0 \\
m_{21} + m_{23} + \ldots + m_{2n} & - & m_{12} + m_{32} + \ldots m_{n2} = 0 \\
\cdot \quad \cdot \quad \cdot & \cdot & \cdot \quad \cdot \quad \cdot \\
m_{n1} + m_{n2} + \ldots + m_{n(n-1)} & - & m_{1n} + m_{2n} + \ldots m_{(n-1)n} = 0
\end{array}
\qquad (3)
$$

The known (minimum) values of movement between facilities may also be represented as constraints of the greater than or equal to type as follows:

$$
\begin{array}{lcl}
m_{12} & \geq & q_{12} \\
m_{13} & \geq & q_{13} \\
 & \cdot & \\
m_{n(n-1)} & \geq & q_{n(n-1)}
\end{array}
\qquad (4)
$$

where q_{12} represents the **minimum** movement from Facility 1 to Facility 2.

By implication $m_{12}, m_{13}, \ldots, m_{n(n-1)} \geq 0$ (5)

The objective function may be stated as:

$$\text{minimize } z = m_{12} + m_{13} + \ldots + m_{n(n-1)} \quad (6)$$

The sets of equations (3), (4) and (5), in conjunction with the objective function (6), represent the problem of minimizing the number of movements between facilities in an appropriate linear programming format. However, it can be seen that there are two significant differences between this format and that of the canonical form, namely the problem is currently one of minimization and not maximization, and the constraints contain a mixture of equalities and inequalities rather than only inequalities.

One way of eliminating these problems would be to:-

a) re-write the minimization problem as a maximization problem. Every minimization problem can be viewed as a maximization problem by maximizing the **negative** of the objective function (Kolman and Beck 1980). For example, the objective function could be re-written as:

$$\text{maximize } z' = -m_{12} - m_{13} - \ldots - m_{n(n-1)}$$

b) reverse the inequalities. By multiplying an inequality by -1 a greater than or equal inequality becomes a less than or equal inequality and vice-versa. For example, the inequality

$$m_{12} \geq q_{12}$$

could be re-written as:

$$-m_{12} \leq -q_{12}$$

c) change the equalities to inequalities. Any equality can be expressed as a pair of inequalities. For example the equality:

$$m_{12} + m_{13} + ... + m_{1n} - m_{21} - m_{31} - .... - m_{n1} = 0$$

could be expressed as:

$$m_{12} + m_{13} + ... + m_{1n} - m_{21} - m_{31} - .... - m_{n1} \leq 0$$

and

$$m_{12} + m_{13} + ... + m_{1n} - m_{21} - m_{31} - .... - m_{n1} \geq 0$$

or, in order to eliminate the greater than or equal to inequality:

$$m_{12} + m_{13} + ... + m_{1n} - m_{21} - m_{31} - .... - m_{n1} \leq 0$$

and

$$-m_{12} - m_{13} - .... - m_{1n} + m_{21} + m_{31} + ... + m_{n1} \leq 0$$

It may seem contradictory to modify an equation, which is already compatible with canonical form, but, generally, although there are exceptions, the Simplex Method requires **all** equations to be in standard form prior to their conversion to canonical form.

Attempts to follow these guidelines have proved to be cumbersome. Alternatively a two stage method may be adopted for solving linear programming problems which contain a mixture of equalities and inequalities. However, a neater, more elegant solution is to consider the dual problem.

The linear programming problem expressed above in either standard or canonical form is known as a **primal** problem. For any primal problem there also exists a **dual** problem. Generally, though not necessarily, the primal problem is one of maximization and so the dual problem is one of minimization. In this particular case the primal problem is one of minimization and so the dual problem will be one of maximization.

The relationships between primal and dual problems are summarised below in Table 3.1. The proofs of these relationships are not provided but can be found in most textbooks concerning linear programming.

Table 3.1 **Relationship between primal and dual problems**
(Source: Kolman and Beck 1980)

Primal problem	Dual problem
Maximization	Minimization
Coefficients of the objective function	Right-hand sides of constraints
Coefficients of the *i*th constraint	Coefficients of *i*th variable, one in each constraint
*i*th constraint is an ≤inequality	*i*th variable is ≥ 0
*i*th constraint is an equality	*i*th variable is unrestricted
*j*th variable is unrestricted	*j*th constraint is an equality
*j*th variable is ≥ 0	*j*th constraint is an ≥ inequality
Number of variables	Number of constraints
Dual problem	Primal problem

The headings of "Primal problem" and "Dual problem" may be inter-changed; this is appropriate in this case and so the headings at the bottom of the table are relevant.

The primal minimization problem expressed in equations (4), (3) and (5), in conjunction with the objective function (6), may now be re-written as the dual maximization problem.

As there are $n(n\text{-}1) + n$ constraints (i.e. equations) in the primal problem there are $n(n\text{-}1) + n$ variables in the dual problem. Also, as there are $n(n\text{-}1)$ variables in the primal problem there are $n(n\text{-}1)$ constraints in the dual problem.

The right-hand side of the constraints in the primal problem represents the coefficients of the objective function in the dual problem. The coefficients of the objective function in the primal problem form the right-hand side of the constraints in the dual problem.

The dual maximization problem may therefore be expressed as:

Find the values of $w_1, w_2, \ldots., w_{n(n-1)+n}$ which will

maximize $z' = q_{12}w_1 + q_{13}w_2 + \ldots. + q_{n(n-1)}w_{n(n-1)}$

subject to the constraints

$$w_1 \quad + w_{n(n-1)+1} \quad - w_{n(n-1)+2} \leq 1$$

$$w_2 \quad + w_{n(n-1)+1} \quad - w_{n(n-1)+3} \leq 1$$

$$\cdot \quad \cdot \quad \cdot \quad \cdot$$

$$w_{n(n-1)} \quad - w_{n(n-1)+n-1} \quad + w_{n(n-1)+n} \leq 1$$

$$w_1, w_2, \ldots. w_{n(n-1)} \geq 0$$

Inspecting Table 3.1 it can be seen that, as the *i*th variable in the primal problem (i.e. the first to $n(n-1)$th variable) is of the greater than or equal to zero type, the corresponding number of constraints in the dual problem (i.e. all the constraints) are of the less than or equal to variety. This has the major advantage of eliminating the mixture of equalities and inequalities, which appeared in the primal problem. However, as it is only the first $n(n-1)$ constraints in the primal problem which are of the greater than or equal to type, then only the corresponding number of variables in the primal problem are of the greater than equal to zero type; all other variables are unrestricted.

The Simplex Method may now be used to solve the primal problem. An example will be used to demonstrate:-

i) the conversion of a linear programming problem in primal form to the associated problem in dual form.

ii) the interpretation of the result of the dual problem to that associated with the primal problem.

3.4.2 An example

For the sake of clarity the example will consider movement between three facilities only (the minimum practical number). The (minimum) number of movements ascribed to each route are:-

Number of movements FROM Facility 1 TO Facility 2 (q_{12}) 2
Number of movements FROM Facility 1 TO Facility 3 (q_{13}) 4

Number of movements FROM Facility 2 TO Facility 1 (q_{21}) 8
Number of movements FROM Facility 2 TO Facility 3 (q_{23}) 3

Number of movements FROM Facility 3 TO Facility 1 (q_{31}) 5
Number of movements FROM Facility 3 TO Facility 2 (q_{32}) 1

The primal minimization problem may be stated as:-

Find values of m_{12}, m_{13}, m_{21}, m_{23}, m_{31} and m_{32}

which will

minimize $z = m_{12} + m_{13} + m_{21} + m_{23} + m_{31} + m_{32}$

subject to the constraints

$$
\begin{array}{rrrrrrcr}
m_{12} & & & & & & \geq & 2 \\
 & m_{13} & & & & & \geq & 4 \\
 & & m_{21} & & & & \geq & 8 \\
 & & & m_{23} & & & \geq & 3 \\
 & & & & m_{31} & & \geq & 5 \\
 & & & & & m_{32} & \geq & 1 \\
m_{12} & + m_{13} & - m_{21} & & - m_{31} & & = & 0 \\
-m_{12} & & + m_{21} & + m_{23} & & - m_{32} & = & 0 \\
 & - m_{13} & & - m_{23} & + m_{31} & + m_{32} & = & 0
\end{array}
$$

(by implication all variables ≥ 0)

The dual maximization problem may be stated as:-

Find values of w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8 and w_9 which will

maximize $z' = 2w_1 + 4w_2 + 8w_3 + 3w_4 + 5w_5 + w_6$

subject to the constraints

$$
\begin{array}{llllllllllll}
w_1 & & & & & & + w_7 & - w_8 & & \leq 1 \\
& w_2 & & & & & + w_7 & & - w_9 & \leq 1 \\
& & w_3 & & & & - w_7 & + w_8 & & \leq 1 \\
& & & w_4 & & & & + w_8 & - w_9 & \leq 1 \\
& & & & w_5 & & - w_7 & & + w_9 & \leq 1 \\
& & & & & w_6 & & - w_8 & + w_9 & \leq 1 \\
& & & & & & w_1, w_2, \ldots, w_6 & & & \geq 0
\end{array}
$$

The dual problem, as stated above, is in standard form. It must now be converted to canonical form. This is done by replacing the inequalities with equalities and introducing additional variables known as slack variables. For example the inequality

$$x =< 6$$

may be replaced by

$$x + u = 6$$

where u is defined as the slack variable.

Introducing slack variables u_1, u_2, ..., u_6 the above constraints may be re-written as:

$$
\begin{array}{lllllllllll}
w_1 & & & & & & + w_7 & - w_8 & & + u_1 & = 1 \\
& w_2 & & & & & + w_7 & & - w_9 & + u_2 & = 1 \\
& & w_3 & & & & - w_7 & + w_8 & & + u_3 & = 1 \\
& & & w_4 & & & & + w_8 & - w_9 & + u_4 & = 1 \\
& & & & w_5 & & - w_7 & & + w_9 & + u_5 & = 1 \\
& & & & & w_6 & & - w_8 & + w_9 & + u_6 & = 1
\end{array}
$$

and the problem is now in canonical form.

The Simplex Method starts with an initial feasible solution and proceeds, step by step, to an optimum solution. The initial feasible solution assumes that all non-slack variables are zero, and so all slack variables initially assume a value greater than zero. While this solution is feasible (it represents the origin), it is obviously not the optimum solution. As the solution approaches the optimum the non-slack variables will assume values greater than zero and some, but not necessarily all, of the slack variables will assume zero values.

The Simplex Method is greatly facilitated by the use of a set of tableaux. The initial tableau for this problem is given below.

Tableau 1

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
u_1	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
u_3	0	0	1	0	0	0	-1	1	0	0	0	1	0	0	0	1
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	0	0	0	0	1	0	-1	0	1	0	0	0	0	1	0	1
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	-2	-4	-8	-3	-5	-1	0	0	0	0	0	0	0	0	0	0

The top row of the tableau lists the variables in the problem. Beneath this, in the body of the tableau, are the corresponding values of the variables in each constraint. The left column contains the dependent variable in each equation; these will change as steps are taken towards the optimum solution. The right column is the solution column and gives the value of the dependent variable in each row - in Tableau 1 all the slack variables have a value of 1, and this is the solution given in this tableau. The bottom row contains the objective function. This has previously been stated as:

$$\text{maximize } z' = 2w_1 + 4w_2 + 8w_3 + 3w_4 + 5w_5 + w_6$$

which, in order to be compatible with the constraints, may be expressed as

$$z' - 2w_1 - 4w_2 - 8w_3 - 3w_4 - 5w_5 - w_6$$

For simplicity z' has been omitted from the tableau.

The value at the right of the bottom row represents the **target function** and is a numerical value of that function which, in this case, is being maximized (i.e. z').

Once an initial feasible solution has been determined the process becomes iterative one - firstly a test for optimality is carried out, and, if the optimum solution has not been obtained, an adjustment is made to the solution and a further optimality test executed. This procedure continues until an optimum solution is found.

The test for optimality is simple. If the objective row of a tableau has zero entries in the columns labelled by the dependent variables, and no negative entries in the other columns, then the solution represented by the tableau is optimal. A simpler rule is that an optimum solution exists when there are no negative entries in the objective row. If the computational procedure has been carried out correctly and there is an optimal solution then the columns labelled by the dependent variables will automatically be zero. In this case, as there are negative entries in the objective row, the optimum solution, as expected, has not been found.

Some adjustment to the proposed solution must now take place. One variable will be brought into the solution and another taken out of the solution. The adjustment process comprises three steps - selecting the entering variable, choosing the departing variable and forming a new tableau. These steps are described below.

i) Selecting the entering variable. The largest increase in the target function, per unit increase in a variable, occurs for the entry in the objective row with the largest negative value. Although there may be circumstances when the largest increase in target function is not achieved by selecting the most negative entry in the objective row, this rule is most commonly followed because of its computational simplicity. In fact, by selecting any negative entry in the objective row, an improvement will be made to the target function; selection of the largest negative value enables the optimum solution to be arrived at more quickly. Where the magnitude of the most negative number is duplicated, selection of the entering variable may be made at random from the two, or more, variables.

The column of the entering variable is called the **pivotal column**.

By inspection of Tableau 1 it can be seen that the largest negative number, -8, corresponds to the third variable, w_3, and therefore w_3 is the entering variable in Tableau 1.

ii) Choosing the departing variable. As one variable comes into the solution another variable must be removed. Initially all the slack variables assumed non-zero positive values. As other variables enter the solution some, if not all, of the slack variables will become zero. Therefore, when the entering variable has been selected, inspection of the constraints will indicate which slack variables have the potential to become zero by the introduction of that variable. This is indicated in the tableau by those values in the pivotal column which have a positive non zero value. However, the slack variables cannot become negative as this would violate the constraints. Therefore, the departing variable is chosen as the one which will allow no slack variables to become negative, one, or more, slack variables to become zero, and the remainder to remain positive. This is determined by selecting the variable corresponding to the smallest non-negative ratio of the right most columns to the corresponding entries in the pivotal column. Where the smallest ratio is not unique, selection of the departing variable may be made from those variables with the minimum ratio. If the smallest non-negative ratio is not chosen then the next solution will not be feasible.

The row containing the departing variable is known as the **pivotal row** and the intersection of the pivotal column and pivotal row as the **pivot.**

In this case there is only entry in the pivotal column which assumes a positive value. This occurs in the third row and the ratio of the right most entry to the corresponding entry in the pivotal column is equal to 1. u_3 is therefore the departing variable.

iii) Forming a new tableau. As variables enter and leave the solution the constraints must be modified and re-arranged. The variable selected as the entering variable will become dependent in the new solution and so must be represented, by a value of one, in the associated constraint. Further, as this variable is a dependent variable in that constraint it cannot be represented in any other constraints, and so has a zero coefficient in all other rows.

The original constraints may be re-written to comply with the above conditions. However, the same result may be achieved by executing the following process, known as **pivoting.**

a) If the pivot is k, multiply the pivotal row by $1/k$, making the entry in the pivot position equal to 1.

b) Add suitable multiples of the new pivotal row to all other rows (including the objective row and target function) so that all other elements in the pivotal column become zero.

c) In the new tableau replace the label on the pivotal row by the entering variable.

By inspection of Tableau 1 it can be seen that the pivot (at the intersection of w_3 and u_3) already assumes a value of 1, and so no modification is required to the pivotal row. It can also be seen that, with the exception of the objective row, all other entries in the pivotal column are zero. Therefore, the only modification, which is required, is to the objective row. In this case 8 times the existing u_3 row is added to the objective row. Finally, w_3 becomes the new label on the pivotal row.

Following the procedure outlined above the new tableau is as shown below.

Tableau 2

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
u_1	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
w_3	0	0	1	0	0	0	-1	1	0	0	0	1	0	0	0	1
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	0	0	0	0	1	0	-1	0	1	0	0	0	0	1	0	1
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	-2	-4	0	-3	-5	-1	-8	8	0	0	0	8	0	0	0	8

The optimum solution has not yet been produced as negative values still exist in the objective row. The largest negative value occurs in the w_7 column and so this column becomes the pivotal column. The minimum ratio of the right most column to the corresponding entries in the pivotal column is 1, which occurs in both the u_1 and u_2 rows. The u_1 row is therefore arbitrarily chosen as the pivotal row. The pivot is already set to 1 and so no modification is required to the pivotal row. However, multiples of this row must be added to all other rows, except the u_4 and u_6 rows, where a zero already appears in the pivotal column. By inspection, the pivotal row must be added once to the w_3 and u_5 rows, added eight times to the objective row and subtracted from the u_2 row. This process produces Tableau 3.

Tableau 3

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	1	0	0	0	1	0	0	-1	1	1	0	0	0	1	0	2
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	6	-4	0	-3	-5	-1	0	0	0	8	0	8	0	0	0	16

The above processes must be repeated until there are no negative values remaining in the objective row. The full set of tableau for this problem is given in Appendix A.1. The optimum solution for this problem is given in Tableau 4 below.

Tableau 4

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
w_2	-1	1	0	0	0	1	0	0	0	-1	1	0	0	0	1	1
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	0	0	0	1	0	1	2
w_5	1	0	0	0	1	-1	0	0	0	1	0	0	0	1	-1	1
w_9	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	7	0	0	0	0	1	0	0	0	9	4	8	3	5	2	31

The solution given in the above Tableau to the dual maximization problem is:-

$$w_7 = 1$$

$$w_2 = 1$$

$$w_3 = 2$$

$$w_4 = 2$$

$$w_5 = 1$$

$$w_9 = 1$$

However, this is not the solution to the primal minimization problem and the final tableau must be interpreted, in order that the solution may be produced. In fact the optimal solution is given in the objective row in the columns corresponding to the original slack variables. The optimal solution to the primal minimization problem is:

u_1 represents $m_{12} = 9$

u_2 represents $m_{13} = 4$

u_3 represents $m_{21} = 8$

u_4 represents $m_{23} = 3$

u_5 represents $m_{31} = 5$

u_6 represents $m_{32} = 2$

The above solution complies with the restriction that the total movement towards any facility should equal the total movement away from that facility. This solution may be compared with the original minimum number of movements ascribed to each route, which highlights the increase in number of movements required to satisfy the constraint that the total number of movements towards any facility must be matched by the same number of movements away from that facility:

$q_{12} = 2$	$m_{12} = 9$
$q_{13} = 4$	$m_{13} = 4$
$q_{21} = 8$	$m_{21} = 8$
$q_{23} = 3$	$m_{23} = 3$
$q_{31} = 5$	$m_{31} = 5$
$q_{32} = 1$	$m_{32} = 2$

The above example demonstrates how the Simplex Method can be used to determine the movement between facilities. The following sections briefly discuss further aspects of the Simplex Method relevant to this problem. This is followed by an example of an alternative method of applying the Simplex Method and this section concludes by discussing the concept of multiple optimum solutions.

3.4.3 The existence of an optimum solution

The Simplex Method can only produce an optimum solution if such a solution exists. In some situations the constraints may be conflicting and so there may be no feasible solutions. Alternatively, although there may be a large set of feasible solutions, the set may be unbounded by the constraints and so no optimal solution exists.

In the problem concerned a feasible solution must always exist as it is always possible to ascribe the maximum value of movement, which exists to all routes. It can also be appreciated that there must be an optimum solution, although this solution is not necessarily unique.

3.4.4 Degeneracy

A degenerate solution occurs in the Simplex Method when one of the variables in the solution column assumes a value of zero. If this variable is selected as the entering variable then the value of the target function will not change. This in itself is not detrimental to the process, but the danger is that, if the feasible solution then remains unaltered, the Simplex Method is in a cycle and will never terminate. Although degeneracy frequently occurs, cycling is encountered only occasionally in practical problems. In the problem in hand no occurrences of cycling accompanying degeneracy have been discovered and so the problem has been disregarded.

3.4.5 Integer programming

The input data to the problem being considered are in integer form. These data represent the number of movements between facilities. The output data also represent number of movements between facilities and so should also be integers. In the general linear programming problem there is no guarantee that the problem will have an integer solution. A procedure known as Gomory's Cutting Plane Method (Rao, 1984) has been developed which adds additional constraints which force the solution to an all-integer point. However, if the optimum solution is in integer form the introduction of such constraints is not necessary. In the problem being considered all the original coefficients in the constraints are unity and the objective function is in integer form, and so no occurrences of non-integer optimum solutions have been found and the introduction of additional constraints has not been necessary.

3.4.6 An alternative approach

The example which was solved in section 3.4.2 introduced slack variables $u_1, u_2, \dots,$ u_6 in order that the less than or equal constraints could be replaced by equalities. The constraints incorporating the slack variables were:

$$
\begin{array}{llllllllllllllllll}
w_1 & & & & & & + & w_7 & - & w_8 & & & + & u_1 & = 1 \\
& w_2 & & & & & + & w_7 & & & - & w_9 & + & u_2 & = 1 \\
& & w_3 & & & & - & w_7 & + & w_8 & & & + & u_3 & = 1 \\
& & & w_4 & & & & & + & w_8 & - & w_9 & + & u_4 & = 1 \\
& & & & w_5 & & - & w_7 & & & + & w_9 & + & u_5 & = 1 \\
& & & & & w_6 & & & - & w_8 & + & w_9 & + & u_6 & = 1
\end{array}
$$

Each slack variable appeared in only one constraint. However, by inspection of the above constraints it can be seen that another set of variables $w_1, w_2, \dots, w_6$ also appear in only one constraint. Therefore, it is possible to replace both sets of variables by a further set. Let

$$
\begin{aligned}
v_1 &= w_1 + u_1 \\
v_2 &= w_2 + u_2 \\
v_3 &= w_3 + u_3 \\
v_4 &= w_4 + u_4 \\
v_5 &= w_5 + u_5 \\
v_6 &= w_6 + u_6
\end{aligned}
$$

and the constraints may be re-written as:

$$
\begin{array}{llllllllllllll}
v_1 & & & & & & + & w_7 & - & w_8 & & & = 1 \\
& v_2 & & & & & + & w_7 & & & - & w_9 & = 1 \\
& & v_3 & & & & - & w_7 & + & w_8 & & & = 1 \\
& & & v_4 & & & & & + & w_8 & - & w_9 & = 1 \\
& & & & v_5 & & - & w_7 & & & + & w_9 & = 1 \\
& & & & & v_6 & & & - & w_8 & + & w_9 & = 1
\end{array}
$$

The linear programming problem may now be represented in a smaller tableau. The initial tableau for the problem, without the incorporation of additional slack variables, is given in Tableau 5.

Tableau 5

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
v_1	1	0	0	0	0	0	1	-1	0	1
v_2	0	1	0	0	0	0	1	0	-1	1
v_3	0	0	1	0	0	0	-1	1	0	1
v_4	0	0	0	1	0	0	0	1	-1	1
v_5	0	0	0	0	1	0	-1	0	1	1
v_6	0	0	0	0	0	1	0	-1	1	1
	-2	-4	-8	-3	-5	-1	0	0	0	0

The same procedure as outlined previously is used to produce a final tableau, which incorporates the optimum solution. The final tableau for this example is shown in Tableau 6 and all tableaux are given in Appendix A.2.

Tableau 6

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
w_2	-1	1	0	0	0	1	0	0	0	1
w_3	1	0	1	0	0	0	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	2
w_5	1	0	0	0	1	-1	0	0	0	1
w_9	0	0	0	0	0	1	0	-1	1	1
	7	0	0	0	0	1	0	0	0	31

Whilst the same procedure has been used in this case, as when the additional slack variables were introduced, the interpretation of the tableau is different. As before the solution to the dual problem is given in the right-most column and the solution to the primal problem is again found in the objective row. However, in this case, the values in the v_1, v_2, ..., v_6 columns represent the increase to the original m_{12}, m_{13}, ... , m_{32} values.

Therefore the solution is as follows:

$$m_{12} = 2 + 7 = 9$$
$$m_{13} = 4 + 0 = 4$$
$$m_{21} = 8 + 0 = 8$$
$$m_{23} = 3 + 0 = 3$$
$$m_{31} = 5 + 0 = 5$$
$$m_{32} = 1 + 1 = 2$$

This corresponds to the solution found previously.

This method has the advantage of reducing the size of the tableau, and, consequently the computational time. For a problem involving 10 facilities a 190 x 90 matrix is required if additional slack variables are used. The present method utilizes a 100 x 90 matrix, which is significantly smaller. Therefore, this method has been adopted in the computer program.

3.4.7 Multiple optimum solutions

It is quite plausible that more than one optimum solution may occur. Continuing with the method described in the previous section, multiple optimum solutions will occur when the following two conditions are both satisfied. Firstly a zero (or zeros) must occur in the solution column (the right most column). In this case the addition of any multiple of the corresponding row will change the objective row (which, in the dual problem, represents the solution) without altering the target function. Secondly, where a zero occurs in the solution column, a row of zeros must also occur in the columns not represented by the slack variables v_1, v_2, ..., v_n. In this case, the addition of any multiple of the corresponding row will not change these values in the corresponding columns in the objective row (which always assume zero values when an optimum solution occurs).

By inspection, the solution given in Tableau 6 is unique as there are no zeros in the solution column. However, consider the solution presented below in Tableau 7.

Tableau 7

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
w_2	-1	1	0	0	0	1	0	0	0	1
w_3	1	0	1	0	0	0	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	2
w_5	-1	0	0	0	1	0	0	0	0	0
w_9	0	0	0	0	0	1	0	-1	1	1
	7	0	0	0	0	1	0	0	0	31

In this case the solution is not optimal as there is a zero in the solution column in the row corresponding to w_5, and the corresponding w_7, w_8 and w_9 columns also contain zeros. Adding the w_5 row to the objective row produces Tableau 8, which provides a different solution from that given in Tableau 7.

Tableau 8

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
w_2	-1	1	0	0	0	1	0	0	0	1
w_3	1	0	1	0	0	0	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	2
w_5	-1	0	0	0	1	0	0	0	0	0
w_9	0	0	0	0	0	1	0	-1	1	1
	6	0	0	0	1	1	0	0	0	31

This process could be repeated until the value in the objective row corresponding to the v_1/w_1 column becomes zero. Simultaneously the value in the objective row corresponding to the v_5/w_5 column will increase but the target function will remain unaltered. This is only an example, and it is important to note that solution cannot be interpreted using the same values as Tableau 6, as the initial solution, which has produced Tableau 7, and Tableau 8 will be different.

Where the necessary conditions for multiple optimum solutions occur in more than one row the above procedure may be repeated. In this case it will also necessary to consider solutions arising from combinations of the addition of such rows to the objective row.

3.5 Data required by the model

The data required by the model has been discussed in the foregoing sections. These data concern three aspects of construction site layout, namely the site boundaries, the location of facilities and movement of materials between these facilities. The precise nature of the data required is summarised in Table 3.2.

Table 3.2 **Site layout data required by the model**

General information	Site Layout Name File Name
Site boundary	No. of sets of co-ordinates to define the boundary (between 3 and 20) For each set of co-ordinates: X co-ordinate Y co-ordinate An indication as to whether the internal angle > 180°
Location of facilities	No. facilities For each facility: Facility name Facility height X co-ordinate Y co-ordinate
Movement of materials	From each facility to every other facility: Total load Average load Maximum load The occurrence (or non-occurrence) of implicit movement

3.6 Summary

Considered in isolation from the position of the crane, there are very few construction site features, apart from global crane movement, that impact on the model. The site boundary should be defined and any facilities served by the crane, and the crane itself, located within this boundary. Details of the location and height of facilities, the amount and maximum weight of materials to be moved and the location and type of any obstructions are also required as input into the model.

Construction activities vary from day to day and the optimum crane position on one day may not necessarily be the same crane position on another day. Therefore, the only viable approach is to assess the total number of crane movements which are expected to occur between installation and dismantling of the crane.

Five categories of movement – explicit, implicit, linking, wasting and balancing - have been defined. Explicit movement is the movement which is distinctly implied when consideration is given to the movements which must occur to facilitate movement of materials from one facility to another. Implicit movement is that which returns an empty crane hook to the original facility so that, if appropriate, the delivery cycle can be repeated. Linking movement is that movement which allows the crane to move from one activity to another. Wasting movement is that movement which will inevitably occur but which is unnecessary. As there is no way to predict the magnitude of this movement it is disregarded. However, linking movement is embodied in the evaluation of the final category of movement, balancing movement. This is movement which must occur to ensure that the basic premise that the total number of movements towards any facility must be matched by an equal number of movements away from that facility. In determining the magnitude of balancing movement, only the minimum balancing movement required to satisfy this premise is considered.

Given that explicit and implicit movements occur, the adoption of the linear programming technique known as the Simplex Method was shown to be a suitable method for solving the problem of how to predict the balancing movement.

Linear programming may be considered as appropriate technique to solve problems where an objective function exists, a series of constraints may be defined and all relationships are linear. In this case the objective function is one of minimizing the total number of movements. Two sets of constraints can be identified. Firstly, for each facility, the number of movements towards that facility must be equal to the number of movements away from that facility. For *n* facilities *n* equations of this type will be generated. Secondly, the known values of number of movements between any pair of facilities may be considered to represent the minimum number of movements which occur and this is less than or equal to the actual number which must occur to satisfy the constraints identified above. For *n* facilities a maximum of *n!* equations of this type may be generated, but this will depend upon the (minimum) number of movements which are known in advance.

In using the Simplex Method to solve the problems outlined above, there are two significant differences between the format of the associated objective function and the constraints and the standard or canonical form required. Firstly, the problem is one of minimization and not of maximization. Secondly, the problem consists of a mixture of equalities (associated with the first set of constraints) and inequalities (associated with the second set of constraints). It may be possible to eliminate these problems by re-writing the minimization problem as a maximization problem, reversing the inequalities and changing the equalities to inequalities by introducing a further set of variables. However, this proved to be cumbersome and adoption of the dual problem was considered to be a more elegant solution. In re-writing the primal problem as the dual problem, the number of constraints in the primal problem becomes the number of variables in the dual problem and the number of variables in the primal problem become the number of constraints in the dual problem. Further, the right-hand side of the constraints in the primal problems represent the objective function in the dual problem and coefficients of the objective function in the primal problem form the right-hand side of the constraints in the dual problem. This has the advantage of eliminating the mixture of equalities and inequalities such that all constraints are in the form of inequalities of the less than or equal to type. Finally, the Simplex Method can be executed via a set of tableaux, which seeks to determine the optimum solution to the problem, that is determining the minimum number of movements which satisfy all the constraints.

CHAPTER 4

TOWER CRANE CHARACTERISTICS

4.1 Introduction

Consideration must also be given to the characteristics of tower cranes in order that their behaviour and properties can be embodied into the model.

The appropriate standards and codes of practice govern the design of tower cranes and these are enumerated. Reference is also made to the relevant regulations concerning crane usage and a brief discourse on the safe use of cranes is included. There are a variety of types of tower crane available; these are briefly discussed, so that their pertinent features may be appreciated, and attention may then be focused on the precise crane type discussed in this thesis.

The function of a crane is to lift and move materials from one point to another. Usually these points will be located within the construction site boundaries, although this is not necessarily the case. However, for the purposes of the model, lifting can only occur within the boundaries defined by the user, though these boundaries may not correspond exactly with the physical boundaries of the site. Therefore, this chapter also examines the derivation of lifting capacity of tower cranes and the factors which influence this capacity.

Formulae are derived which enable the lifting capacity at any radius to be calculated, and the load predicted by these equations are compared with the loads provided by the crane manufacturers. The data required by the model, discussed in Chapter 5, are enumerated.

Finally, an initial check on crane lifting capacity is discussed. It is a fundamental requirement that a crane is located so that it can reach every facility it is intended to serve and that it can lift the maximum load required at each facility. Such requirements have implications both in respect of crane location and crane capacity.

4.2 Tower crane standards, codes of practice, regulations and safe use

A standard may be defined as "*an established or accepted model*" and a code of practice as "*an established method or set of rules for dealing with a particular situation*" (Davidson *et. al.* 1985). However, a regulation may be defined as "*a rule or order prescribed*" (Davidson *et. al.* 1985). Therefore, while it is the appropriate standards and codes of practice which formalize the accepted and proper way of executing a task it is the regulations, which embody the concept of a law expressly enacted by legislation, which impose a requirement of correct and proper behaviour upon the parties concerned. Further to this, time and experience have produced additional informal precepts and guidelines concerning the safe use of cranes, which, while not incorporated informally into the regulations, should be adopted by responsible organizations.

4.2.1 Standards and codes of practice

National engineering standards and codes of practice for tower cranes have been developed in most leading countries. Naturally, there are some discrepancies between these standards and what may be acceptable in one country may be unacceptable in another. In the United Kingdom, British Standards (BS) and Codes of Practice (CP) are those normally adopted. However, there is an increasing use of standards prepared by the International Organisation for Standardisation and adopted as British Standards (BS ISO).

Under the heading of "Tower cranes", The BSI Standards Catalogue (British Standards Institution 1999) refers to two standards and codes of practice relevant to tower cranes; under the heading "Cranes" a further thirteen standards are listed. Seven of these standards and codes of practice may currently be considered to have direct relevance to tower cranes, namely:

BS 3810: Glossary of terms used in materials handling.

BS 3810: Part 4: 1968: Terms used in connection with cranes.

While this standard provides only limited definitions in respect of tower cranes, it nevertheless provides a useful definition of a tower crane (see section 4.3).

Code of Practice CP 3010: 1972.

Code of practice for safe use of cranes (mobile cranes, tower cranes and derrick cranes).

This code of practice gives guidance concerning the safe use of tower cranes and makes recommendations for testing, maintenance, erection and dismantling procedures and siting of cranes. During the review of CP 3010 it was decided that it was essential to broaden the scope to recognize the need for planning the operation and for the adoption of safe systems of work as these are the foundation stones upon which the successful operation should be built. BS 5171 partially replaces BS 5744: 1979 (concerned with the safe use of cranes but excluding tower cranes) and CP 3010: 1972. BS 7121: Part 5: Tower Cranes was published in 1997 (Cranes UK 1997b).

BS 2799: 1974 (obsolescent): Specification for power-driven tower cranes for building and engineering construction.

The emphasis of this code in on the structural, mechanical, electrical and hydraulic specifications of cranes. The code also describes a range of tests to be carried out and, while it is assumed that these are correctly and regularly executed, the code has little direct application to the model described in this thesis.

BS 2573: Rules for the design of cranes.

BS 2573: Part 1: 1983: Specification for classification, stress calculations and design criteria for structures.

BS 2573: Part 2: 1980: Specification for classification, stress calculations and design for mechanisms.

This standard is concerned with the number of movements and type of loads a crane is expected to move during its life; relevant aspects are discussed in more detail in section 4.4.

BS 7121: Code of practice for safe use of cranes.

BS 7121: Part 1: 1989: General.

BS 7121: Part 2: 1991: Inspection, testing and examination.

BS 7121: Part 5: 1997: Tower cranes.

Part 5 of the code makes reference to Parts 1 and 2 and encompasses many issues relating to the safe use of tower cranes including management and planning of the lifting operation, selection and duties of personnel, selection and siting of cranes, erecting and dismantling, operating conditions and testing and examination. Further discussion on the safe use of cranes is given in section 4.2.3.

BS 7262: 1990: Specification for automatic load indicators.

This standard specifies the constructional and testing requirements of automatic safe load indicators. These devices often work in conjunction with other devices to prevent further motion of the crane after the point has been reached when overload occurs. Further discussion concerning safe load indicators in given in the following section.

BS ISO 12478: Cranes. Maintenance manual

BS ISO 12478: Part 1: 1998. General.

This standard establishes guidelines on the general requirements necessary for the preparation and presentation of maintenance manuals for cranes. Part 3: Tower cranes has yet to be published.

The only aspect of the design of cranes, which is relevant to this thesis, is the determination of load lifting capacity. This is discussed in section 4.4. where reference is made to the appropriate standards. The standards also provide definitions and guidance concerning safe use; reference is made to these standards as and when appropriate.

4.2.2 Regulations

CP 3010: 1972: Code of practice for safe use of cranes (mobile cranes, tower cranes and derrick cranes) lists seventeen statutory regulations relating to cranes. BS 7121: Code of Practice for Safe Use of Cranes: Part 1: 1989 refers specifically to the Health and Safety at Work Act 1974 and also provides an enhanced and updated list of thirty-two relevant statutory regulations. These regulations are both wide-ranging and comprehensive and relate to matters beyond the scope of this thesis. The Health and Safety at Work Act imposes duties on employers to ensure, so far as is reasonably practicable, the health and safety at work of all employees and that undertakings are conducted in such a way as to ensure that employees are not exposed to risks. However, the Act does not incorporate any specific clauses appertaining to tower cranes. The Construction Regulations Handbook (Royal Society for the Prevention of Accidents 1975) summarizes the relevant clauses in the statutory regulations, which appertain to the operation of cranes. The most influential and relevant legislation concerning the use of cranes on construction sites, and cited in both CP 3010 and BS 7121, is still The Construction (Lifting Operations) Regulations 1961 (1961). However, the majority of the legislation is of little relevance to this thesis. The clauses which are pertinent are listed in Appendix B.

The regulations recognize that, for a crane operating on site, the load lifting capacity is not likely to be governed by the structural capacity of the crane, but by the anchoring and ballasting arrangements; if these are in accordance with the manufacturer's guidelines and recommendations then the stipulated safe working loads can be assumed to apply. The model presumes that the safe working loads (calculated according to formulae given in 4.4.1) are valid and will not allow the user to proceed when these values are exceeded.

Wind loading is an important consideration in the determination of load lifting capacity (refer to 4.4) and there is an upper wind speed limit for safe working. Beyond this limit the design assumes that the crane will be "out of service". Under these circumstances the load should be removed from the hook, the hook itself raised to the highest working position at a radius close to the tower and the power switched off. The jib should be left in free slew on the leeward side of the tower (Building Employers Confederation 1996).

These precautions have implications for the determination of total movement of the crane hook, but have been disregarded in the analysis, which follows.

The regulations state that an indicator clearly visible to the driver must be provided which shows the operating radius and corresponding safe working load. This may take a variety of forms. For example on a saddle jib tower crane (see section 4.3.2) a series of metal flags may be fitted at various points along the jib which display the safe working load and radius of operation. In order to prevent the safe working load being exceeded an automatic safe load indicator must be fitted. Such indicators may be mechanical or electronic and are required to give visual warning to the driver as the safe working load (SWL) is approached and an audible warning to those in the vicinity of the crane of an overload state. The precise points at which these devices operate vary but, correctly set, the driver receives his visual warning at between 90% and 97.5% SWL and the audible warning is given at 102.5% to 110% SWL (Building Employers Confederation 1996). Some devices also incorporate a cut out which prevents further movement of the load.

Crane manufacturers provide data concerning the safe working loads at given radii. In terms of selecting an appropriate crane for a particular job the most economical choice is one which is lifting at or near its maximum capacity. The model developed in this thesis assumes that the safe working load is never exceeded. An initial check on crane lifting capacity is discussed in section 4.6.

The model is concerned with distance travelled by the crane hook and it is assumed that time has a relationship with distance, which is a function of the horizontal, radial and vertical components of movement involved. Disruption to movement of the crane hook due to a requirement in the Construction (Lifting Operations) Regulations (clause 32(1)) such that when the crane is lifting a "*load which is equal to or slightly less than the relevant safe working load and which is not already wholly sustained by the appliance*" that "*the lifting should be halted after the load has been raised a short distance and before the operation is proceeded with.*" has been disregarded as the crane will mostly be operating at significantly less than capacity.

4.2.3 Safe use of tower cranes

Unless otherwise stated, the discussion in this section is based on CP 3010: 1972: Code of practice for safe use of cranes (mobile cranes, tower cranes and derrick cranes) and BS 7121: Code of practice for safe use of cranes: Part 5: 1997: Tower cranes.

The tower crane is designed as a high speed crane, required to lift loads accurately and quickly. This may produce a conflict between the demands of safe working practice and high productivity. Often such cranes are located on congested city centre sites where members of the public pass near to, or within, the radius of operation; in such cases safe working practice is of paramount importance. The danger posed by the use of cranes was highlighted by a survey which showed that, between 1984 and 1994 , there were 502 crane-related fatalities in the United States of America (Thomsen 1998). This amounts to nearly one person per week being killed, although it is appreciated that not all of these incidents are connected with tower cranes. The most common cause of death is electrocution (39%), with crane assembly and dismantling, boom and rigging failure and crane over-turning being other significant causes of death.

Erection and dismantling of cranes should only be carried out in daylight, and should be carried out strictly in accordance with the manufacturers' instructions (Health and Safety Executive 1989). A plan of the procedure to be adopted should be drawn up and a crane erection supervisor appointed to be responsible for such activities.

In siting a crane for operation, particular attention should be given to the crane's support conditions and the presence of proximity hazards. In the first case the ground on which the crane is standing must have adequate bearing capacity, the crane must not be positioned where there is a danger of flooding and tracks, for rail-mounted cranes, should be firm and level. Consideration must be given to the proximity of power cables (for which precise guidelines are provided), other cranes, structures and buildings. This is discussed in more detail in the next chapter which considers the interaction of the crane and the construction site on which it is located. The model described in this thesis assumes that the crane foundation is adequate and that movement of the crane's jib is not impeded by any hazards within close proximity.

Testing procedures are required to be carried out when a crane is first erected and at intervals thereafter, ranging from regular weekly inspections to thorough examinations and tests at 14 monthly intervals. Before commencing work the crane driver should be satisfied that test and examination certificates are current and that the weekly inspection register is up to date. All controls and indicators must function correctly. The cab should be uncluttered and visibility not impaired by dirty windows. There are no statutory regulations restricting working hours but all personnel involved in lifting operations should have opportunity for sufficient rest. Signalling and communication systems should be well practised. Load placing accuracy is enhanced if the driver is in telecommunication with an experienced banksman at ground level. Where visual signals are used those recommended by the Building Employers Confederation and Federation of Civil Engineering Contractors should be adopted.

Safe load placing depends greatly upon the driver's ability to correct, and, if necessary, reverse unsafe movements. This ability is enhanced by placing the cabin in such a position that the driver is high up with an unobstructed view of the load path. Ergonomic studies have recently suggested that the positioning of the driver's cabin slightly to the side improves observation, and therefore accuracy; the geometry of the crane provides one frame of reference while the view of the driver provides another. A further psychological advantage is that the driver does not feel that he is directly in the load path. In contrast, attempts to locate cabins far out on the jib have proved to be unsuccessful (Weinreich, 1989).

Some cranes incorporate cut out devices (see previous section) but the sudden activation of such a device can also be dangerous. Ideally the load should be slowed down smoothly, even in a potentially dangerous situation. Loads should be lifted gently from the ground, not snatched, and moved quickly to their destination, which should be approached at an easily manageable speed. While smooth handling and safe load placing depend largely upon the skill of the operator, sophisticated devices such as eddy-current brakes and semi-stepless or stepless hydraulic drives can all assist in safe working practice.

While lifting and lowering present few problems, excessively fast slewing, traversing and, where appropriate, travelling, all create horizontal inertia in the load, which can quickly lead to loss of load control. Other situations can also present safety hazards. For example, cranes are designed to lift loads, not drag them, and dragging loads sideways is a particularly hazardous manoeuvre. Attempting to snatch free loads, which are stuck, should be avoided. Loads should only be moved when authorized by the banksman. The driver should not begin any slewing movements until the swing path is unobstructed by personnel or material. Initially loads should only be lifted a short way to enable an assessment to made that the load is properly slung.

Multiple tower cranes on site can present a problem if they are working in close proximity. In such circumstances a crane coordinator should be appointed. Eight tower cranes, working in overlapping zones, have been successfully used in construction work at Copenhagen airport (Cranes Today 1998a). Such circumstances require that strict rules regarding priority of movement and communications between crane operators must be established. However, in respect of this thesis, it is only concerned with the location of a single tower crane within a construction site.

The model is primarily concerned with the distance moved by the crane hook and the time associated with this movement. The model does not attempt to embody the concept of safe working practice into its philosophy. For the sake of simplicity two features of safe working practice discussed above are disregarded in the model. Firstly, no allowance is made for any reduction in speed of the crane at the beginning or end of the lifting operation. The precise way in which distance and time are correlated, taking due account of overlapping movement, is discussed more fully in the next chapter. Secondly, continuous operation is assumed, and therefore the practice of removing the load from the hook and raising the hook to the highest working position during out of service periods is also disregarded. However, it is not expected that this omission will influence the optimum crane location.

4.3 Types of tower crane

BS 3810: Part 4: 1968 "Glossary of terms used in Material Handling" defines a tower crane as:

> *"A crane normally used for temporary site application, consisting of a fixed or mobile tower, supporting a horizontal jib, which may or may not slew with the tower, with traverse trolley or luffing jib. The tower may be adapted as a self-climbing frame."*

Further to this CP 3010: 1972: "Code of Practice for the Safe Use of Cranes" describes tower cranes as having a vertical tower, designed to be free-standing up to a specified height. The International Organization for Standardization, under the auspices of committee ISO TC 96 SC 7, has developed the following definition of a tower crane:

> *"A slewing jib type crane with jib located at the top of a vertical tower.... This power-driven appliance shall be equipped with a means for raising and lowering suspended loads and for movement of such loads by changing the load-lifting radius, slewing or travelling of the complete appliance. Certain appliances may comply with only one or several of these movements. The appliance may be installed in a fixed position or equipped with means for travel and/or climbing."*

Tower cranes may be static or mobile and are available in a wide variety of types and configurations according to the particular combination of tower, jib and base, which they employ. CP 3010: 1972: "Code of Practice for Safe Use of Cranes" and BS 7121: Part 5: 1997 : "Safe use of cranes: Tower cranes" both provide classifications of tower cranes, which share some common ground, but which are not absolutely identical. The following classification is based on CP 3010: 1972, unless otherwise stated.

4.3.1 Types of tower

Tower cranes may have either fixed or slewing towers. With the former, the slewing ring, that part of the crane which allows the crane to rotate, is situated at, or near, the top of the tower and so the tower remains stationary during the slewing motion. Cranes with a slewing tower have their slewing ring located at the bottom of the tower, and so the whole of the tower and jib assembly rotates when any slewing motion occurs.

Towers may be further divided into three principal types - mono towers, inner and outer towers and telescopic towers.

Mono	-	the jib is carried by a single tower structure
Inner and outer	-	the jib is carried by an inner tower, which is supported at the top of an outer tower.
Telescopic	-	the jib is carried by two or more main sections, which nest into each other.

Mono and inner and outer towers may have a fixed or slewing base and provision may be made for the tower to be extended at an appropriate juncture in the construction programme. Telescopic towers are usually of the slewing type and by their nature may be extended without the need for partial dismantling.

While tower cranes are designed to be freestanding, above heights of approximately 100 metres provision must be made for some form of tying to the structure under construction. The purpose of such bracing is to prevent horizontal movement, and this is most efficiently achieved by the use of a lattice frame incorporating diagonal bracing. In this way tower cranes may be extended up to 200 metres. In order that the bracing may be adequately fixed, cranes requiring bracing will need to be located near to or within the structure. The bracing may only be fixed after the structure has reached a certain height, so provision will need to be made for the tower, regardless of type, to be extended as and when necessary.

With respect to the type of crane to be incorporated into the model, whether the tower is fixed or slewing is of no consequence: the model quantifies radial movement of the jib, which will occur in either case. Any difference in the radial velocity, due to the different type of movement, will be assimilated in the model.

The tower type is also inconsequential, except in so much as the model assumes a constant height of operation (excluding luffing jib cranes, which are to be discussed). For a constant height of operation a mono tower is the obvious choice of tower, as other types will incur additional costs for no benefit.

In theory, whether the tower crane is freestanding or tied the structure is of no importance in the model. However, if a crane is of such a height that tying in to the structure is required, this implies that the height of the crane must be increased during the construction phase, at a time when the structure has reached an appropriate height. This is incompatible with a constant height of operation, which the model assumes. Further, the use of a tied-in crane restricts the position of the crane, which must be located within the structure, or adjacent to it.

4.3.2 Types of jib

CP 3010: 1972 recognizes four main types of jibs used on tower cranes - saddle jib, luffing jib, fixed radius jib and rear-pivoted luffing jib.

Saddle - the jib is horizontal and held in position by jib ties. The hook is suspended from a saddle (or trolley) and movement of the saddle along the jib alters the radius of the hook.

Luffing- the jib is pivoted at the jib foot, which is located at the top of tower and to the front of its centre line. The jib is supported by a rope passing over a pulley at the jib head, which is anchored to kentledge (or ballast or counterweight) at the base of the crane.

Changing the angle of inclination of the jib alters the radius of the hook.

Fixed radius - the jib is mounted on pivots at the jib foot but held in position by jib ties at a fixed angle of inclination. In this case the radius of the jib cannot be altered, but there are other types which incorporate a saddle (or trolley) and so behave in a similar manner to a saddle jib.

Rear-pivoted luffing - the jib is pivoted at the jib foot, which in this case, is at the top of the tower, but behind the centre line of the tower. Such an arrangement usually necessitates the use of hydraulic rams to luff the jib and so alter the radius.

BS 7121: Part 5: 1997 also recognizes four jib types – horizontal trolley jib, inclined trolley jib, luffing jib and fixed radius jib. The horizontal trolley jib is synonymous with the saddle jib and so three jib types are common to both standards. The inclined trolley jib is similar to the horizontal trolley jib (saddle jib) except that the jib may be set at a significant angle of inclination, but the radius of operation is altered by trolleying and not by luffing.

In addition to these main jib types, there are several hybrid varieties. A further jib type, a jack-knife jib, has been identified by Harris (1994). This type of jib comprises two jibs, of approximately equal length, which pivot at their connection, in addition to the pivot at the jib foot. Cranes with this jib configuration are able to work in extremely tight quarters. Two luffing jib cranes with moving counterweights slung under, rather than above, the crane body, were used in the redevelopment of the Royal Opera House in London (Cranes UK 1997a). The advantage of the moving counterweight is that it creates a well balanced crane at all working configurations, whilst placing the counterweight below the body of the crane keeps the upper works of the crane uncluttered. A relatively recent but increasingly popular jib configuration is the flat top cantilever jib tower (Cranes Today 1998c, Dahm 1998). Proponents of these jibs claim that the benefits include ease of erection, enhanced stability and greater opportunity for multi-crane working, as jibs can oversail each other more easily.

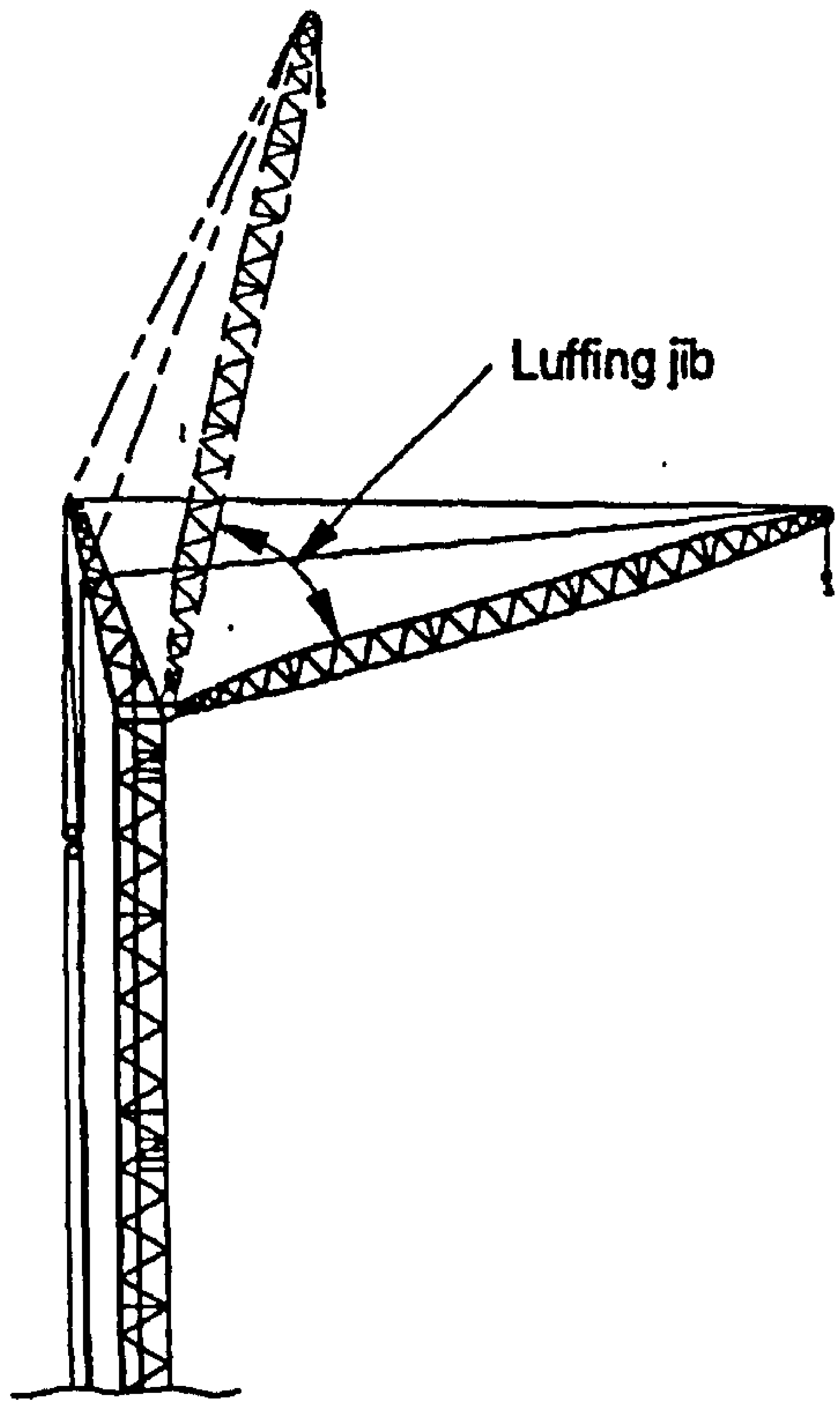
It can be appreciated that a change in radius may only be effected by trolleying (i.e. moving the saddle along the jib) or luffing (i.e. changing the angle of inclination of the jib). With respect to the type of jib to be incorporated into the model it is therefore essential to consider both saddle and luffing jibs, as their behaviour (i.e. the way in which the radius is altered) is different, and this will effect the determination of load lifting capacity. Of the other jib types it can be appreciated that a fixed radius jib is of little practical value on a construction site. Where a fixed radius jib incorporates a saddle to effect a change in radius its behaviour is synonymous with that of a saddle jib. Rear-pivoted luffing jibs and jack-knife jibs both behave in a similar manner to a luffing jib, in that in both cases the jib must be luffed in order to change the radius. The fundamental difference between the luffing jib and rear- pivoted luffing jib is the point at which the jib luffs in relation to the centre-line of the tower. Therefore, in the following analysis, the saddle jib is discussed separately from the luffing jib.

Figure 4.1 illustrates the saddle and luffing jibs. A further type of saddle jib, generally associated with self-erecting tower cranes, can be identified. In this case the counter jib is removed and the required counterbalance is provided by kentledge at the base. Nevertheless the determination of load lifting capacity is based on identical principles to those associated with a saddle jib.

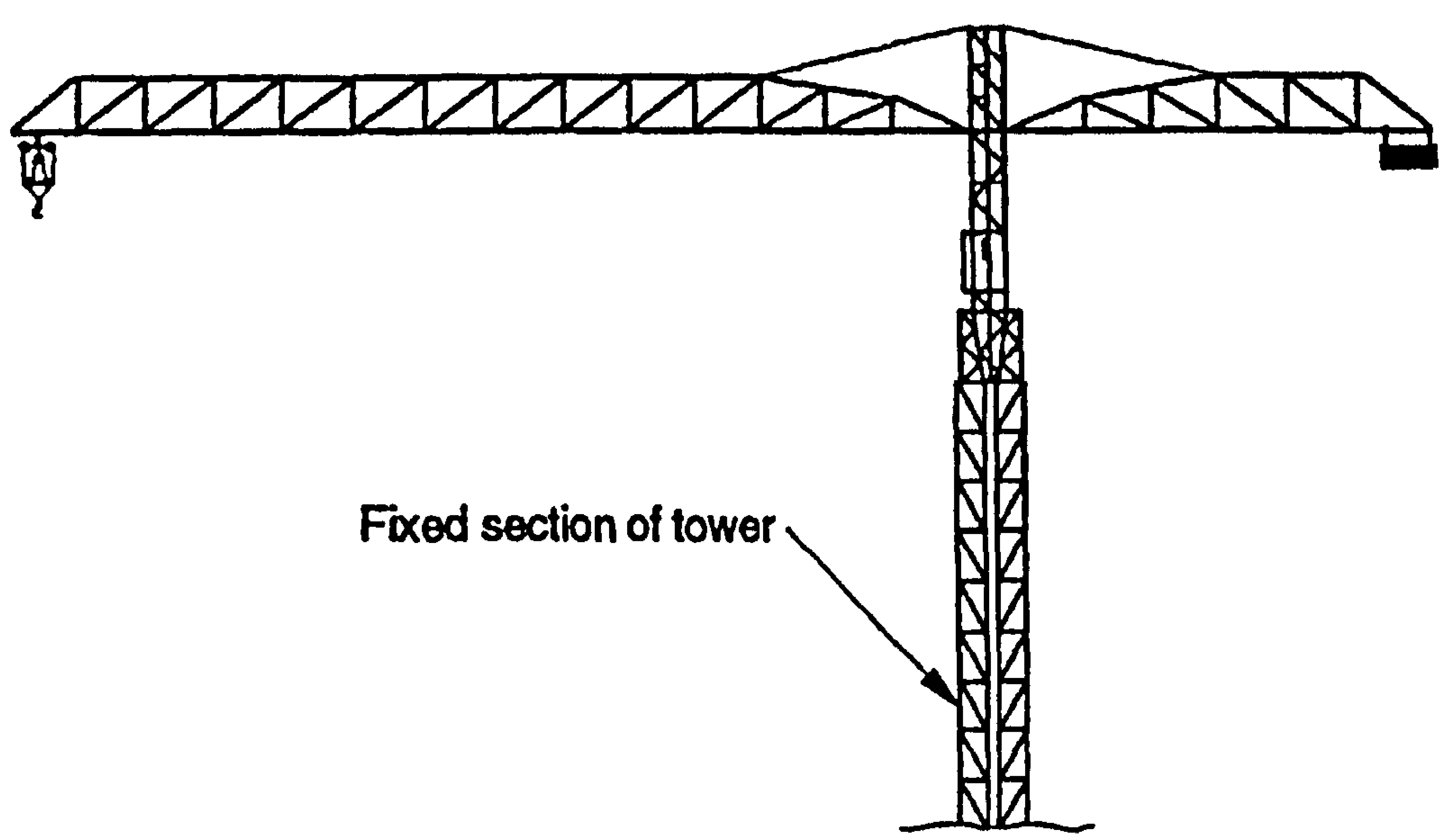
4.3.3 Types of base

Bases may be either static or moving. A moving tower crane may be either truck, wheel or crawler mounted, in which case total freedom of movement, within the confines imposed by type and slope of the terrain, is possible, or, rail-mounted, in which case movement is limited by the extent of the track. Moving bases are outside the scope of this thesis.

Static bases may be divided into three further types - in-situ base, on own base and climbing crane.



b) Luffing jib



a) Saddle (horizontal) jib

Figure 4.1 **Tower crane jibs**
Saddle jib and luffing jib
Source: BS 7121: Part 5: 1997

In-situ - the crane is mounted onto a frame cast into a concrete foundation block, which usually remains after the crane has been dismantled.

On own base - the crane is mounted onto a chassis, which in turn stands on a concrete base. The base may or may not be held in position by means of holding-down devices.

Climbing crane - the crane is supported by the structure to which it is attached by a frame. As the height of the structure increases the crane usually climbs, using winches or hydraulic jacks.

With regard to the model the type of base is unimportant. However, as a constant height of operation is assumed a climbing crane will be outside the scope of the model.

4.3.4 Summary

In summary, the type of crane considered by the model may have a fixed or slewing tower which will generally be of the mono type. Saddle jib and luffing jib cranes are considered separately as determination of load lifting capacity is different in both cases. The base may be in-situ or the crane may have its own base. A constant height of operation is assumed.

In addition to the tower crane configurations described above, BS 7121: Part 5: 1997 also recognizes climbing tower cranes, tower cranes mounted on rails, lorries, wheels and crawler bases and micro tower cranes. These are all considered to be outside the scope of this thesis, as a fixed point of operation and constant height are assumed.

4.4 Crane lifting capacity

Consideration of the design of tower cranes is outside the scope of this dissertation. However, the determination of load lifting capacity at a given radius is a fundamental requirement of the model.

A tower crane rests on its foundation, which for the purposes of the model, is assumed to be static. At the point of contact the crane is subject to four basic forces and moments:

i) vertical forces;
ii) horizontal forces;
iii) moments that result from the slewing action of the crane; and
iv) overturning moments that result from both the load (including the self-weight) and the wind force.

Beaufort 8 (20m/s or 45 miles/hour) is the normal upper limit of cargo handling with a tower crane (Weinreich 1989). Although not in operation, the crane will be subject to wind loads in excess of this and the crane design should be adapted to prevailing local wind speed conditions.

For the crane to be stable in operation, each of these forces or moments, listed above, must be balanced by an equal reactive force or moment. The ability of the crane to resist such forces is a function of the bearing force and weld-strength of the steel infrastructure and the soil conditions and load-bearing capacity of the foundation. In addition, the expected life of the crane and the possibility of tilting the crane during erection must also be considered.

In his 1957 lecture to the Liverpool Branch of the Engineer Surveyors' Association concerning tower cranes, Meyer (1957) stated that one of the most critical points concerning the safety of tower cranes was stability, and that the only correct definition of stability, in his opinion, was contained within the relevant German code of practice, which defined stability as:-

"... *the sum of the righting moments divided by the sum of all overturning moments, all moments based on the tipping fulcrum.*"

According to this definition, stability assumes a value greater than or equal to unity for different combinations of loading and the controlling of stability in this way has a direct bearing on the crane lifting capacity.

The current British Standards and Codes of Practice attempt to establish a frame of reference for tower cranes, enabling fast and repeated multi-lifts to be achieved over a long life span, taking due account of the dismantling and reassembly which will inevitably occur.

BS2573: 1983: Rules for the design of cranes: Part 1: "Specification for classification, stress calculations and design criteria for structures" gives eight group classifications, which depend upon class of utilization and maximum number of operation cycles of the crane and the state of loading. For tower cranes in general use on building sites, the specified class of utilization is described as ranging from "*infrequent use*" to "*fairly frequent use*" with a maximum number of operating cycles between 63,000 and 250,000. An operating cycle is assumed to commence when a load is picked up and end at the moment when the crane is ready to pick up the next load. The model assumes that there is no restriction on the number of movements which may occur, but the range specified provides an interesting comparison with those which typically occur on any one contract. The state of loading is described as either "*light*", where the crane moves the safe working load very rarely and normally moves light loads only, or "*moderate*", where the crane moves the safe working load fairly frequently and normally moves moderate loads. While this confirms that a typical tower crane on a construction site has more than adequate capacity, and indeed normally works well below capacity, this factor has no influence on the model.

Various load combinations are considered; the crane must be capable of resisting the combination which results in the maximum stress. The load combinations considered include "*crane in use with in-service wind*", "*crane in out-of-service condition*" and "*crane being erected or dismantled*" and the loads which constitute these combinations include dead loads, live loads including the hook load, skew loads due to travelling and load due to the service wind acting horizontally in any applicable direction.

BS2573: 1980: Rules for the design of cranes: Part 2: "Mechanisms" considers the service life (hours in motion) of mechanisms or components. Hoisting, traversing, luffing, slewing and travelling are considered and classified separately according to class of utilization and state of loading. For tower cranes for normal duty use on building sites, the class of utilization is defined as "*irregular use*" with 1600 service life hours. State of loading is defined as either "*light*", "*moderate*" or "*heavy*" where mechanisms are subjected to loads varying from very light to those of medium magnitude. Again, this has little direct relevance to the model as it is assumed that the crane is working under perfect conditions.

4.4.1 Formulae for load lifting capacity

For a given type of tower crane, produced by an individual manufacturer, the load lifting capacity varies according to the radius of lifting, the length of jib and the type of trolley, block and hook arrangement.

Generally the larger the radius the less the load lifting capacity, although there is a range of radii, near to the tower, and sometimes known as the heavy load range, where load lifting capacity remains constant and does not decrease as the radius increases. This range is an artificial limit, resulting from considerations other than tipping, for example, volume of load near the tower and strength of components. Further, for a given type of tower crane there is generally a range of several maximum jib lengths available. As shorter jibs are lighter and therefore detract less from the ability of the crane to carry loads, load lifting capacity, at corresponding radii, is higher for jibs of shorter length. The arrangement of the trolley, block and hook is usually two or four falls (alternatively referred to as two or four fall reeving) although three falls is also available. This refers to the number of cables used to lower and raise the block and hook. Generally, four falls are used in conjunction with heavier loads. Some manufacturers produce trolleys, which can be changed from two to four falls instantaneously from the driver's cabin.

For each specific crane, with a specified jib length, the load lifting capacity may be represented by a load-radius chart (or duty chart) which shows the safe working load that the crane is allowed to carry, with respect to different radii, ranging from the minimum radius to the maximum radius (British Standard Institution: CP3010: 1972). A typical example of a load-radius chart is shown in Table 4.1 for a Liebherr 1250HC saddle jib tower crane for five jib lengths ranging from 40.0m to 80.8m.

This information may also be displayed graphically and a example is shown in Figure 4.2 for the 80.8m jib length only.

Table 4.1 **Capacity (kg) of a Liebherr 1250HC Saddle jib tower crane**
Source: Manufacturer's data sheet

Radius (m)	Length of jib (m)	40.0	51.5	63.3	75.0	80.8
	Maximum capacity (m/kg)	5.2 -36.4 40000	5.2 -32.9 40000	5.2 -30.2 40000	5.2t -27.3 40000	5.2 -26.7 40000
26.0		40000	40000	40000	40000	40000
28.0		40000	40000	40000	38920	37930
32.0		40000	40000	37560	33570	32700
36.0		40000	36210	32950	29400	28360
40.0		36000	32200	29260	26060	25360
44.0			28910	26230	23320	22690
48.0			26160	23710	21040	20460
51.5			24000	21730	19250	18710
52.0				21580	19110	18580
56.0				19750	17460	16960
60.0				18160	16020	15560
63.3				17000	14970	14530
64.0					14770	14330
68.0					13660	13250
72.0					12670	12280
75.0					12000	11630
76.0						11420
80.0						10650
80.8						10500

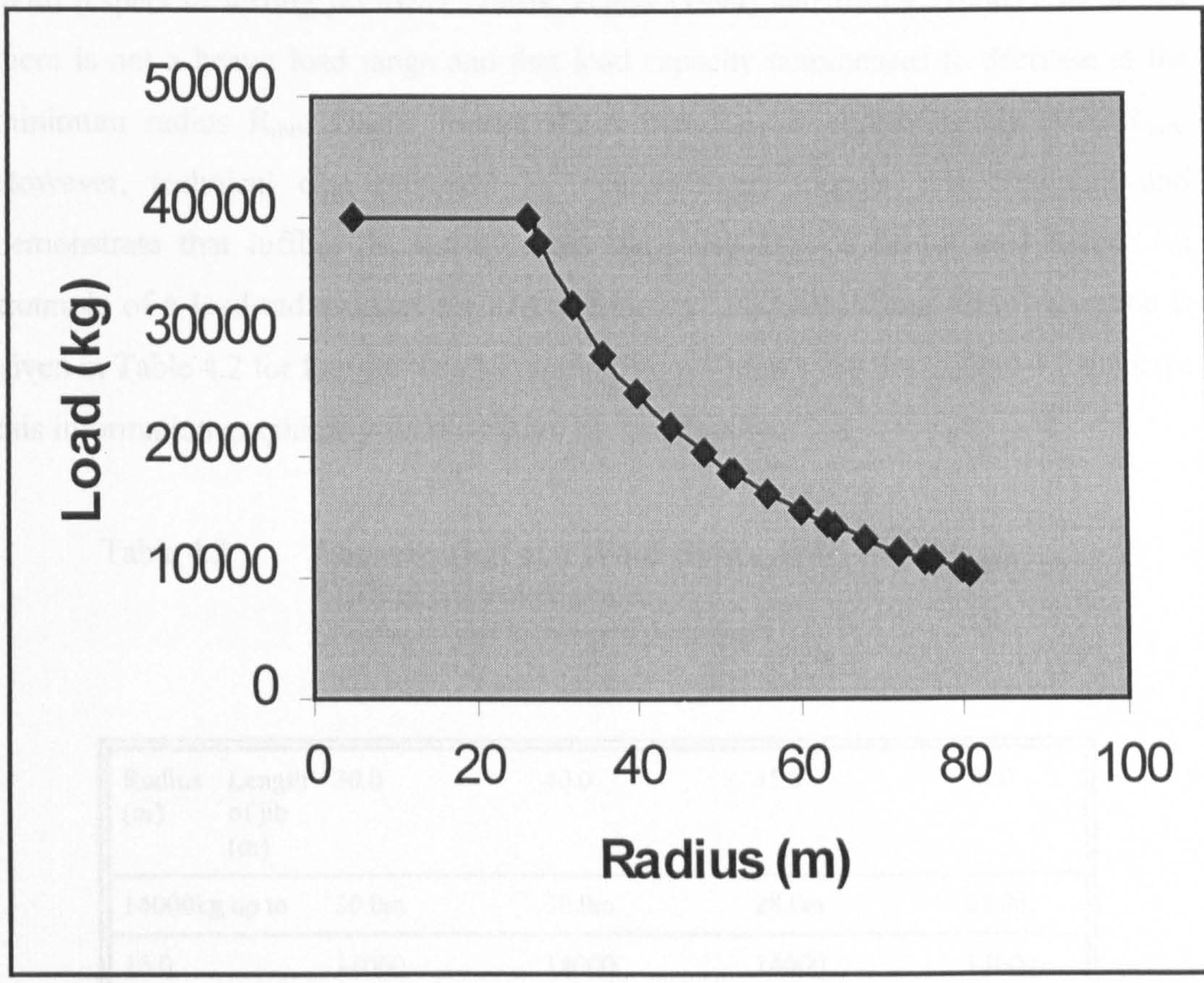


Figure 4.2 **Graphical illustration of load-radius characteristics Liebherr 1250HC saddle jib tower crane 80.8m jib length**

As previously mentioned, there is a range of radii, near to the tower, where load lifting capacity remains constant. This is clearly illustrated in Figure 4.2, which also shows that there is a minimum operating radius, which, in this example, occurs at 5.2m. Harris (1994) states that, for saddle jib cranes, the minimum operating radius, R_{min}, is limited to approximately 0.05 - 0.20 of the maximum radius, R_{max}, and that the radius at which load capacity commences to decrease, R_m, is approximately 0.25 - 0.40 R_{max}. This statement is valid for the 75.0 and 80.8m length jibs given in Table 4.1. but is invalid in respect of R_m for the remaining jib lengths where the heavy load range is extended. Nevertheless the general principle remains valid although the limits are only approximate.

With respect to luffing jib tower cranes, Harris (1994) and Butler (1966) concur that there is not a heavy load range and that load capacity commences to decrease at the minimum radius R_{min}. Harris further states that R_{min} is approximately 0.25 R_{max}. However, technical data provided by manufacturers dispute this argument and demonstrate that luffing jib tower cranes may also have a heavy load range. An example of a load-radius chart for a Wolff Hydro 320B-SP luffing jib tower crane is given in Table 4.2 for four jib lengths ranging from 30.0m to 50.0m. Figure 4.3 displays this information graphically for the 50.0m jib length only.

Table 4.2 **Capacity (kg) of a Wolff Hydro 320B-SP Luffing jib tower crane**
Source: Manufacturer's data sheet

Radius (m)	Length of jib (m)	30.0	40.0	45.0	50.0
14000kg up to		30.0m	30.0m	28.0m	27.0m
15.0		14000	14000	14000	14000
20.0		14000	14000	14000	14000
25.0		14000	14000	14000	14000
30.0		14000	14000	12870	12200
35.0			11700	10610	9800
40.0			10000	8920	8000
45.0				7600	6600
50.0					5500

Load-radius charts may be used to determine whether a specific crane can satisfy the load lifting requirements. However, data expressed in terms of a load-radius chart must be converted into mathematical symbols, prior to input into the optimization of crane location model. Ideally these symbols should be in the form of equations which enable the load capacity at any radius, within the operating range where load varies, to be calculated.

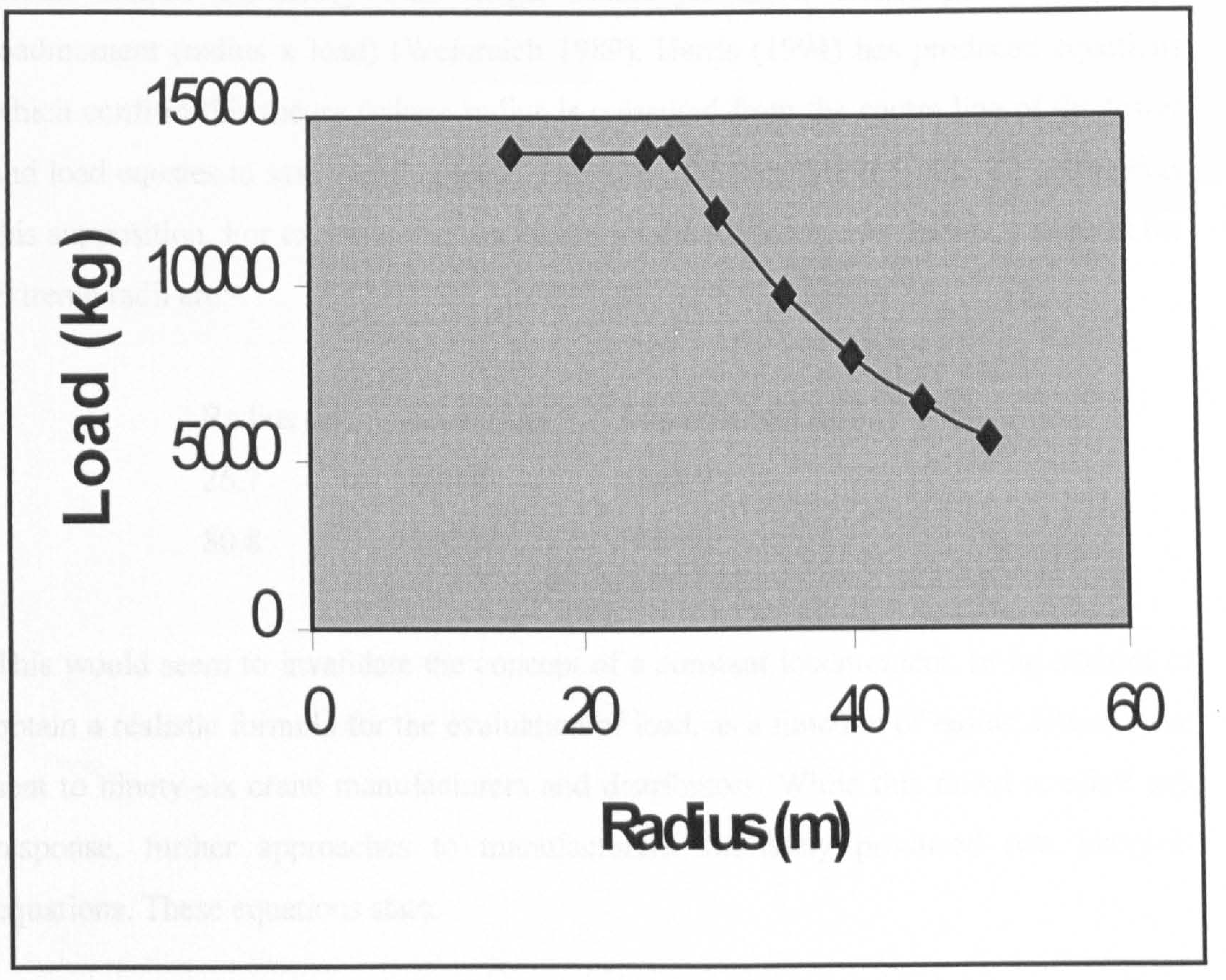


Figure 4.3 **Graphical illustration of load-radius characteristics Wolff Hydro 320B-SP luffing jib tower crane 50.0m jib length**

As discussed previously, the characteristics of saddle jib and luffing jib tower cranes are different. Therefore, formulae for these two types of jib will be considered separately.

<u>4.4.1.1 Saddle jib tower cranes</u>

Observation of the type of tower crane currently in use indicates that saddle jib tower cranes dominate, although more recently, luffing jibs have enjoyed and upsurge in popularity. The Cranes Today Handbook (Brent 1985) which lists 288 saddle jib tower cranes but only 58 luffing jib tower cranes also reflect this bias towards the use of saddle jib tower cranes. It may be concluded that tower cranes are predominantly of the saddle jib type. It would seem to be a commonly held belief that beyond the radius which defines the heavy load range, saddle jib tower cranes have a constant loadmoment (radius x load) (Weinreich 1989). Harris (1994) has produced equations which confirm this theory (where radius is measured from the centre line of the tower and load equates to safe working load). However, the data within Table 4.1 contradicts this supposition. For example, for the 80.8m jib the loadmoments (radius x load) at the extreme radii are:-

Radius (m)	Load (kg)	Loadmoment (tm)
26.7	40000	1068.0
80.8	10500	848.4

This would seem to invalidate the concept of a constant loadmoment. In an attempt to obtain a realistic formula for the evaluation of load, as a function of radius, letters were sent to ninety-six crane manufacturers and distributors. While this failed to elicit any response, further approaches to manufacturers ultimately produced two identical equations. These equations state:

$$M_o = (P + Q) \times (R - D) \quad .... \quad \textit{Equation 4.1}$$

where M_o = constant moment about O (mkg)

P = weight of the load at hook (kg)

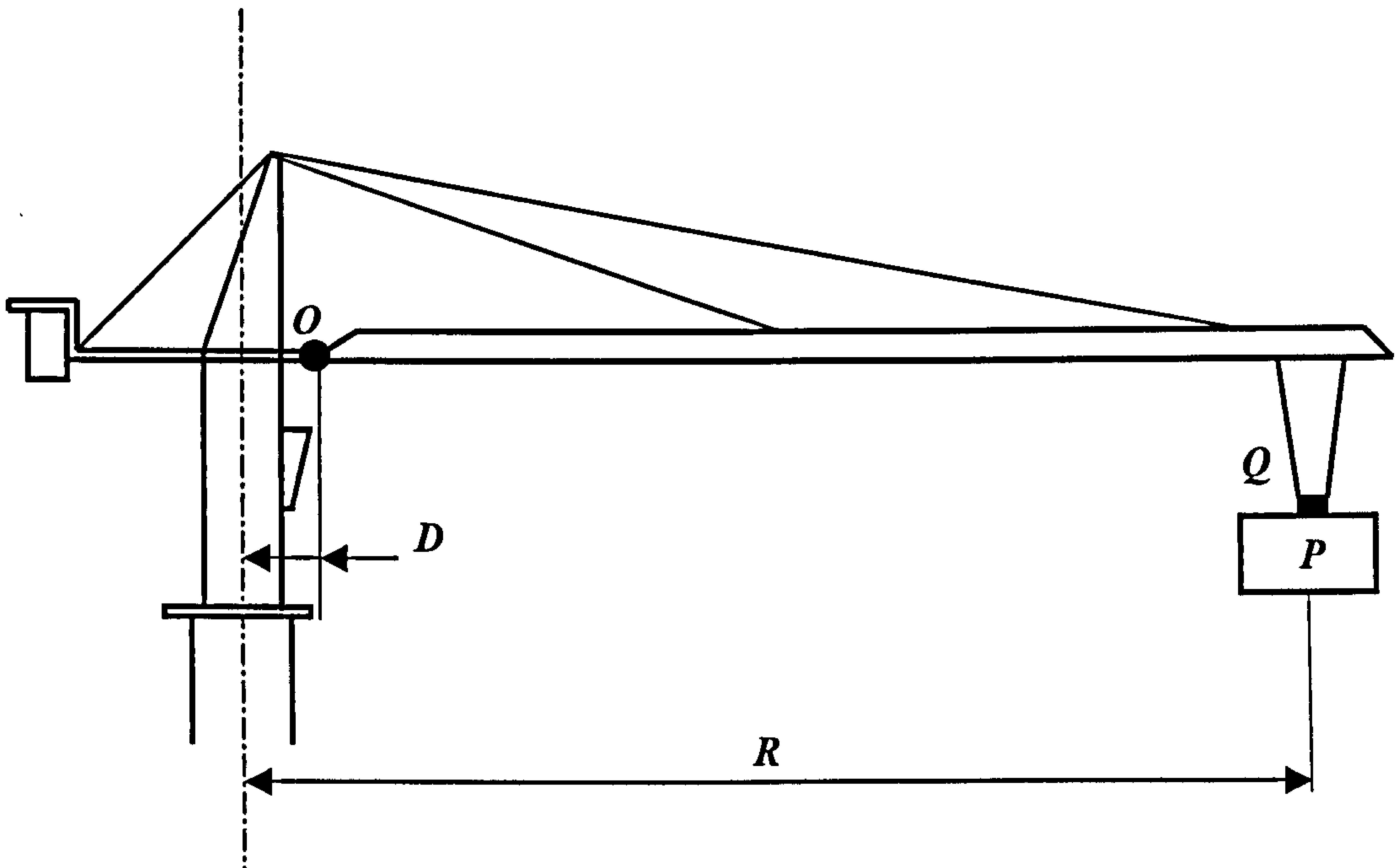
Q = weight of trolley, hook and ropes (kg)

R = radius about the centre line of the tower (m)

D = distance from O to the centre line of the tower (m)

O is the point of jib articulation. See Figure 4.4.

This equation confirms the concept of a constant loadmoment. However the following points should be noted:-



Constant moment M_o about O (the point of jib articulation)

$$= (P + Q) \times (R - D)$$

where:

P	=	weight of the load at the hook (kg)
Q	=	weight of the trolley, hook and ropes (kg)
R	=	the radius about the centre-line of the tower corresponding to P (m)
D	=	the distance from O to the centre-line of the tower (m)

Figure 4.4 **Constant loadmoment for a saddle jib tower crane**

i) within the calculation of loadmoment, the element of length $(R - D)$ is represented by the distance from the centre line of the tower to the load, commonly referred to as the radius (R), minus that distance from the centre line of the tower to the point of jib articulation (D).

ii) within the calculation of loadmoment, the element of weight $(P + Q)$ is represented by the weight of load at the hook (P) and the weight of trolley, hook and ropes (Q).

Equation 4.1 can therefore be used by the model to predict the load capacity at any radius. At a given radius R_n the corresponding load capacity load P_n is given by:

$$P_n = \frac{M_o}{R_n - D} - Q \quad .... \quad \textit{Equation 4.2}$$

The above equation contains three unknowns, M_o, D and Q. Therefore, three sets of data, $(P_1 R_1)$, $(P_2 R_2)$ and $(P_3 R_3)$ are required to enable values for these unknowns to be obtained and the load P_n, at radius R_n, to be predicted. This raises the issue of which three sets of data should be used for this purpose. As the equation is an attempt to predict load between a certain range of radii it would seem prudent to choose the first and last points of the load-radius curve i.e. P_{max} corresponding to R_m (the radius at which load capacity commences to decrease) and P_{min} corresponding to R_{max}. An additional intermediate data set is also required. However, random inspection of the results produced by selecting three such data sets shows that meaningless values of D and Q may arise in this way. For example D may be larger than the jib length and Q may assume a negative value. A possible explanation for this is that the values of radius and load capacity, which appear in the technical information, have been rounded up or down. However, although these values produce predicted loads reasonably close to the load capacity provided by the manufacturers, meaningless values of these variables are clearly nonsensical and therefore invalid.

An alternative solution is to input the value of either D or Q, in addition to the load and radius at the extreme points. Whilst neither of theses values is provided directly by the manufacturer in the normally available technical data sheets, inspection of these reveal that, in most cases, an evaluation of D, the distance from the centre line of the tower to the point of jib articulation, may be made. Therefore, by using two data sets, (P_1 R_1) and (P_2 R_2), and a value of D, Q may be solved as follows:

$$(P_1 + Q) \times (R_1 - D) = (P_2 + Q) \times (R_2 - D)$$
$$P_1R_1 + QR_1 - P_1D - QD = P_2R_2 + QR_2 - P_2D - QD$$
$$P_1(R_1 - D) + QR_1 = P_2(R_2 - D) + QR_2$$

$$Q = \frac{P_1(R_1 - D) - P_2(R_2 - D)}{(R_2 - R_1)} \quad .... \quad \textit{Equation 4.3}$$

Generally, the two data sets used correspond to the extreme points of the load-radius curve. In cases where there is no other evidence it will not be unreasonable to assume a value of D of 1.0m. Table 4.3 tabulates the predicted load for a BPR GT 217B2 saddle jib tower crane using values of D of 1.23m and 1.0m. The value of 1.23m has, in this particular instance, been provided directly by the manufacturer. The value of 1.0m is that value which has been inferred from the data sheet. In both cases a minimum radius of 12.9m, with a corresponding load capacity of 8000kg, and a maximum radius of 50.0m with a corresponding load capacity of 1400kg, have been used.

Examination of the data in Table 4.3 shows that small errors do occur, even when the value of D provided by the manufacturer is used. These may be explained by the rounding errors inherent in such data. Table 4.3 further indicates that the adoption of a value of D of 1.00m also produces relatively small errors, although this value has been estimated or inferred and it is not the precise value. Typically D is 2 - 5% of R and so its influence in the determination of loadmoment is low. Therefore deviations in the value of D do not unduly effect the outcome. Further evidence for this is given in Appendix C, which provides examples for four further makes of crane. In each case the value of D has been inferred from the technical data but the errors are of a small magnitude.

Table 4.3 **Predicted loads for D = 1.23m and D = 1.00m BPR GT 217B2 saddle jib tower crane**

MANUFACTURER'S DATA		PREDICTED DATA					
		D = 1.23m Q = 676.1kg M_o = 101249.7kgm			D = 1.00m Q = 717.0kg M_o = 103732.1kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error	Load (kg)	Error (kg)	%Error
12.9	8000.0	8000.0	0.0	0.00	8000.0	0.0	0.00
14.0	7250.0	7252.6	-2.6	-0.04	7262.4	-12.4	-0.17
16.0	6200.0	6179.0	21.0	0.34	6198.5	1.5	0.02
18.0	5350.0	5361.5	-11.5	-0.21	5384.9	-34.9	-0.65
20.0	4700.0	4718.2	-18.2	-0.39	4742.6	-42.6	-0.91
22.0	4200.0	4198.7	1.3	0.03	4222.6	-22.6	-0.54
24.0	3700.0	3693.8	6.2	0.17	3716.0	-16.0	-0.43
26.0	3400.0	3411.5	-11.5	-0.34	3432.3	-32.3	-0.95
28.0	3100.0	3106.1	-6.1	-0.20	3124.9	-24.9	-0.80
30.0	2850.0	2843.2	6.8	0.24	2860.0	-10.0	-0.35
32.0	2600.0	2614.5	-14.5	-0.56	2629.2	-29.2	-1.12
34.0	2400.0	2413.6	-13.6	-0.57	2426.4	-26.4	-1.10
36.0	2250.0	2235.9	14.1	0.63	2246.8	3.2	0.14
38.0	2100.0	2077.5	22.5	1.07	2086.6	13.4	0.64
40.0	1950.0	1935.5	14.5	0.74	1942.8	7.3	0.37
42.0	1800.0	1807.4	-7.4	-0.41	1813.1	-13.1	-0.73
44.0	1700.0	1691.2	8.8	0.52	1695.4	4.6	0.27
46.0	1600.0	1585.5	14.5	0.91	1588.2	11.8	0.74
48.0	1500.0	1488.5	11.2	0.75	1490.1	9.9	0.66
50.0	1400.0	1400.0	0.0	0.00	1400.0	0.0	0.00

Note:- i) Q is calculated from Equation 4.3

ii) M_o is calculated from Equation 4.1

iii) Predicted load is calculated from Equation 4.2

iv) Error = Load - Predicted Load

v) %Error = (Error/Load) x 100

To summarize, the load at any radius, within the variable load capacity range, may be predicted by using Equation 4.2. Firstly, an estimation of D, the distance from the centre line of the tower to the point of jib articulation, is required. This, in conjunction with the radius and load at the extremes of the range, may be used to estimate Q, the weight of the trolley, hook and ropes (Equation 4.3). Finally, the constant loadmoment may be calculated by using Equation 4.1. In order for the full load-radius characteristics to be defined, the minimum operating radius and the radius at which load capacity commences to decrease are also required.

4.4.1.2 Luffing jib tower cranes

As mentioned earlier, luffing jib tower cranes are not used as frequently as saddle jib tower cranes, but they have been included for the sake of completeness. As the operating characteristics are different from those of saddle jibs the question to be asked is whether the concept of a constant loadmoment still applies. Examination of the data for a Wolff Hydro 320B-SP luffing jib tower crane, tabulated in Table 4.2, for a 50.0m jib length, produces the following:

Radius (m)	Load (kg)	Loadmoment (tm)
27.0	14000	378.0
50.0	5500	275.0

However, as in the case of the saddle jib crane, while this would initially appear to invalidate the concept of constant loadmoment, no allowance has been made for the distance to the point of jib articulation (the point at which the jib slews) from the centre line of the tower or the weight of the hook and block. In the latter case this will be less significant than in the case of the saddle jib as there is no trolley.

Predicted loads from Equation 4.1 have been tabulated in Table 4.4 for a Wolff Hydro 320B-SP luffing jib tower crane with a 50.0m jib. In this particular case D assumes a value of 0.00m as the point at which the jib slews coincides with the centre line of the tower.

Table 4.4 **Predicted loads for D = 0.00m**
Wolff Hydro 320B-SP luffing jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		D = 0.00m Q = 4478.3kg M_o = 498913.0 kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
27.0	14000.0	14000.0	0.0	0.00
30.0	12200.0	12152.2	47.8	0.39
35.0	9800.0	9776.4	23.6	0.24
40.0	8000.0	7994.6	5.4	0.07
45.0	6600.0	6608.7	-8.7	-0.13
50.0	5500.0	5500.0	0.0	0.00

Note:- i) Q is calculated from Equation 4.3

ii) M_o is calculated from Equation 4.1

iii) Predicted load is calculated from Equation 4.2

iv) Error = Load - Predicted Load

v) %Error = (Error/Load) x 100

It can be seen that the errors given in the above table are small. However, Harris (1994) has found that the tipping load of a luffing jib crane, illustrated in Figure 4.5, may be calculated from the following principles.

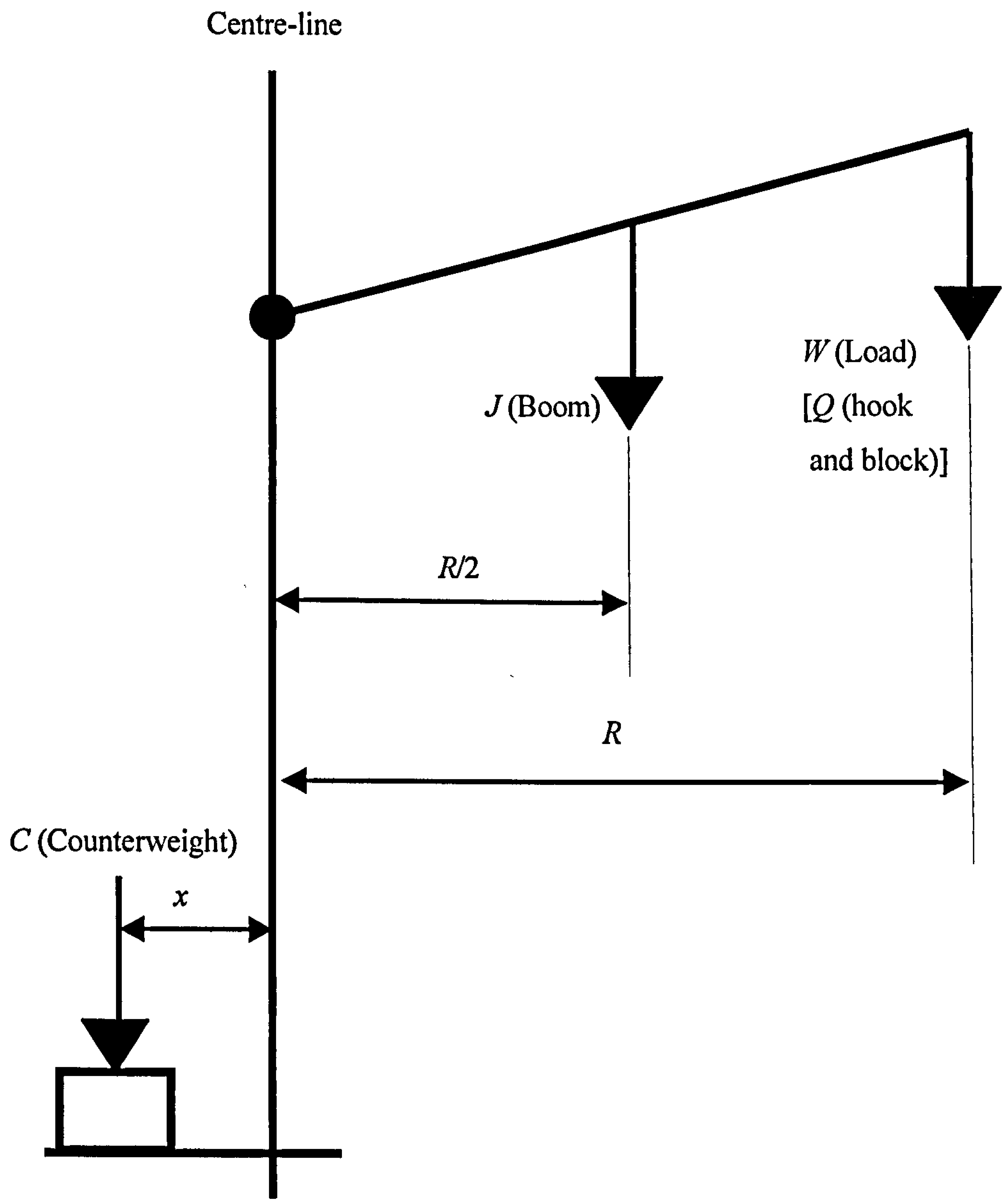


Figure 4.5 **Forces acting on a luffing jib tower crane**
Source: Harris (1994)

Taking moments about the centre of rotation

$$WR + J\frac{R}{2} = Cx$$

$$W = \frac{Cx}{R} - \frac{J}{2}$$

$$Safe\ working\ load\ P = W\ -\ safety\ margin$$

$$P = \frac{Cx}{R} - \frac{J}{2} - safety\ margin \quad .... \quad Equation\ 4.4$$

However, CP3010: 1972: "The Code of Practice for the Safe Use of Cranes" states that safety margins are applied as factors of safety. In this case the safe working load will be in direct proportion to the maximum applied load.

Equation 4.4 may therefore be re-written as:

$$P = \gamma(\frac{Cx}{R} - \frac{J}{2})$$

where γ = factor of safety

$$P = \gamma(\frac{Cx}{R}) - \gamma(\frac{J}{2})$$

It can be recognized that this formula expressing safe working load is, in its present form, inappropriate for inclusion in the model, as it contains constants, the values of which are unlikely to be known by the user.

The previous equation may alternatively expressed as:-

$$P = \frac{K_1}{R} - K_2 \quad .... \quad Equation\ 4.5$$

where K_1, K_2 = constant

A further enhancement to Equation 4.4, disregarded by Harris (1994), is the incorporation of the weight of the hook and block Q. If this is taken into consideration, then taking moments about the centre of rotation, in Figure 4.5:

$$WR + QR + J(\frac{R}{2}) = Cx$$

$$W = \frac{Cx}{R} - Q - \frac{J}{2}$$

$$P = \gamma(\frac{Cx}{R}) - \gamma(Q + \frac{J}{2})$$

$$P = \frac{K_1}{R} - K_2$$

The above equation is identical in form to Equation 4.5. However, with the inclusion of the weight of the hook and block Q, K_2 more properly represents (Q + (J/2)).

Considering Equation 4.5, the values of K_1 and K_2 may be solved when two data sets (P_1 R_1) and (P_2 R_2) are known. Substituting in known values of (P_1 R_1) and (P_2 R_2) into Equation 4.5:

$$P_1 = \frac{K_1}{R_1} - K_2$$

$$P_2 = \frac{K_1}{R_2} - K_2$$

To solve for K_1 subtract one equation from another:

$$P_1 - P_2 = \frac{K_1}{R_1} - \frac{K_1}{R_2} = \frac{K_1(R_2 - R_1)}{R_1 R_2}$$

Therefore:

$$K_1 = \frac{(P_1 - P_2)R_1 R_2}{R_2 - R_1} \quad .... \quad \text{Equation 4.6}$$

To solve for K_2 re-write the equations:

$$P_1 R_1 = K_1 - K_2 R_1$$

$$P_2 R_2 = K_1 - K_2 R_2$$

Subtract one equation from another:

$$P_1R_1 - P_2R_2 = K_2(R_2 - R_1)$$

Therefore:

$$K_2 = \frac{P_1R_1 - P_2R_2}{R_2 - R_1} \quad .... \quad \textit{Equation 4.7}$$

Substituting the values of K_1 and K_2 into the original equation:

$$P = \frac{(P_1 - P_2)R_1R_2}{(R_2 - R_1)R} - \frac{P_1R_1 - P_2R_2}{R_2 - R_1}$$

$$P = \frac{(P_1 - P_2)R_1R_2 + R(P_2R_2 - P_1R_1)}{(R_2 - R_1)R} \quad .... \quad \textit{Equation 4.8}$$

Generally, the two data sets used correspond to the extreme points of the load radius curve. Equations 4.6, 4.7 and 4.8 have been used to predict loads for a Wolff Hydro 320B-SP luffing jib tower crane with a 50.0m jib. These loads are tabulated in Table 4.5.

Inspection of the predicted loads produced in Tables 4.4 and 4.5 indicates that these loads, using the method embodied in Equations 4.1, 4.2 and 4.3, are identical to those using the method embodied in Equations 4.6, 4.7 and 4.8, when D = 0.00m. Further to this K_1 represents M_o and K_2 represents Q. This may be confirmed by substituting D = 0.00m into Equation 4.2, in which case the load capacity P_n, at a given radius R_n is given by:

$$P_n = \frac{M_o}{R_n} - Q$$

Table 4.5 **Predicted loads**
Wolff Hydro 320B-SP luffing jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		K_1 = 498913.0 K_2 = 4478.3		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
27.0	14000.0	14000.0	0.0	0.00
30.0	12200.0	12152.2	47.8	0.39
35.0	9800.0	9776.4	23.6	0.24
40.0	8000.0	7994.6	5.4	0.07
45.0	6600.0	6608.7	-8.7	-0.13
50.0	5500.0	5500.0	0.0	0.00

Note:- i) K_1 is calculated from Equation 4.6
ii) K_2 is calculated from Equation 4.7
iii) Predicted load is calculated from Equation 4.8
iv) Error = Load - Predicted Load
v) %Error = (Error/Load) x 100

which is identical in form to Equation 4.5. However, this contradicts the argument discussed previously in which K_2 represents $(Q + (J/2))$. The value of Q given in Table 4.4 (4478.3kg) is also of such a magnitude that while it would seem to be a reasonable estimation of $(Q + (J/2))$ it is too large to represent the weight of the hook and block alone.

If the weight of the jib is J and, in the case of the saddle jib crane, is of length L, then taking moments about O, Equation 4.1 may be re-written as:

$$M_o = (P + Q) \times (R - D) + (J \times (\frac{L}{2}))$$

$$M_o - (J \times (\frac{L}{2})) = (P + Q) \times (R - D)$$

However, as $(J\,x\,(L/2))$ is a constant this may be re-written as:

$$M_o = (P + Q)\ x\ (R - D) = Constant$$

In the case of the saddle jib crane the inclusion of the weight of the jib will still result in a constant loadmoment. In the case of a luffing jib crane, when $D = 0.00$m the jib is of length R and Equation 4.1 may be re-written as:

$$M_o = ((P + Q)\ x\ R) + (J\ x(\frac{R}{2}))$$

$$\frac{M_o}{R} = P + Q + (\frac{J}{2})$$

$$P = \frac{M_o}{R} - (Q + (\frac{J}{2}))$$

Therefore, in the case of the luffing jib crane, when the centre line of the tower (the point from which the radius is measured) coincides with the point at which the jib slews K_2 is represented by $(Q + (J/2))$ and the method of determining load lifting capacity embodied in Equations 4.1, 4.2 and 4.3, when $D = 0.00$m, is identical to that embodied in Equations 4.6, 4.7 and 4.8. All the technical data available for luffing jib cranes confirm that the point at which the jib slews does coincide with the centre line of the tower. Even if this is not the case it has been shown previously that errors in the estimation of D do not result in large errors in the determination of load lifting capacity.

In the case of rear-pivoted luffing jib cranes the point at which the jib slews clearly will not coincide with the centre line of the tower and indeed D will assume a negative value, as the point at which the jib slews is in the opposite direction from that in which the radius is measured. Predicted loads are tabulated for a Peiner SN500-08 rear-pivoted luffing jib crane in Table 4.6 using both methods. In the first case an estimation of D = - -2.7m has been made.

From inspection of the data in Table 4.6 it can be seen that the second method, in which an estimation of $D = 0.00$m is inherent, produces errors which are smaller than the first method, when a more realistic estimation of D has been made. However, in both cases the errors are of a sufficient magnitude to be acceptable.

Table 4.6 **Predicted loads**
Peiner SN500-08 rear-pivoted luffing jib tower crane

MANUFACTURER''S DATA		PREDICTED DATA					
		D = -2.70m Q = 2082.8kg M_o = 556949.0kgm			K_1 = 486244.5 K_2 = 1304.1		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error	Load (kg)	Error (kg)	%Error
28.1	16000.0	16000.0	0.0	0.00	16000.0	0.0	0.00
30.0	14900.0	14949.3	-49.3	-0.33	14904.1	-4.1	-0.03
34.0	13000.0	13093.0	-93.0	-0.72	12997.2	-2.8	-0.02
37.0	11800.0	11946.2	-146.2	-1.24	11837.7	-37.7	-0.32
40.0	10800.0	10960.5	-160.5	-1.49	10852.0	-52.0	-0.48
44.0	9700.0	9843.5	-143.3	-1.48	9746.9	-46.9	-0.48
47.0	9000.0	9123.5	-123.5	-1.37	9041.6	-41.6	-0.46
50.0	8400.0	8485.5	-85.5	-1.02	8420.8	-20.8	-0.25
54.0	7700.0	7740.0	-40.0	-0.52	7700.5	0.5	0.01
57.0	7200.0	7246.0	-46.4	-0.64	7226.5	-26.5	-0.37
60.0	6800.0	6800.0	0.0	0.00	6800.0	0.0	0.00

Note:- i) Q is calculated from Equation 4.3

ii) M_o is calculated from Equation 4.1

iii) K_1 is calculated from Equation 4.6

iv) K_2 is calculated from Equation 4.7

v) Predicted loads are calculated from Equation 4.2 and Equation 4.8

vi) Error = Load - Predicted Load

vii) %Error = (Error/Load) x 100

Examination of predicted loads for other rear-pivoted luffing jib cranes also reflects this trend. It can be seen that when an estimate of D has been made the predicted loads are larger than those provided by the manufacturer. This occurs because taking moments about a point in opposition to that in which the radius is measured will result in a larger lever arm and a subsequently larger constant loadmoment and predicted load. Therefore, a value of D = 0.00m is erring on the side of safety and, in all cases, the adoption of this method gives predicted loads which are closer to those provided by the manufacturer.

To summarize, for any type of luffing jib crane, the load at any radius, within the variable load capacity range, may be predicted from Equation 4.8. No estimate of D is required as this method assumes D = 0.00m.

4.5 Data required by the model

In addition to the data concerning load lifting capacity it is also necessary to enter further data concerning the crane into the model. These data comprise:

i) trolleying speed;
ii) slewing speed;
iii) hoisting speed - raising;
lowering;
iv) height to jib pivot (luffing jib only);
v) maximum hook height (luffing lib only); and
vi) underhook height (saddle jib only).

The speeds are necessary in order to calculate the relative time ratio inherent in travelling between different locations. The heights are required as a check that the crane is adequate for the prescribed task. The height to jib pivot and maximum hook height apply to luffing jib cranes only, which have a variable hook height, depending on the lifting point. For saddle jib cranes the underhook height is a constant.

Combining these data with those concerning load lifting capacity the precise nature of the data required is summarized in Table 4.7.

Table 4.7 **Crane data required by the model**

General information	Crane description File Name
Crane type	Saddle jib or Luffing jib
Load capacity	Minimum radius Radius at which load capacity begins to decrease and corresponding load capacity Maximum radius and corresponding load capacity Distance from centre line of tower to the point of jib articulation (*saddle jib only*)
Speeds	Trolleying speed Slewing speed Hoisting speed - raising lowering
Heights	Height to jib pivot (*luffing jib*) Maximum hook height (*luffing jib*) Underhook height (*saddle jib*)

4.6 Initial check on crane lifting capacity

Complete coverage of the site facilities is a fundamental requirement of a tower crane (Twort and Gordon 1985). Calvert (1986) suggested that cranes may be superimposed on a scaled site plan to ensure that the required reach is available. The model overcomes this problem by using a built-in checking device, based on an concept proposed by Shapiro *et al.* (1991), which will alert the user if this requirement is not satisfied. The philosophy of this device is described below.

Generally speaking every tower crane has a ring shape operational area, outside which it is not possible for the crane to serve. The inner radius of the ring is determined by the crane's minimum radius. The outer radius is ultimately governed by the weight of the load to be lifted. This is illustrated diagrammatically in Figure 4.6.

The most economical use of a crane occurs when it is lifting the maximum load at the given radius. Ideally this should correspond to the maximum load at minimum radius. For a given quantity of material to be moved from one facility, the frequency of movement to and from that facility will decrease if the load per lift is increased. However the crane's working radius will reduce. It is the maximum load to be lifted, to and from any facility, which will determine the maximum distance between the crane and the facility, and thus control and limit the relative position of the crane to an area around the facility. Such an area may be defined as a crane locating area, and is the area where a crane can be free to locate in order to serve that facility. The radius of the crane locating area is defined as the effective radius, and corresponds to the maximum distance that the crane may be located from that facility. Using the same data as in Figure 4.6 the theory of crane locating area is illustrated diagrammatically in Figure 4.7.

In practice a crane will be serving a minimum of two facilities and generally more. Therefore the crane must be located at a position which is inside the resultant crane locating area, representing the intersection of crane locating areas of all facilities. An example of this is illustrated in Figure 4.8.

The model uses a checking device to ensure that the load lifting requirements are satisfied. The checking device is based upon the principles discussed. Only if the crane satisfies the requirements so defined does the model proceed to the next stage. The steps taken by the model to check that the load lifting requirements are satisfied are enumerated in detail in Chapter 5.

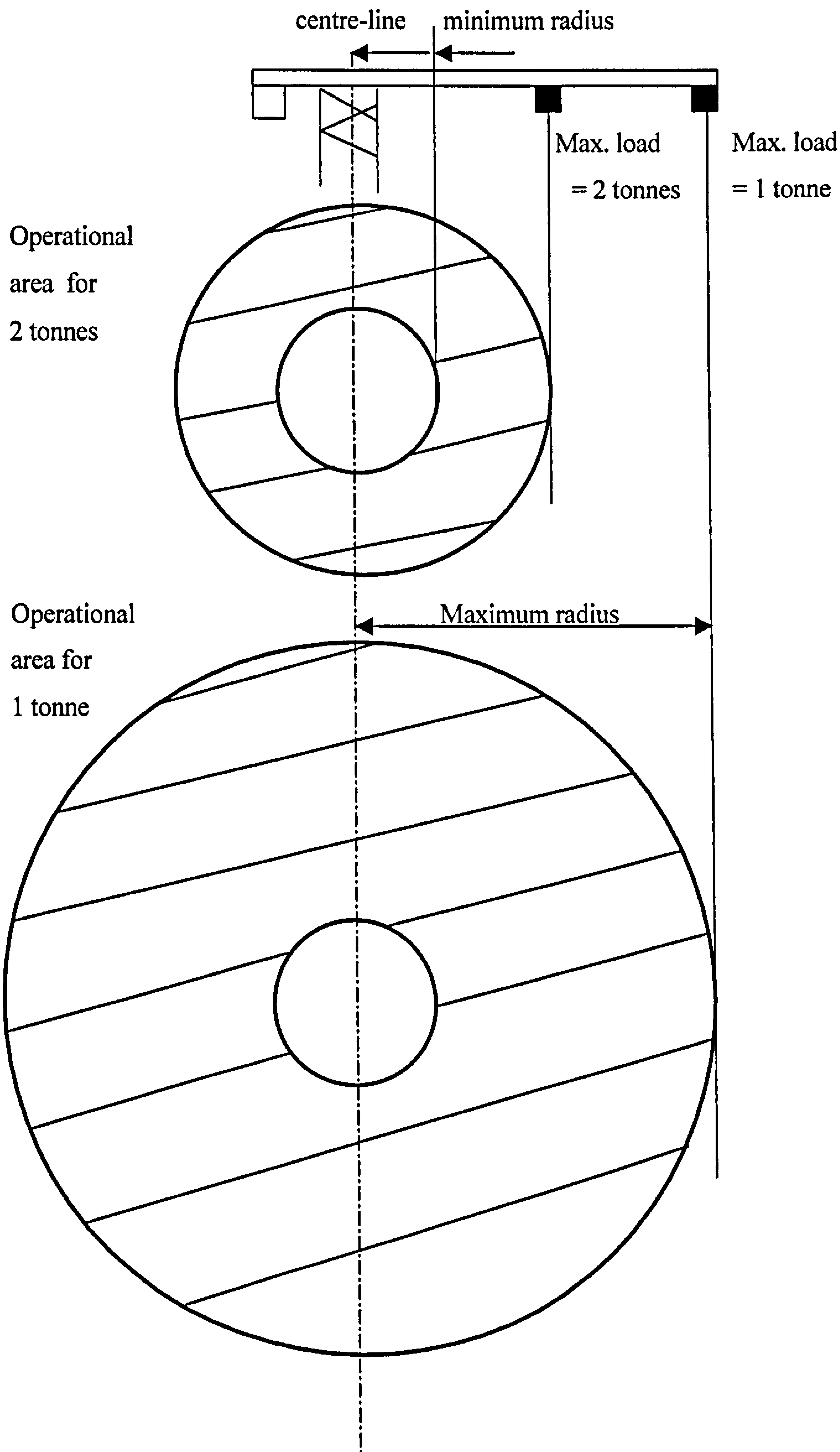


Figure 4.6 **Typical operational area of a crane dependent upon load**
(adapted from Choi 1985)

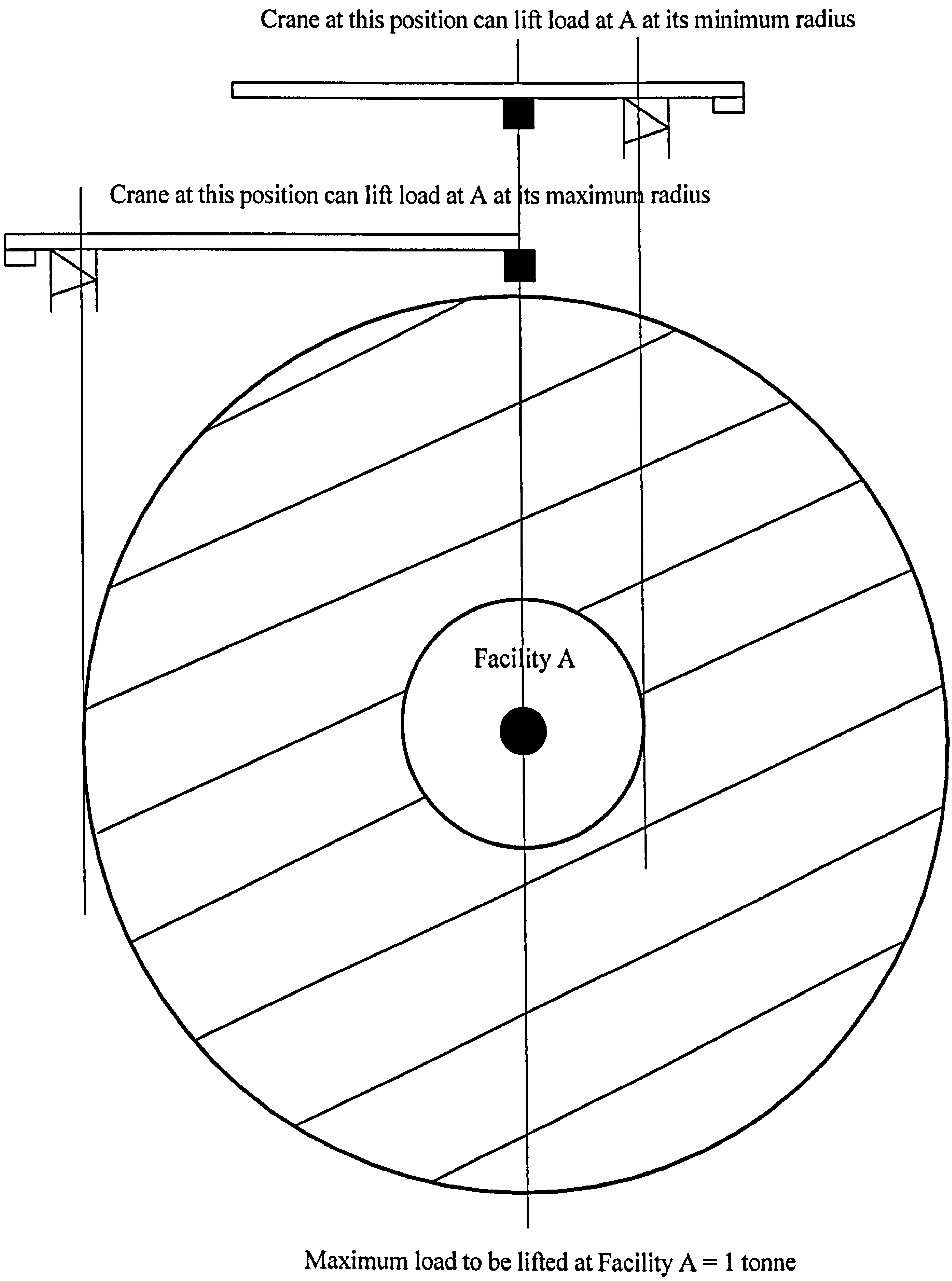


Figure 4.7 **Crane locating area for maximum load 1 tonne at Facility A**
(adapted from Choi 1985)

Crane data: Minimum radius = 12.4m
Load capacity = 1 tonne at maximum radius 40m
Load capacity = 2 tonnes at radius of 22.96m

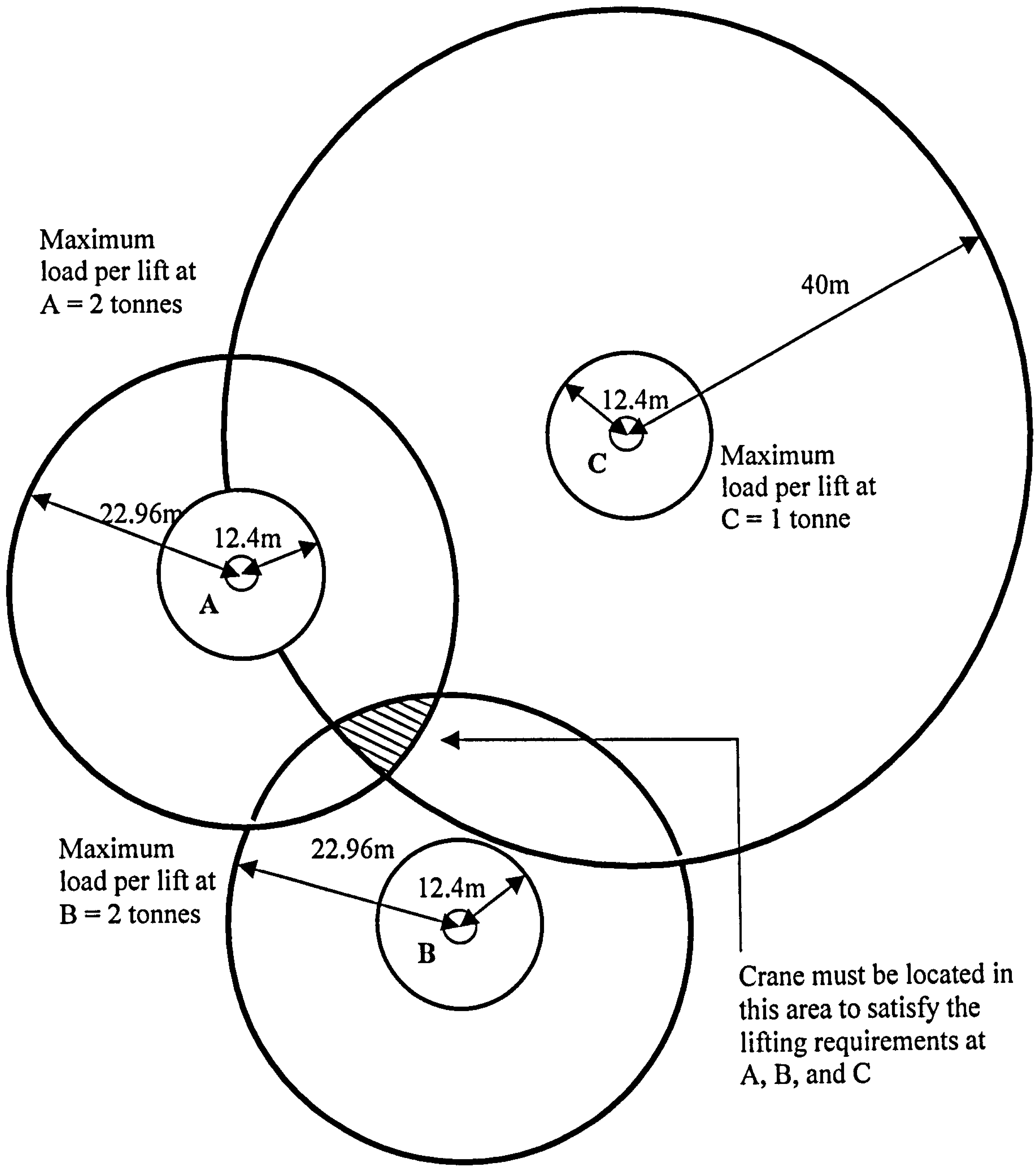


Figure 4.8 **Intersection of crane locating areas**
(adapted from Choi 1985)

4.7 Summary

The most pertinent features of tower cranes, as far as the model is concerned, are the range of operating radii and the load lifting capacity. The two features are very much interrelated because, as a general rule, the load capacity of a crane depends on the radius, with load lifting capacity increasing as the radius decreases. Hence the maximum load capacity occurs at the minimum radius and least load capacity occurs at the maximum radius.

Both saddle jib and luffing jib cranes have a range of radii, from the minimum radius at which it is physically possible to lift loads, determined by such factors as the type of tower, to the maximum radius, determined by the length of jib. In addition, tower cranes also have a range of radii, near to the tower, and sometimes known as the heavy load range, where load lifting capacity remains constant and does not increase or decrease as the radius decreases or increases. This range is an artificial limit, resulting from consideration of factors such as the strength of crane components.

In selecting an appropriate crane, attention must be paid to the maximum radius, as it is vital that the crane can reach all facilities, from its chosen location. However, it is equally important that the crane has adequate load capacity to pick up all anticipated loads at each facility. The load which a given crane can lift at a specified radius may be determined by load-radius charts, provided by the manufacturer; such charts plot the load against the radius for the range of operating radii. However, as far as this model is concerned this is an inappropriate format, and the model requires such information to be in the form of equations which the model can use to predict load capacity at any radius. In formulating such equations, saddle jib and luffing jib cranes have different characteristics with regard to the determination of the relationship between radius and load.

In respect of saddle jib tower cranes, an equation (Equation 4.1), provided by crane manufacturers, and based on the concept of a constant loadmoment, may be re-arranged (Equation 4.2) to enable the load capacity at a given radius to be predicted.

$$P_n = \frac{M_o}{R_n - D} - Q \quad .... \quad \textit{Equation 4.2}$$

where P_n = load capacity (kg) at radius R_n

M_o = constant moment about O (mkg)

R_n = radius about the centre line of the tower (m) with corresponding load capacity P_n

D = distance from O to the centre line of the tower (m)

Q = weight of trolley, hook and ropes (kg)

O is the point of jib articulation.

To enable Equation 4.2 to be used, values of M_o, D and Q are required. Firstly, an estimation of D, the distance from the centre line of the tower to the point of jib articulation is required. This may be provided by the manufacturer. If this is not available, a value may be inferred from the manufacturer's data sheet; investigations have shown that as D is typically 2 – 5% of R, adopting this method does not unduly effect the outcome. Secondly, a value of Q, the weight of the trolley, hooks and rope can be calculated by using two data sets ($P_1 R_1$) and (P_2 R_2), representing the load and radius at the extreme ends of the range, and either the provided or estimated value of D. Finally, Equation 4.1 can be used to compute the value of load moment M_o. Using the values of D, Q and M_o, Equation 4.2 can be used to predict the load for a given radius. In order for the load-radius characteristics to be fully defined, the radius at which the load capacity commences to decrease (i.e. the extent of the heavy load range) is also required.

In respect of luffing jib tower cranes, because of the jib and tower configuration, no estimate is required for D, the distance from the centre line of the tower to the point of jib articulation, and hence the process for determining the load at a given radius is much simpler than the process described above. Therefore, using two data sets ($P_1 R_1$) and ($P_2 R_2$), representing the load and radius at the extreme ends of the range, Equation 4.8 may be used to predict the load P at a given radius R.

$$P = \frac{(P_1 - P_2)R_1R_2 + R(P_2R_2 - P_1R_1)}{(R_2 - R_1)R} \quad .... \quad \textit{Equation 4.8}$$

In selecting an appropriate crane, the crane characteristics and location must be considered together; a certain crane may be suitable in one position but unsuitable in another position. As mentioned earlier, attention must be paid to both the maximum radius, as it is vital that the crane can reach all facilities from its chosen location, and to the load capacity of the crane, in order to ensure that the crane can pick up all anticipated loads at each facility. However, these aspects can only be considered when the interaction of the specific construction site and specific tower crane are considered together. This is part of the modelling process, and is discussed in more detail in the following chapter.

CHAPTER 5

FORMULATION AND DEVELOPMENT OF THE OPTIMIZATION OF CRANE LOCATION MODEL

5.1 Introduction

The intention of this chapter is to outline the development and formulation of a model which attempts to optimize crane location within a construction site. The chapter draws upon the discussion in the two preceding chapters concerning construction site and tower crane characteristics and describes the interaction of these two separate entities.

Brief reference is made to the principles of modelling, particularly with respect to the model to be developed, and so the philosophy behind the model is described and the resulting mathematical formulation derived. It is upon this model, and its inherent philosophy, that the subsequent computer programs and associated simulations emanate; these are discussed in this and Chapter 7 respectively.

As it is intended that computer programs be used to facilitate the modelling process, continual reference is made to the way in which these programs require data to be entered into the model.

Finally guidance is provided to the reader concerning the use of the computer programs required to run the model.

5.2 Principles of modelling

5.2.1 Definition of a model

The word model (without the adjective 'mathematical') has been used in a number of senses both by philosophers and scientists alike (Aris and Dempster 1974). In the context of this research a definition given by di Roccaferrera (1964) is appropriate:-

> "*A model is a simplified representation of an operation or process in which only the basic aspects or the most important features of a typical problem under investigation are considered.*"

Further to this definition a model may be used for the purposes of both optimization and appraisal, allowing scientists and engineers not only to predict optimal solutions of real life problems, but also to improve their understanding of the ways in which a system behaves. A prime requisite for a model is that it is able to predict the behaviour of a system within the range of concern.

Therefore the model described herein is a lucid symbolization of the behaviour of a single tower crane within a construction site. The essential purpose of the model is one of optimization of crane position arising from due consideration of the function of the crane, operating within the physical constraints so imposed; these constraints include the physical site boundaries and the maximum crane capacity at a given point. The model incorporates those characteristics fundamental to the behaviour of the elements of the process; these attributes were initially determined by observation. The simulations in Chapter 7 serve to illustrate the relative importance of each such characteristic.

5.2.2 Types of model

Models may be classified according to purpose (Leigh 1983) or type (Aris 1978). Although the classification of models is a subjective issue, three basic types of model may be distinguished (di Roccaferrera 1964 and Merrit 1979):-

Iconic - an iconic model bears a physical resemblance to the real system. It differs from the real system in scale and is often simpler. Examples of this kind of model are car models, wind tunnel tests or a globe representing the earth.

Analogue - an analogue model is a real system but with physical properties different from those of a natural system. The actual properties are replaced by more manipulative ones. For example a slide rule is an analogue model which represents numbers by distance. Analogue models can also be used to represent dynamic situations.

Symbolic - a symbolic model is a representation, by symbols, of the conditions imposed on the real system, and the reactions of the system to those conditions. Symbolic models may be either graphical or mathematical.

The model representing the optimization of crane location is a mathematical symbolic model. It may also be described as:

- a descriptive (as opposed to a prescriptive) model, where application of the model does not in itself lead the user to an optimum solution, but only describes the current situation and requires the user to suggest alternatives which lead to improvement, and, ultimately, the optimum solution; and

- a deterministic (as apposed to a stochastic) model, where the data used by the model assume fixed values. Although it may be argued that the use of probabilistic data would be a more realistic representation of real life, such data would be very difficult to obtain and, in any event, there is an element of uncertainty about the data input into the model.

It may further be described as a quantitative model as its application gives rise to objective quantitative data. Whilst it is not intended to eliminate entirely a subjective qualitative approach - indeed it would be dangerous to do so - it the intention of this thesis to illustrate the benefits of adopting a rigorous quantitative approach in locating tower cranes within a construction site.

5.2.3 Model development

The stages of model development parallel the classical steps of the scientific method (Lewis and Smith 1979). This may alternatively be described as an iterative process consisting of six major steps (Hamilton 1969) as illustrated in Figure 5.1.

Formulation of the initial model requires the assembly of equations, representing the appropriate physical mechanisms, which may be manipulated to obtain a framework for the desired mathematical model (Leigh 1983). Often different types of information available exist at different levels of quality and precision and so are, initially, incompatible. All equations, which will have a significant effect on the behaviour of the model, must be included. It is also necessary to consider equations whose effect is initially unknown. These must be considered and can only be eliminated when there is evidence to show they are of little or no consequence.

As the process is an iterative one it is unlikely that a validated model will be evinced at the first attempt. This chapter describes the formulation of the existing model, which has been suitably modified since its inception.

5.3 Optimization of crane location model

5.3.1 Problem definition

The crane location model, to be described, embodies the behaviour of a tower crane within a construction site, in order that its position may be optimized. Justification of the criterion by which the model will be assessed has been discussed in detail in Chapter 2, which established that the problem definition or objective function may be stated as:

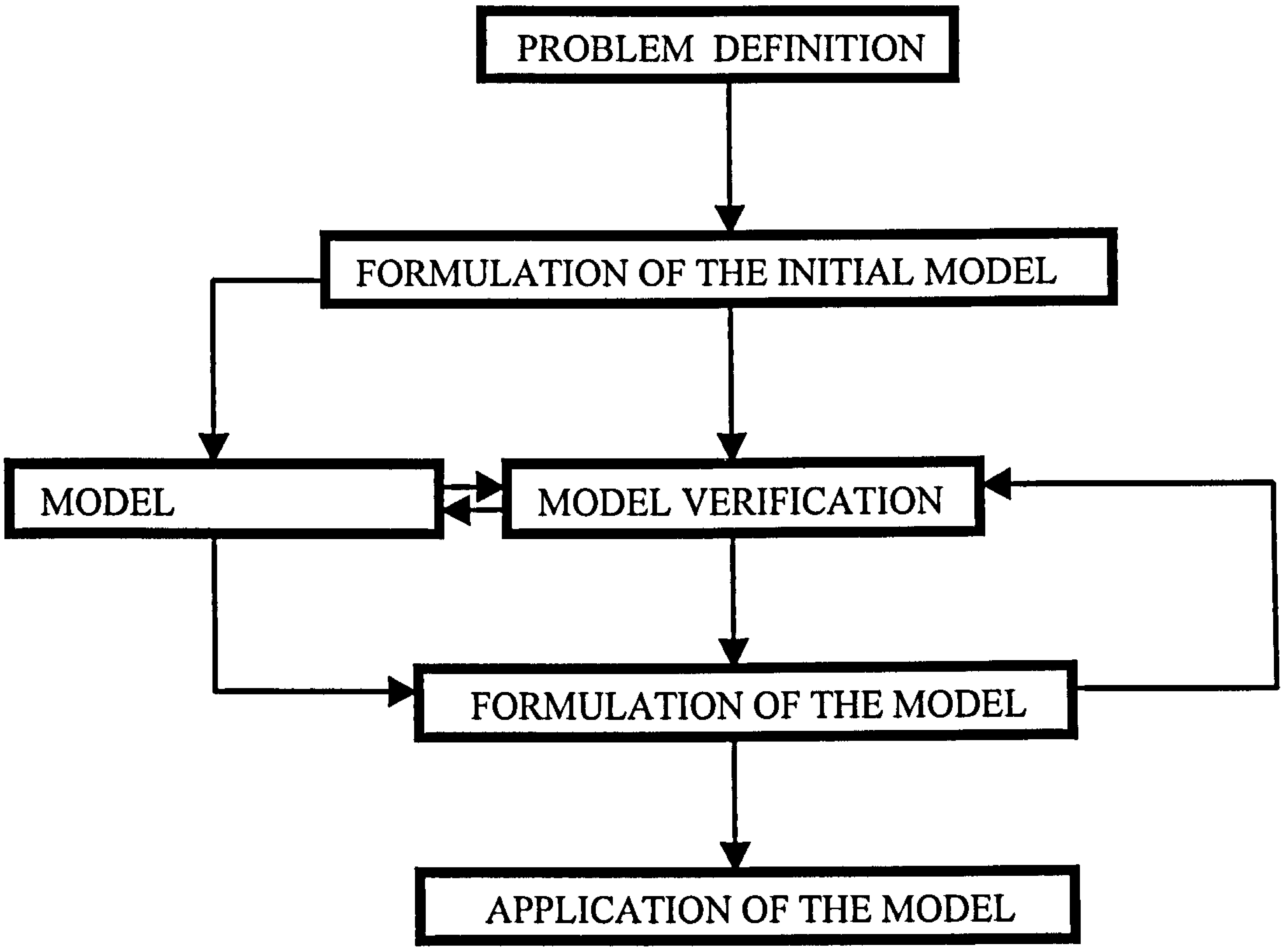


Figure 5.1 **Development of a model** (Hamilton,1969)

> " *the location of a single tower crane within a construction site in order that the time required to move materials between components of the system is minimized.*"

With regard to this definition it should be appreciated that the model only considers global movement of materials. In the case of the movement of components on an individual day, the optimum location of the tower crane may, or may not, lead to the minimization of travel time.

5.3.2 Formulation of the initial model

In the formulation process it is apparent that the model is required to depict the interaction of two separate independent entities, namely the characteristics of the construction site and the crane located within it. It is only when the two interact together that the behaviour of the crane within the individual site can be conceived. If either of these components is modified then it is likely that a different solution will arise, as illustrated in Figure 5.2. For example, Crane Type 1 combined with Construction Site 1 will produce a different solution to Crane Type 1 combined with Construction Site 2. Further, Construction Site 2 combined with Crane Type 1 will produce a different solution from when the same site uses Crane Type 2.

Therefore, in the modelling process, the data concerning both the construction site and the crane type may be considered as the input, the interaction of both as the model, and the solution (optimum crane position) as the output (see Figure 5.3).

5.3.3 Data input and interaction of data

As outlined, the input data to the model comprise two separate independent entities, data concerning the construction site layout and data concerning the crane. The salient characteristics of these two items have been discussed in detail in Chapters 3 and 4 respectively. The model relies upon the interaction of these entities. It is only when the relevant data concerning these have been input into the model that the interactive modelling process may commence.

For any one position of a tower crane within a given construction site the modelling process involves numerous systematic mathematical computations. These may be summarized by the following four stages:-

1. Computation of balancing movement between facilities in order that the condition that the number of movements towards a given facility equals the number of movements away from that facility is satisfied for each facility.

2. Initial check on crane coverage of the site and lifting capacity (and subsequent advice about the suitability, or otherwise, of a given crane on a given site).

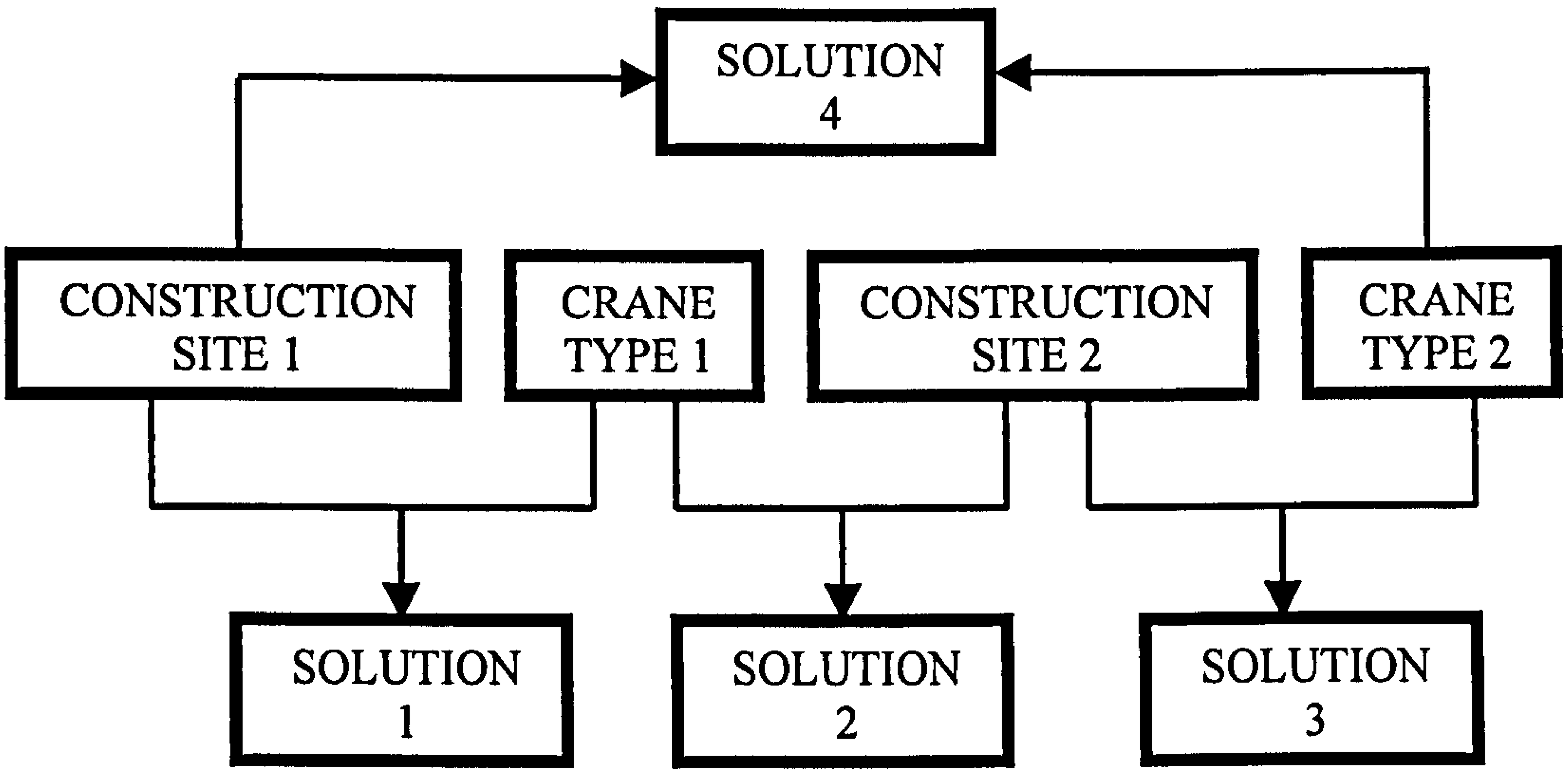


Figure 5.2 **Interaction of construction site and crane**

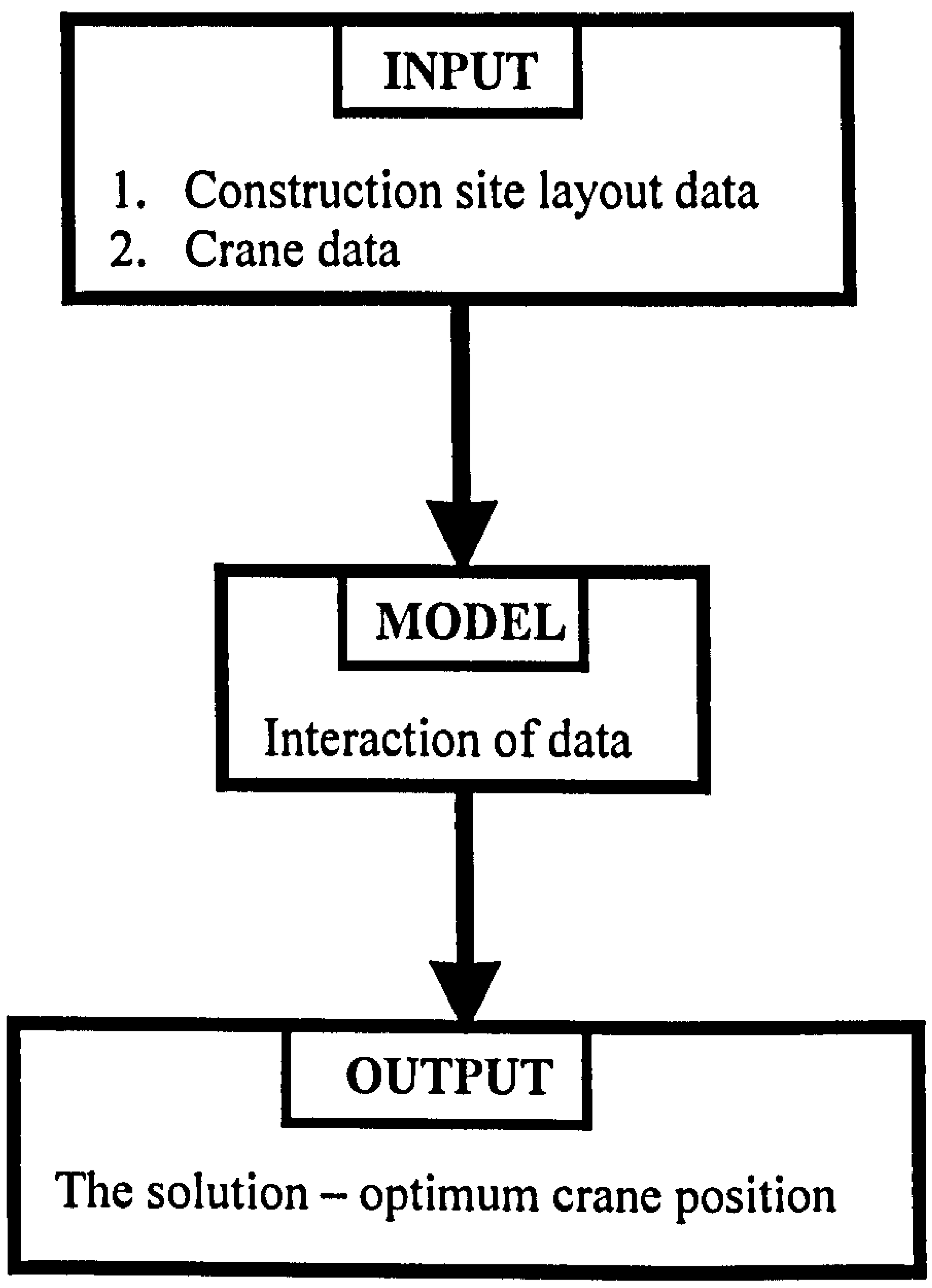


Figure 5.3 **The modelling process**

3. An assessment of any obstructions which occur on the site and an evaluation of their influence on movement between facilities.

4. Computation of total time taken to execute all the movements between facilities.

The processes involved in these steps are further described below.

5.3.3.1 Computation of balancing movement

Computation of the balancing movement between facilities does not rely upon the interaction of data pertinent to both the construction site and crane but is totally dependent upon the movement required between facilities located within the site. A detailed description of the evaluation of balancing movement has been provided in Chapter 3. Nevertheless a further brief discussion of its evaluation, which comprises numerous computations, has been included here as this forms part of the modelling process.

Firstly, an **explicit trip value** must be assigned to each route. For the purposes of the model a route is assumed to exist between each facility and every other facility. However, it is apparent that many routes will have a zero explicit trip value as movement will never take place between certain facilities. For those routes where movement does occur, the model calculates the explicit trip value by dividing the total number of units to be moved by the mean (average) number of units per trip (Equation 3.2). Where implicit movement occurs (see Chapter 3, section 3.3) the same value is assigned to the opposing route.

The data generated by determining explicit and implicit movement form the constraints in the Simplex Method. Balancing movement is then calculated on the basis that movement towards any facility is equal to movement away from that facility. The results of the application of the Simplex Method are used in the computation of total crane movement time, which is dependent, among other factors, upon the precise location of the crane within the site.

5.3.3.2 Initial check on crane lifting capacity

Before the model can proceed and calculate the total crane movement time an initial check must be made to ensure that, at the specified position, the crane is suitable to lift the maximum load at each facility. In addition to satisfying this criterion, none of the facilities must be too near the crane (as there is always a minimum operating radius) or beyond the reach of the crane. There are also further constraints concerning facility height, which must be taken into consideration in determining the suitability of a given crane in a given position.

The principles concerning the determination of feasible areas in which to locate the crane have been discussed in Chapter 4 (section 4.6). It is upon these principles that the checking device, in the model, functions. The flow chart in Figure 5.4 enumerates the steps taken by the model to check that the load lifting requirements are satisfied, when the chosen crane performs on the given site, at the location selected. If the requirements are not satisfied the user may relocate the position of the crane or facilities, reduce the maximum load to be lifted at a given facility, or, alternatively, select a crane of a larger capacity.

In addition to the steps embodied in Figure 5.4 checks are also required concerning the height of the facilities and crane. In the case of a saddle jib the check is quite simple as the height of all facilities must be less than the underhook height. In the case of a luffing jib the height of the jib at a given radius is a function of the distance of the facility from the crane and can be calculated from Equation 5.1.

$$h_{uh} = \frac{r_{fac}}{r_{\max}}(h_{\max} - h_{pivot}) + h_{pivot} \quad \ldots\ldots \quad \textit{Equation } 5.1$$

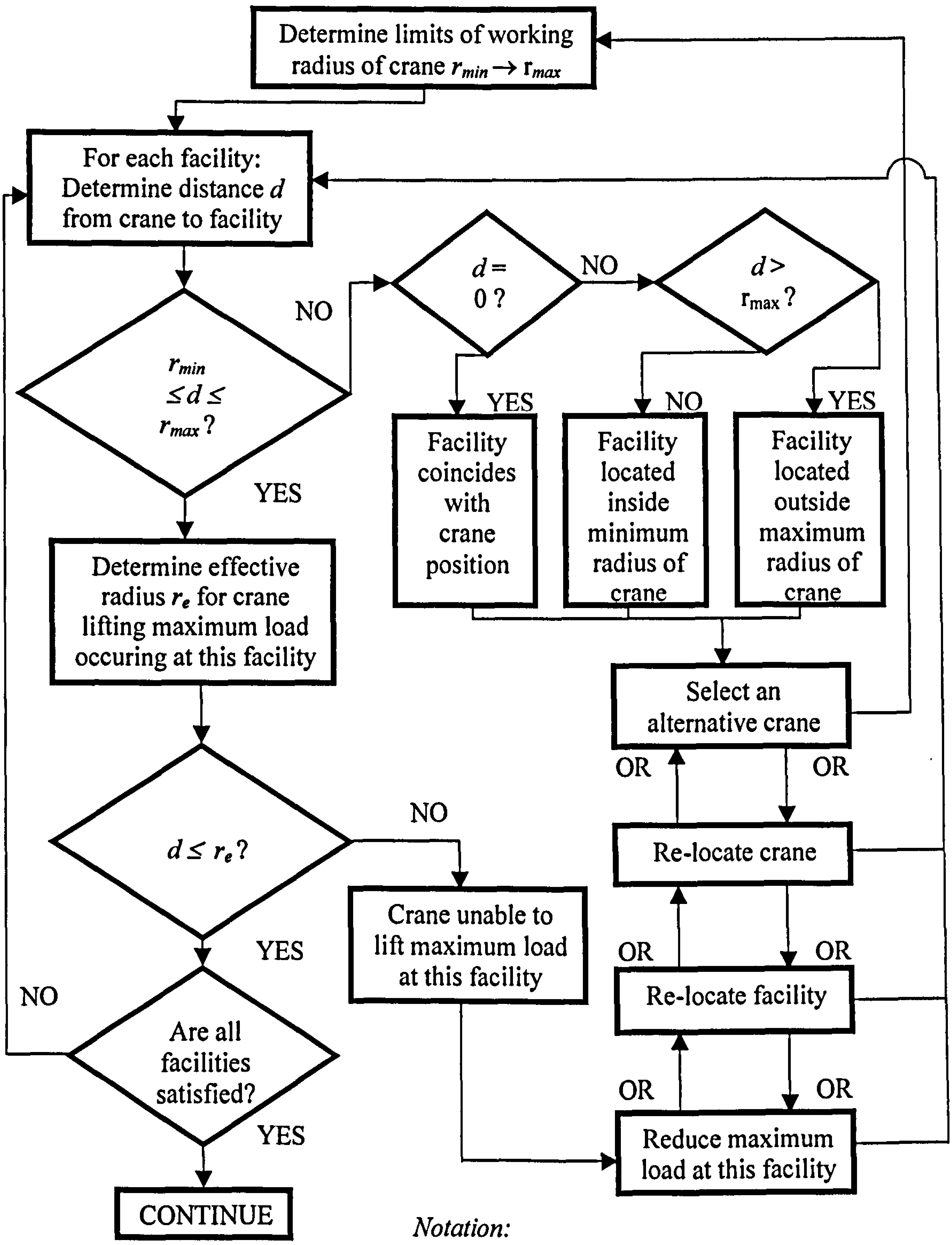
where h_{uh} = (underhook) height of the crane at the given radius of the facility

r_{fac} = radius of the facility relative to the crane

r_{max} = maximum radius of the jib

h_{pivot} = height to the jib pivot

h_{max} = maximum hook height



Notation:

r_{min} - Minimum radius

r_{max} - Maximum radius

r_e - Effective radius for crane lifting maximum load at each facility

d - Distance from crane to each facility

Figure 5.4 **Flow chart of the procedure to check crane lifting capacity relative to all facilities**

The height of each facility must therefore be less than the height of the crane at the given radius of the facility.

The crane must satisfy all the requirements in respect of load capacity, radius and height. Only if the crane satisfies all these requirements does the model proceed to the next stage.

5.3.3.3 Assessment of obstructions

The effect created by an obstruction cannot be evaluated until its position is assessed in relation to that of the crane. For example, the location of an obstruction may dictate that certain facilities, in their initial position relative to the crane, are unreachable by the crane jib. This situation is illustrated in Figure 5.5, which also depicts another potentially unsupportable situation, where movement between facilities is impossible.

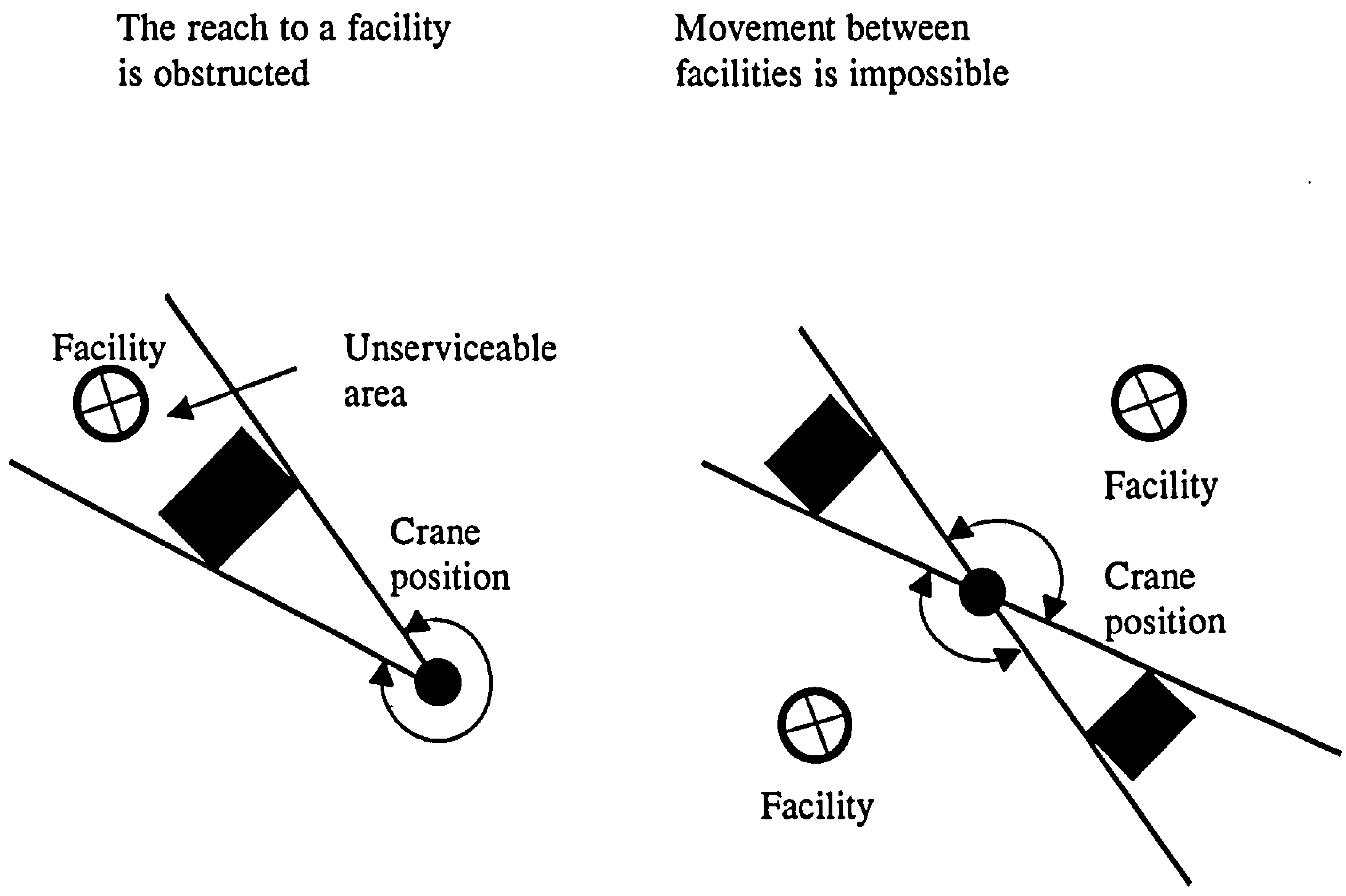


Figure 5.5 **Examples of potentially unsupportable situations caused by obstructions on site**

In both cases the full implications of such an occurrence cannot be realised until the height of the obstruction, in relation to the height of the crane hook, has been assessed. The differing operating characteristics of saddle jib and luffing jib cranes also influence the potential restrictions in each case.

Clearly, any obstructions may restrict the movement of the crane. In addition to the occurrence of potentially unsupportable situations, as illustrated in Figure 5.5, obstructions may also result in situations where the crane is unable to move along the most direct route between two facilities but may need to take a longer indirect route.

In order that the impact of such obstructions may be assessed it is necessary to consider the following:

a) location of the crane;
b) type of crane;
c) maximum crane hook profile;
d) location of obstruction;
e) type of obstruction; and
f) height of obstruction.

All these factors may be critical in the determination of a potentially unsupportable situation or one where the most direct movement between two facilities is prevented.

Obstructions may be categorised as follows.

1. Solid obstructions of a permanent status (e.g. nearby buildings)
2. Non-materialised obstructions (e.g. nearby highway)
3. Obstructions of an occasional status (e.g. the jib of another crane)

An obstruction of an occasional status due to interference from another crane jib will only occur on construction sites where there are multiple tower cranes. Consideration of multiple cranes on construction sites is outside the scope of this dissertation.

5.3.3.3.1 Solid obstructions of a permanent status

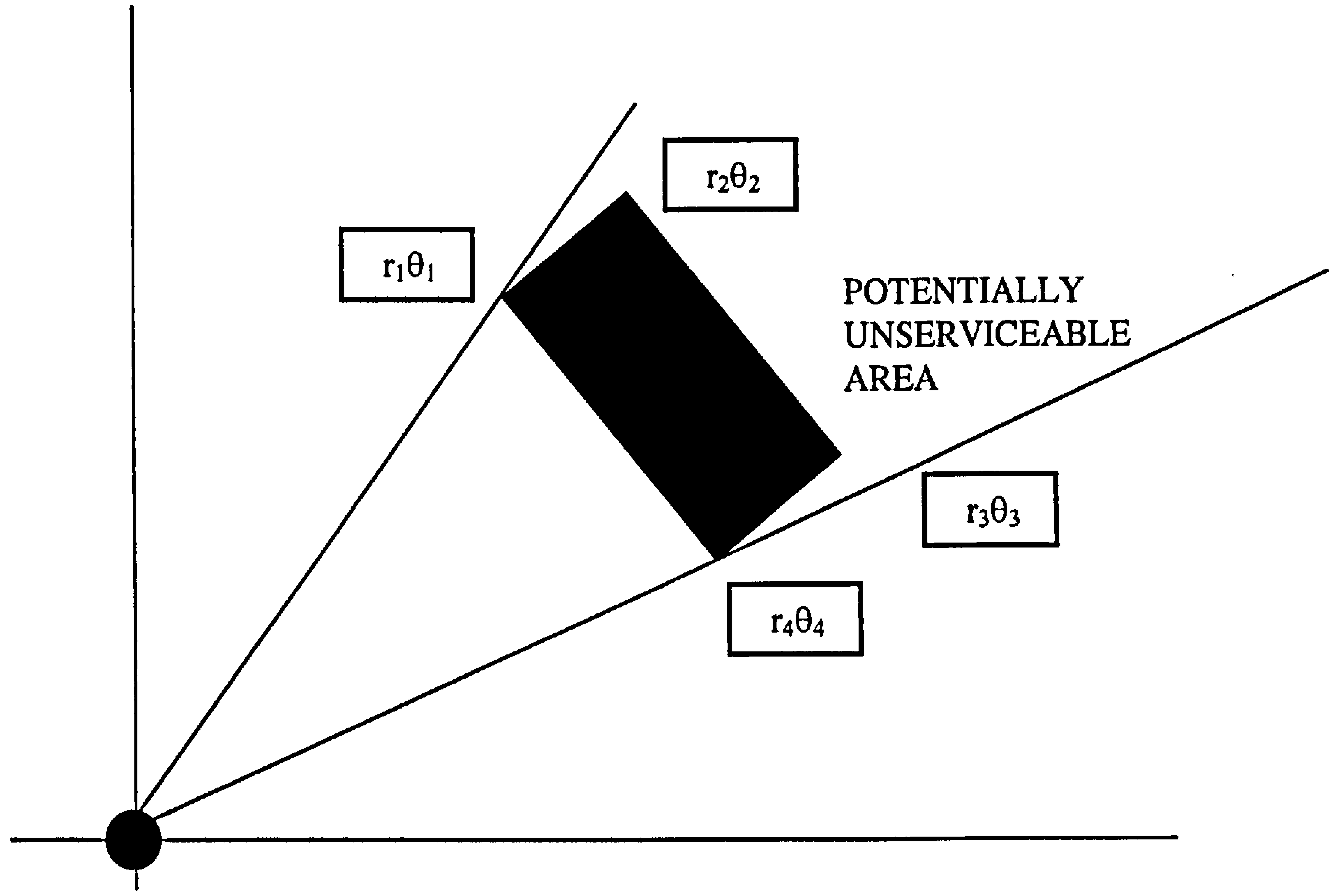
A permanent obstruction must be qualified with both permanent status and intrusion into the operational area of the crane. However, such obstructions may be further classified as:

1a. an obstruction with a height greater than the maximum hook height of the crane at that position, which will create a potentially unserviceable area by preventing the crane from reaching beyond the obstruction to any facilities which may be located there; or

1b. an obstruction with a height less than the maximum hook height of the crane at that position, which will not create an unserviceable area, but which may prevent the crane from using the most direct route to move to and from any facility located beyond the obstruction (relative to the crane).

Saddle jibs cranes have a constant height of operation and therefore the determination of which category a given obstruction falls into is relatively simple. In the case of a luffing jib crane, the height of operation depends on the radius at which the crane is operating and, therefore, this calculation is slightly more complicated.

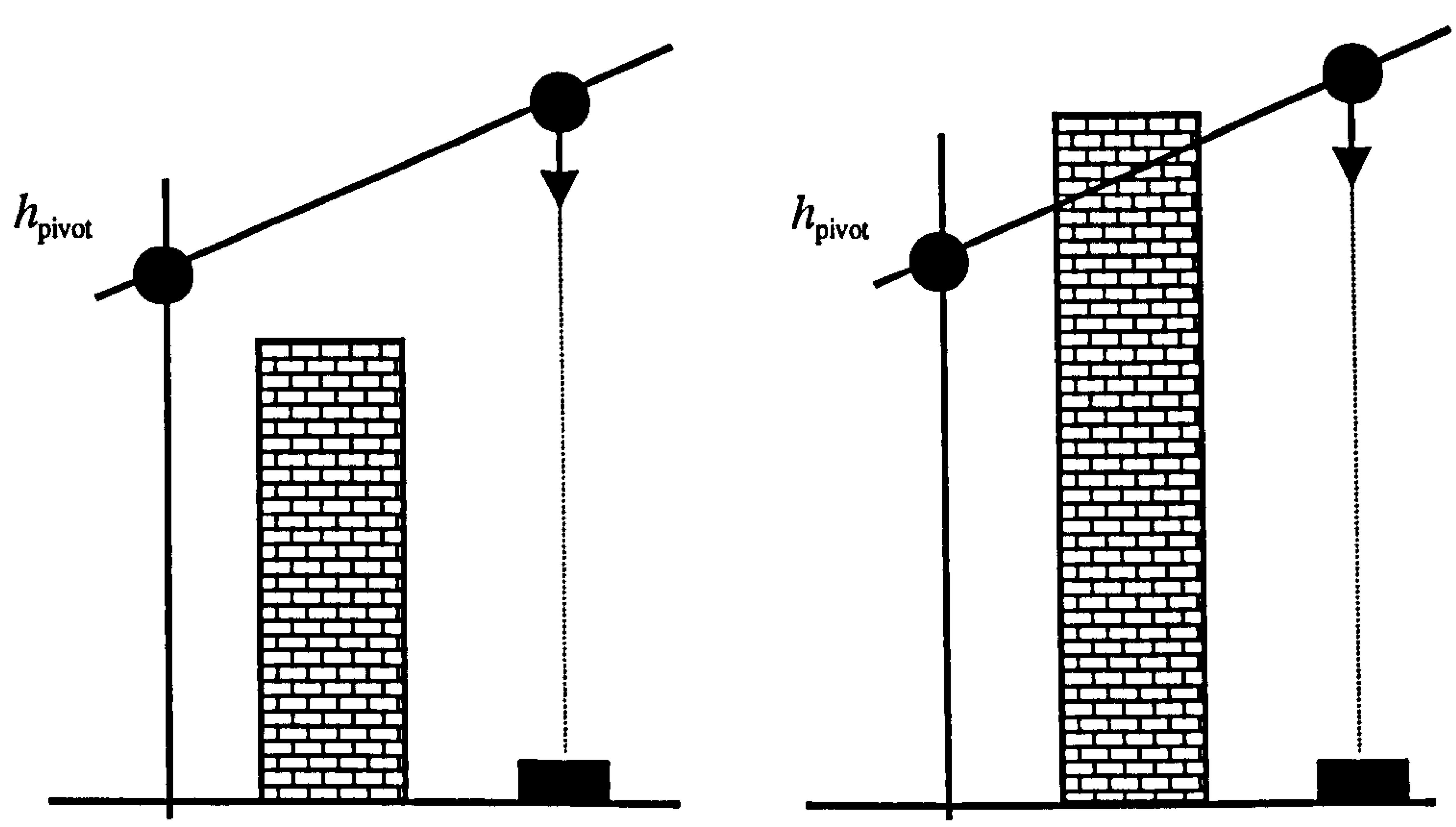
Therefore, the first stage in determining whether an obstruction creates a potentially unserviceable area, as illustrated in Figure 5.6, is to compare the height of the obstruction with the maximum hook height at the position of the obstruction. Clearly, the effect of an obstruction is dependent upon the crane location. A flow chart to determine the existence of potential obstructions is illustrated in Figure 5.7. However, it should be noted that a potentially unserviceable area will only become an unserviceable area if a facility is located such that the crane needs to reach past the obstruction to reach that facility.



Luffing jib crane:

Height of obstruction does not create an unserviceable area

Height of obstruction does create an unserviceable area



Saddle jib crane:

An unserviceable area will be created when the height of the obstruction exceeds the height of the jib

Figure 5.6 **Determination of an unserviceable area created by an obstruction**

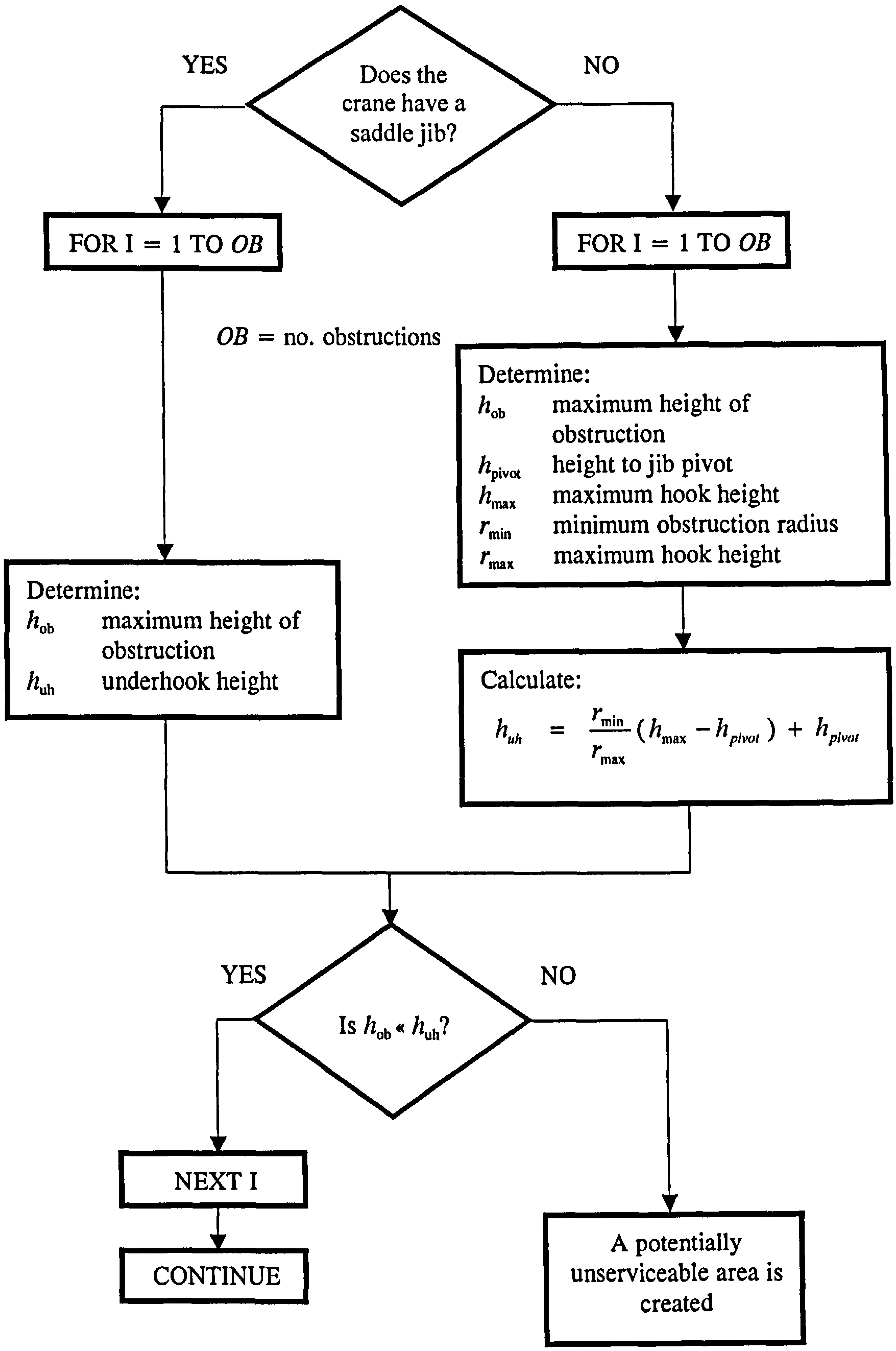


Figure 5.7 **Flow chart of the procedure to check the existence of potentially unserviceable areas**

Firstly, if a potentially unserviceable area is shown to exist, as illustrated in Figure 5.6, it is then necessary to establish whether or not a facility is located in the area beyond the obstruction, relative to the crane position. This, as mentioned in the previous paragraph, will have the effect of turning the potentially unserviceable area into an unserviceable area. This situation will only occur if the height of the obstruction exceeds the maximum height of the crane hook at this point. The unserviceable area, relative to the crane, is calculated using polar co-ordinates, and is defined as that area of radius greater than r_{ob} with an angle, relative to the crane, exceeding θ_{min} but less than θ_{max}.

The flow chart in Figure 5.8 illustrates the steps taken by the model to evaluate these values and subsequently check whether such a situation arises, issuing a warning to the user if this is the case. In such instances it is necessary to relocate the crane, facility or obstruction or select a crane with an improved hook profile.

Secondly, consider the restriction in movement between facilities imposed by the occurrence of multiple obstructions, as illustrated in Figure 5.9. Such a situation only applies to saddle jib cranes, as a luffing jib crane has the ability to luff its jib and so circumvent any such obstruction, although this may result in the quickest movement route not being selected; this is discussed in a following paragraph. In a situation where a large number of obstructions occur is unlikely that a single saddle jib crane would be selected.

It should be appreciated that a problem may still occur, although a facility may be located at a radius, relative to the crane, less than that circumscribed by an obstruction. This is clearly the case as it is the arc circumscribed by the crane jib, and not the crane hook, which is the critical factor. The flow chart in Figure 5.10 enumerates the steps taken by the model to determine whether such a situation arises.

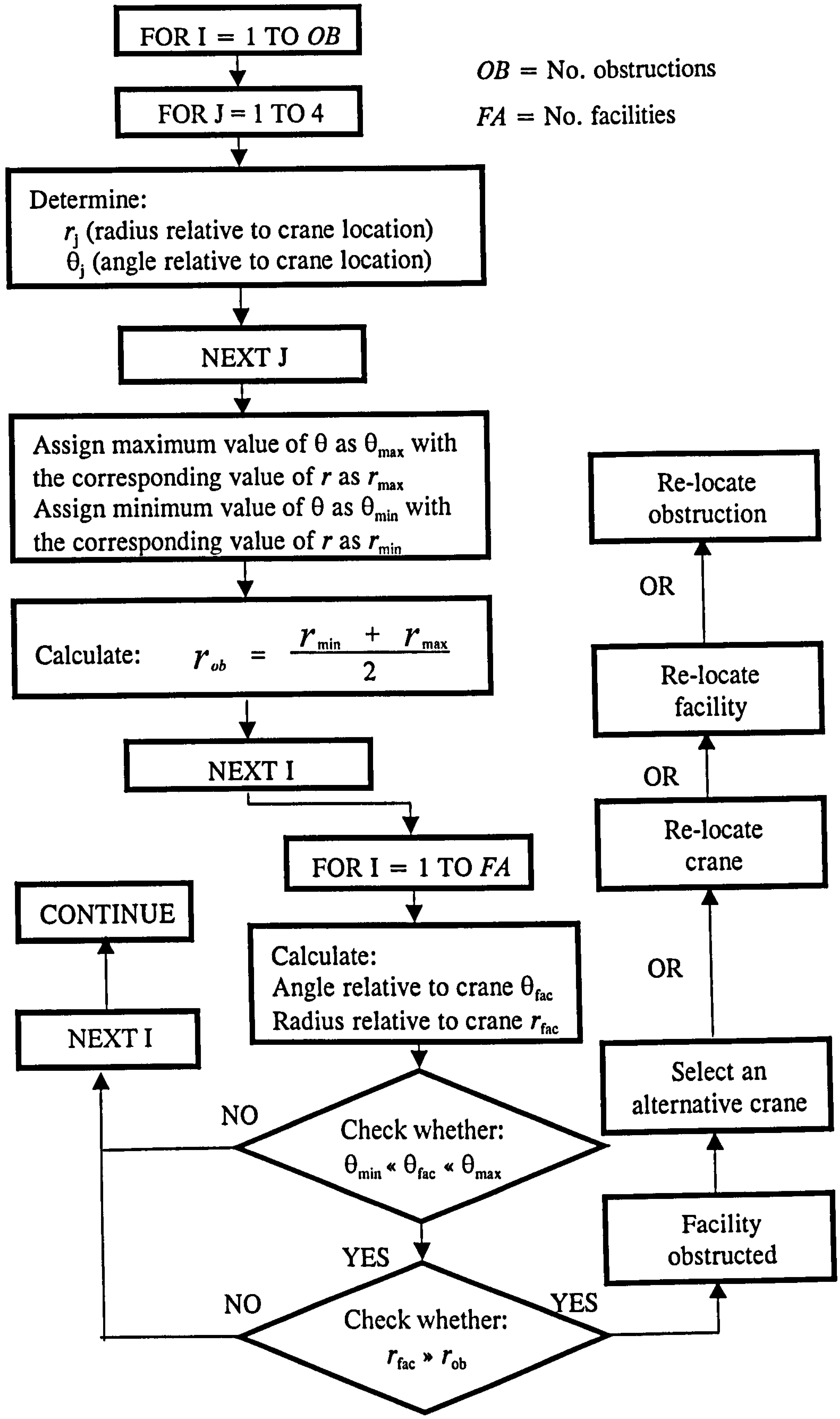


Figure 5.8 **Flow chart of the procedure to check the determination of unserviceable areas**

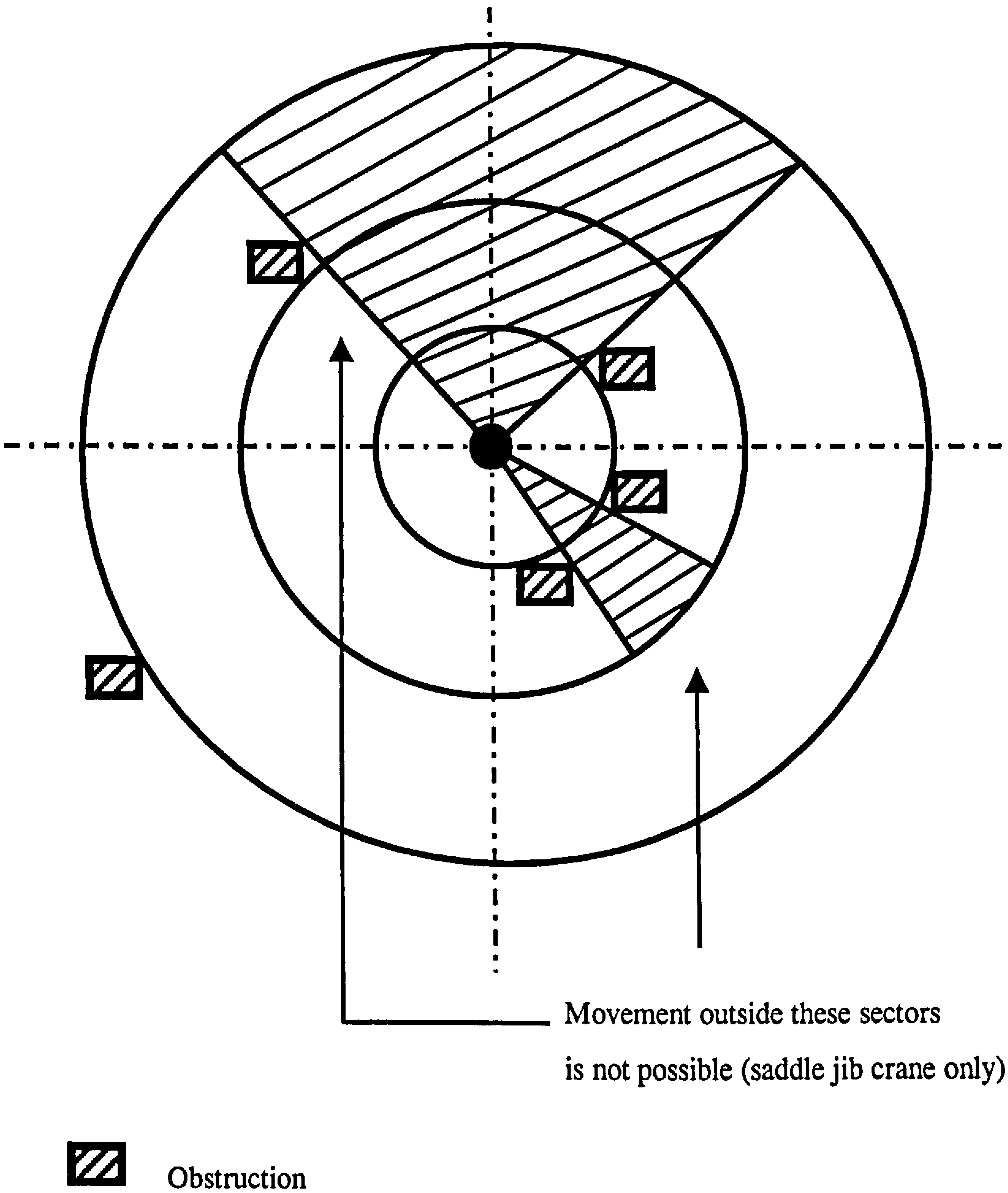


Figure 5.9 **Restrictions in movement between facilities imposed by the occurrence of multiple obstructions**

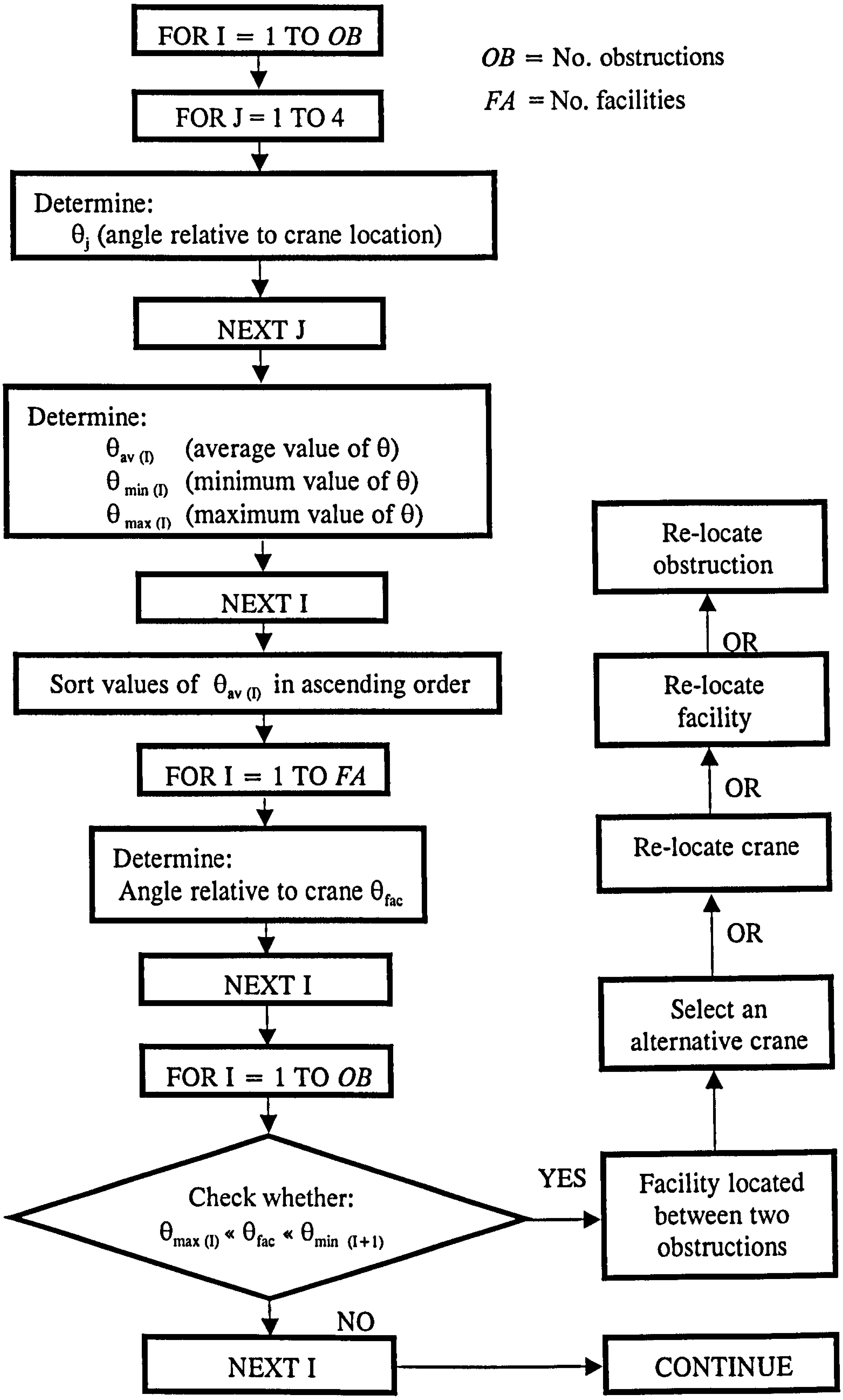


Figure 5.10 **Flow chart of the procedure to check the effect of multiple obstructions**

Finally consider the situation which arises when obstructions dictate that the crane is unable to move along the most direct route between two facilities but may need to take a longer indirect route. This is illustrated in Figure 5.11, where it is assumed that the height of the obstruction exceeds that of the crane jib, at that point. In the first example it is anticipated that the obstruction does not prevent the most direct movement between the two facilities, although it must be borne in mind that that the model, giving due consideration to all three dimensions and their relative movement velocities, assumes movement along the quickest route, which may or may not be the shortest route. However, in the second example, it is likely that movement along the quickest route is prevented and that the movement which will occur will be along the slowest route. However, in the case of a luffing jib crane it is possible that it may still be quicker to take the shortest route and luff the jib, as illustrated in Figure 5.12. The flow chart in Figure 5.13 enumerates the steps taken to determine if such a situation arises and, if so, to evaluate the resulting movement.

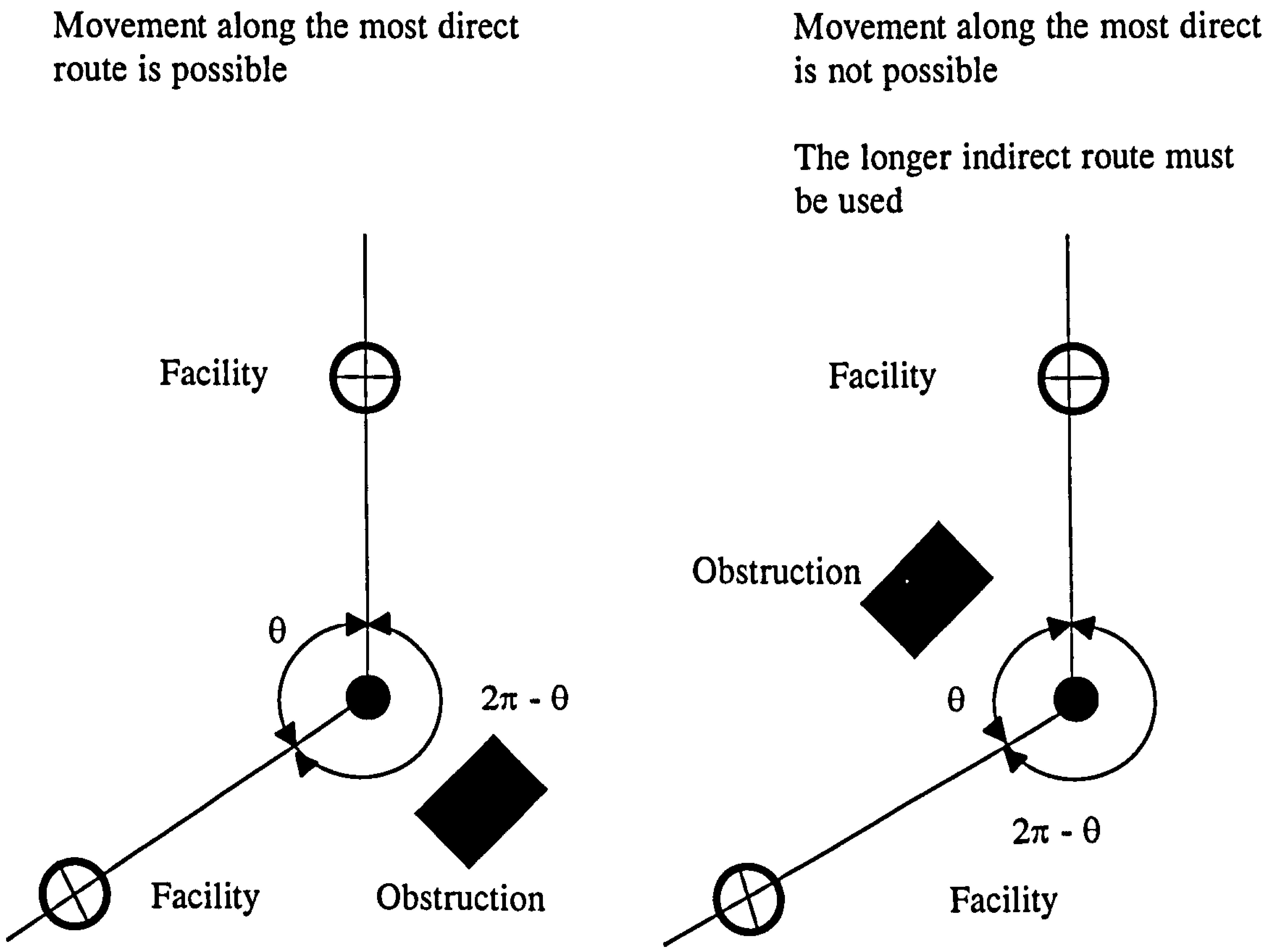


Figure 5.11 **Movement restrictions due to the effect of obstructions**

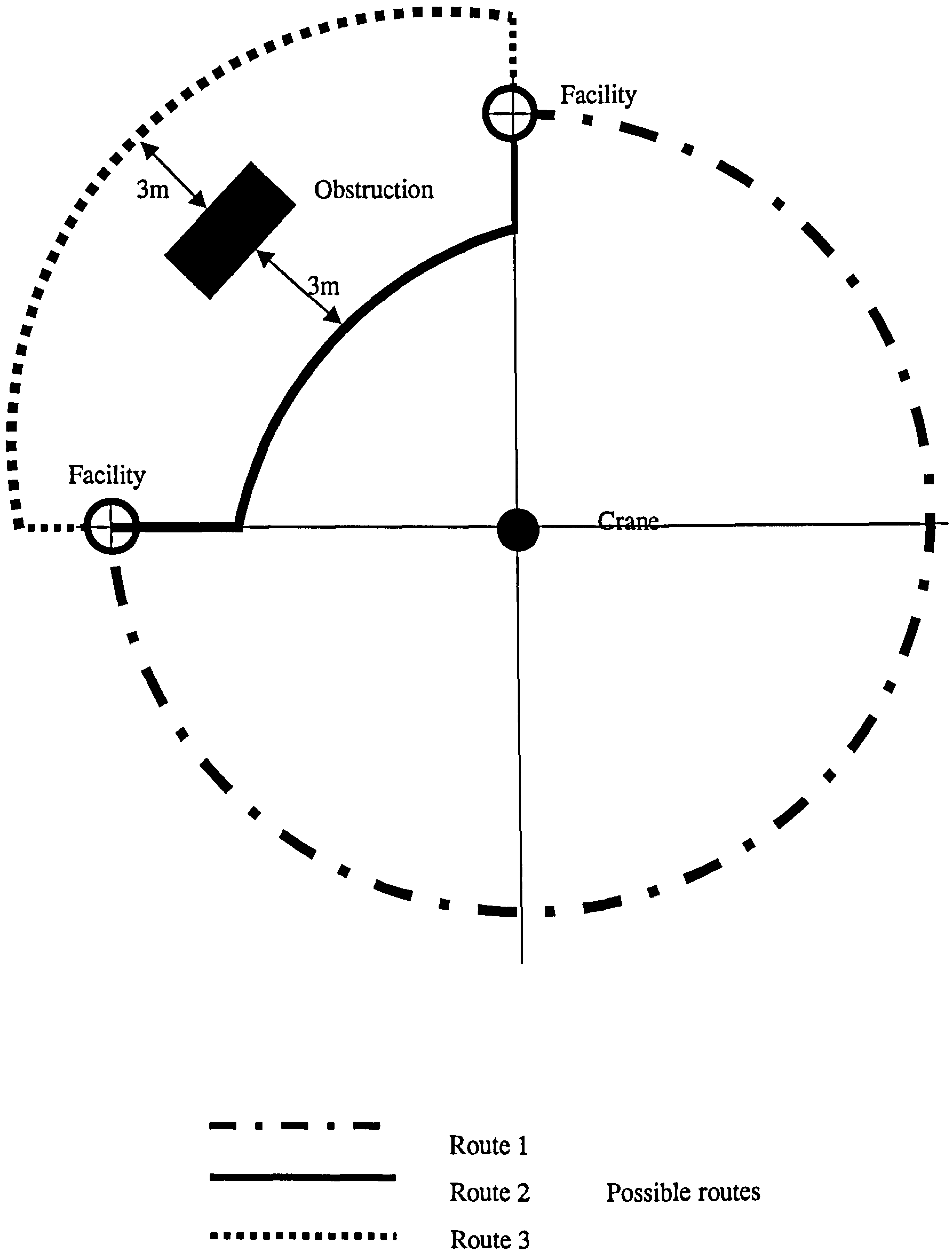
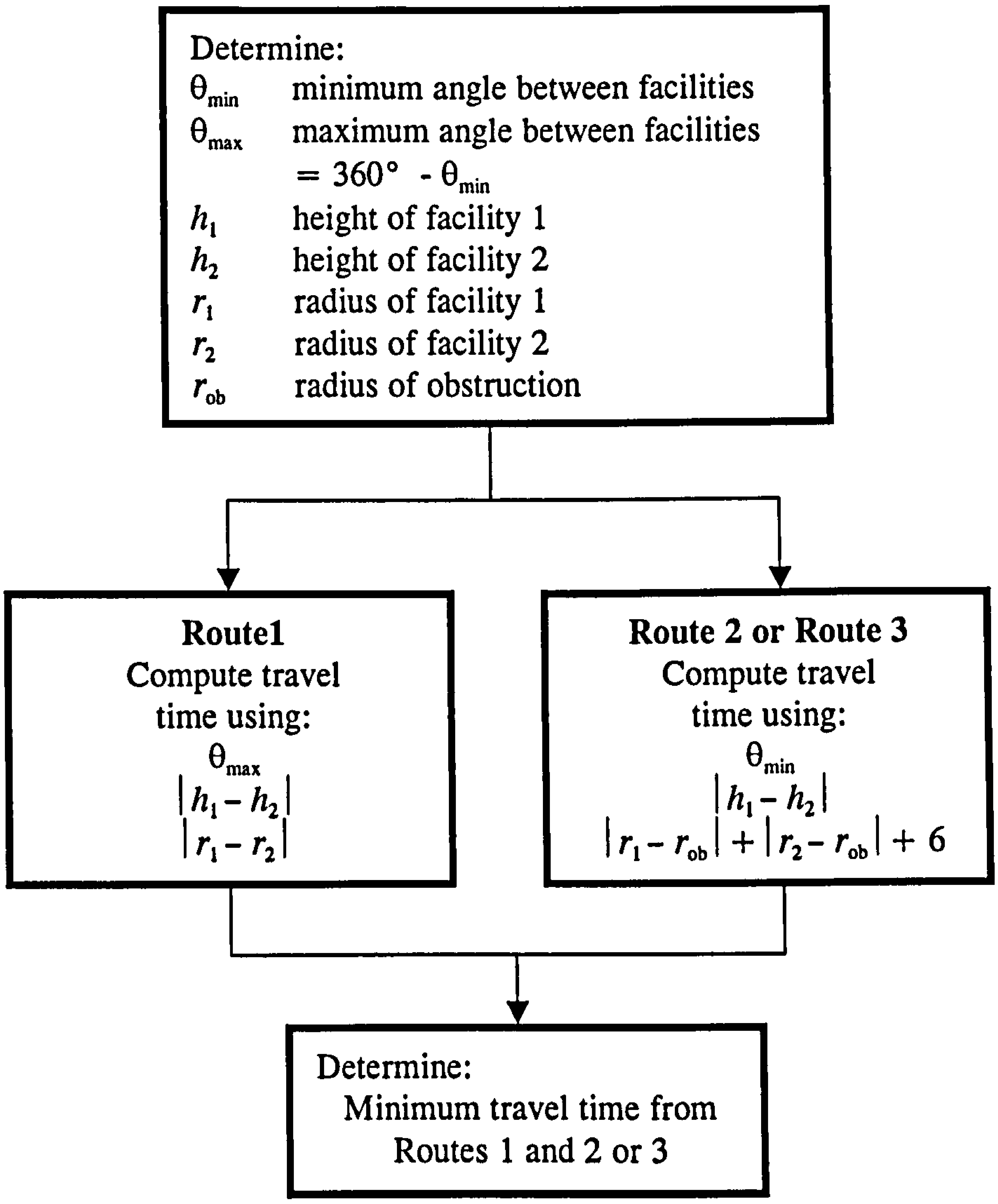


Figure 5.12 **Alternative movement routes due to the effect of obstructions**



NOTE:

- It is assumed that the presence of an obstruction between two facilities has previously been identified.
- The selection of Route 2 or Route 3 will depend upon the relative positions of the two facilities and the obstruction.
- Calculation of movement time is detailed in the following section (5.3.3.4).
- 3m has been chosen arbitrarily as the distance by which the crane hook will circumvent the obstruction, which gives a total of 6m additional movement.

Figure 5.13 **Flow chart of the procedure to evaluate alternative movement routes**

5.3.3.3.2 Non-materialised obstructions

In the case of a non-materialised obstruction, consideration must be given to the appropriate bye-laws. A further consideration, which may render certain proposed crane positions unacceptable, is that of over-swing onto adjacent property. Such action may fall into two categories, that of over-swing onto public property and that of over-swing onto private property.

Over-swing onto public property will generally be in the form of encroachment onto the public highway. The method of obtaining permission to do so depends upon the local authority concerned. For example, the City of Portsmouth, in its bye-laws, requires contractors to apply for a licence where a crane would over-swing the highway (Choi, 1985). On the other hand, Manchester City Council do not have such formal arrangements. However, permission to over-swing the highway must be obtained and the contractor must indemnify the Council against the consequences of any damage arising as a result of such action. In the case of over-swing onto British Rail property it is a statute requirement that jibs shall not infringe such property.

As regards over-swing onto private property this matter was tested in the courts in 1970 in the case of Woollerton and Wilson Ltd. v Richard Costain Ltd. (All England Law Report 1970), when the judgement was given that unauthorized invasion of the airspace above land constitutes trespass. This does not prevent such an event occurring but the contractor is obliged to obtain permission from the owner of the land, who will inevitably charge a not inconsiderable amount of money to grant such permission.

As with obstructions of a permanent status, the full impact of a non-materialised obstruction cannot be assessed until its position is viewed in relation to the crane. In order that an evaluation of the effect of such an obstruction may be made it is necessary to define whether such an obstruction is:

a) a totally restricted obstruction which cannot be overswung by the crane regardless of height; or

b) a partially restricted obstruction which may be overswung by the crane but the not the crane hook when it is lifting a load.

These situations are illustrated graphically in Figure 5.14. It is assumed that such situations can only occur in respect of saddle jib cranes and that luffing jib cranes have the ability to luff their jibs and so avoid such obstructions. Figure 5.15 illustrates how the philosophy upon which the check is based. It is assumed that A and B are two boundary points and that the line connecting these two points represents the boundary. It is necessary to calculate θ, the angle subtended between the proposed crane position P, boundary point and boundary point B. Then the angle subtended between boundary point A, the proposed crane position P and C, a point between A and B, such that PC is at right angles to AB, will be (90 - θ). Therefore the distance CP, which represents the shortest distance from the proposed crane position to the boundary, can be calculated as $CP = AP\, sin\theta = AP\, cos\, (90 - \theta)$. Such an obstruction will only occur if this distance is less than the maximum jib length. This procedure should be repeated for each consecutive set of boundary points.

5.3.3.3.3 Obstructions of an occasional status

An example of an obstruction of an occasional status is that of another crane jib. It is obvious that if two cranes are located on the same site, and there is overlap between the area circumscribed by the two jibs, great care must be taken. This situation is illustrated in Figure 5.16. However, consideration of this problem is outside the scope of this thesis, as the problem is confined to the location of a single tower crane on a construction site.

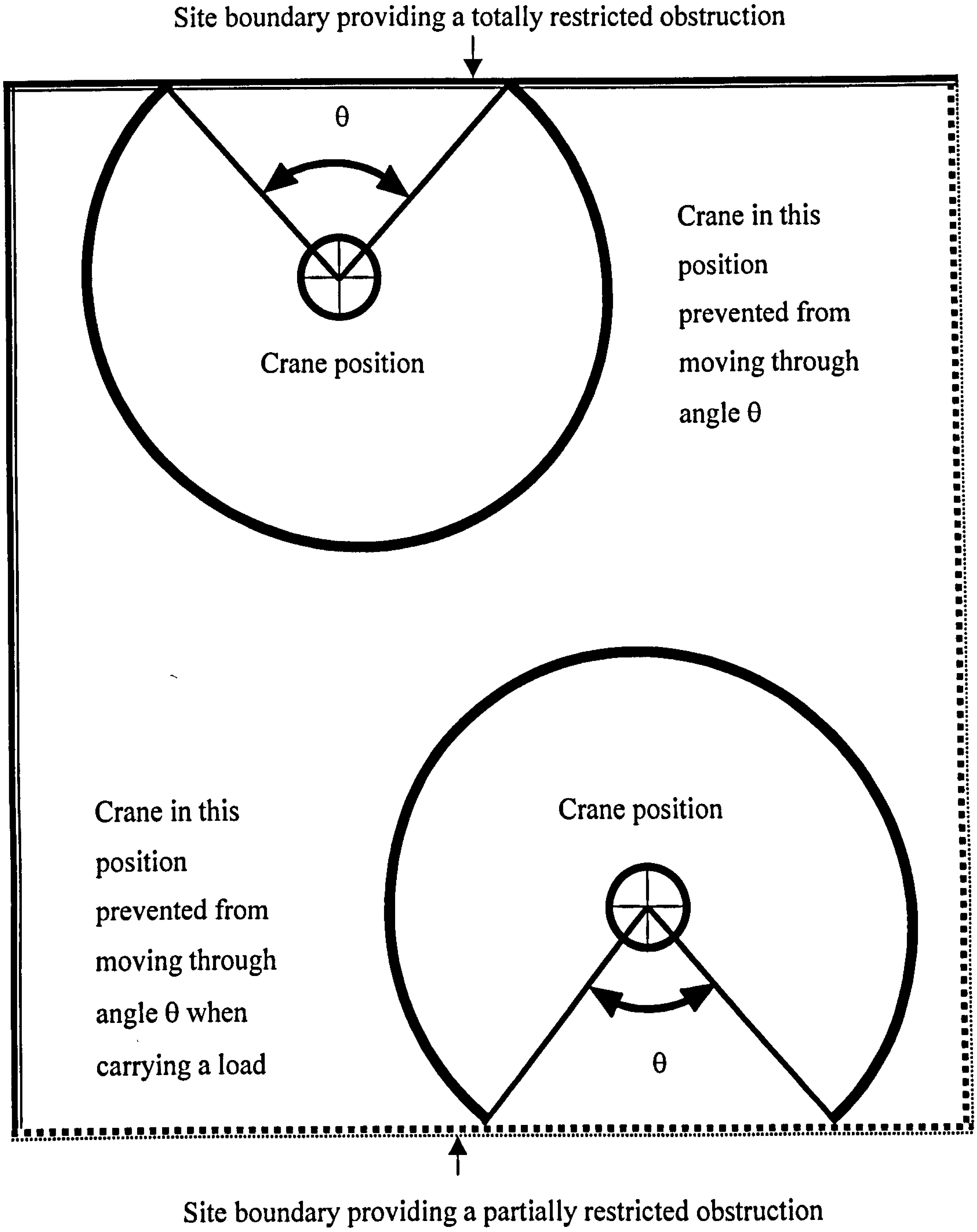
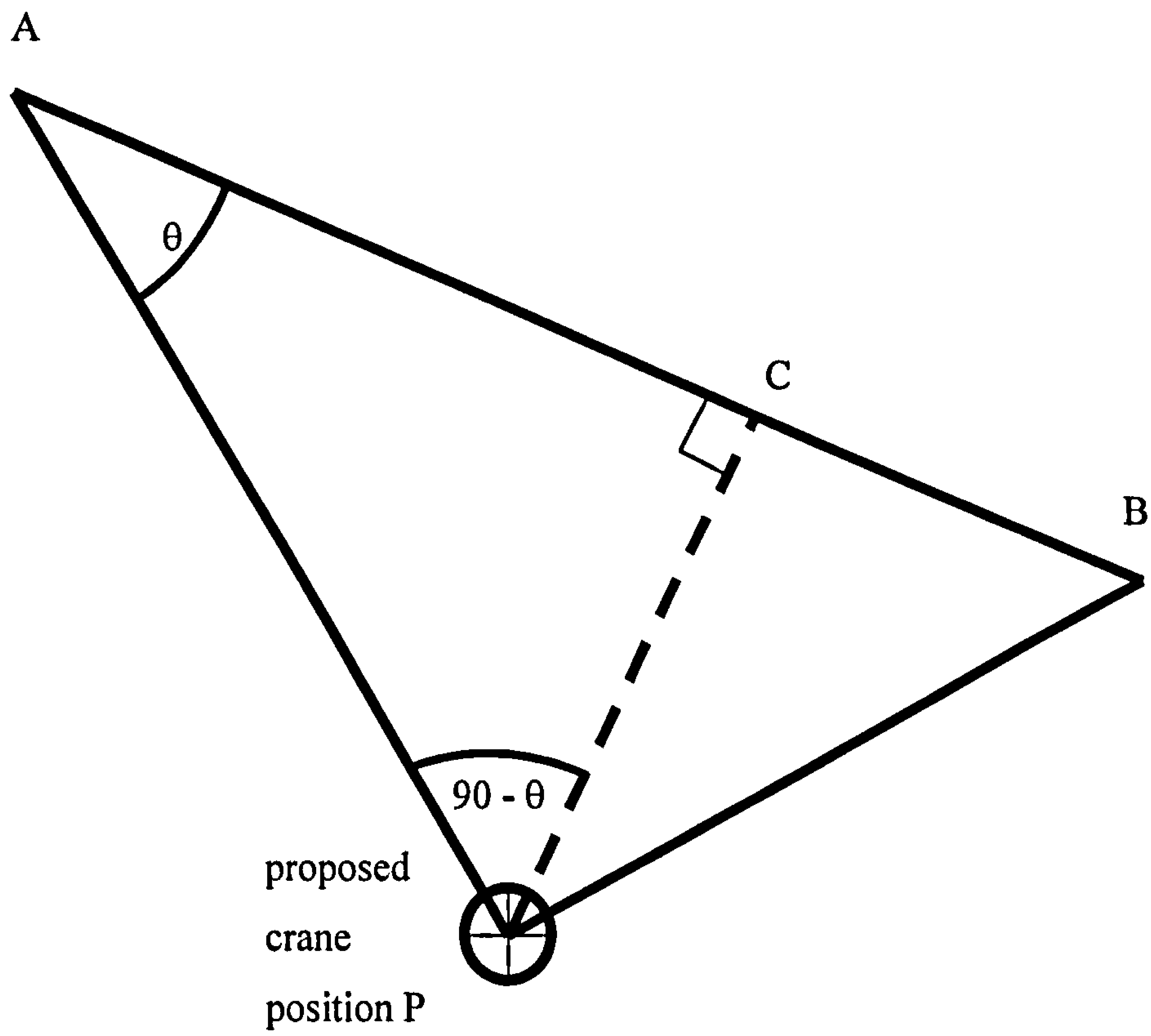


Figure 5.14 **Potential effects of non-materialised obstructions**



Length CP = AP $sin\ \theta$ = AP $cos\ (90 - \theta)$

Figure 5.15 **Philosophy of the procedure to check the effect of non-materialised obstructions**

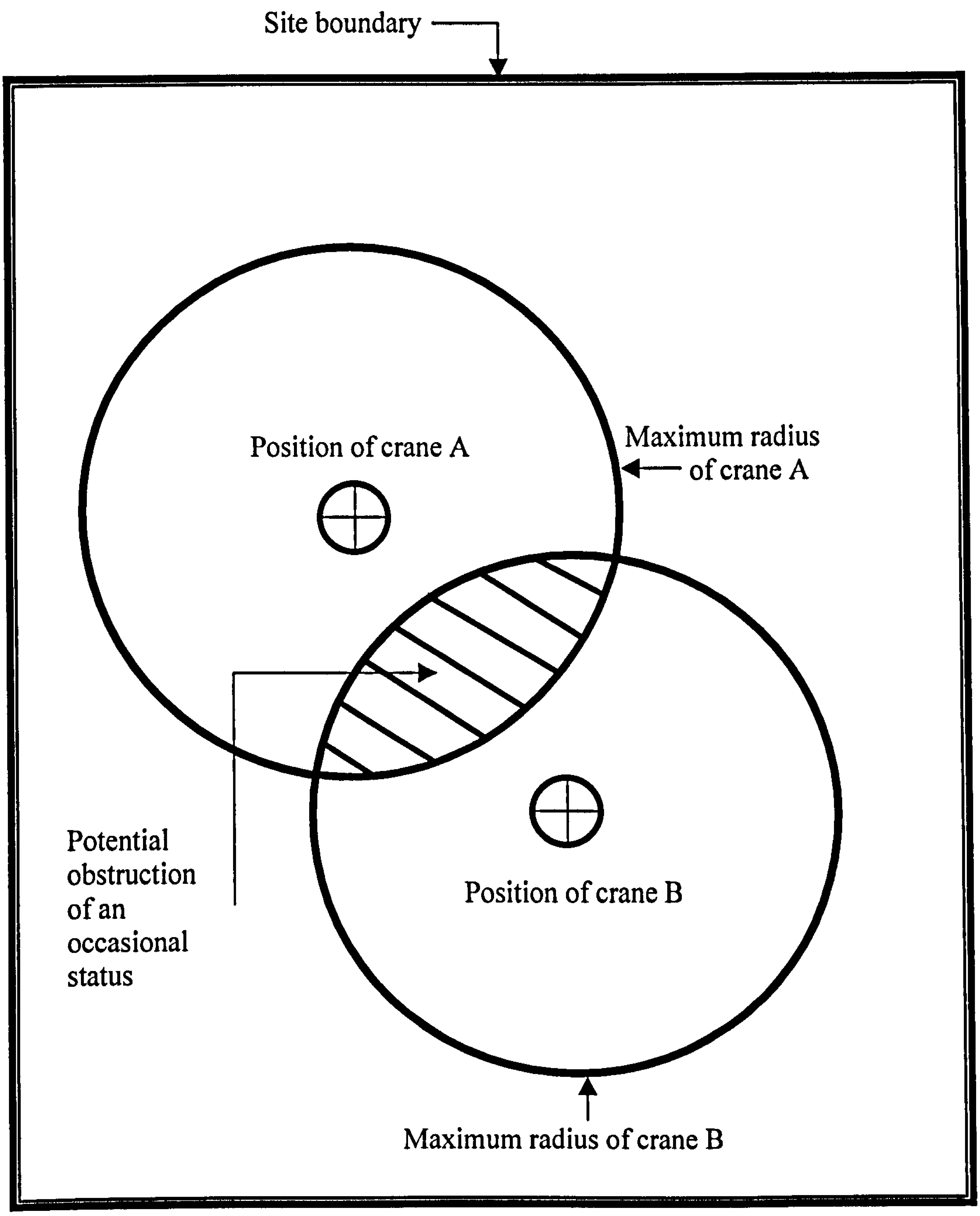


Figure 5.16 **Example of an obstruction of an occasional status**

5.3.3.4 Computation of total crane movement time

It is necessary to compute total crane movement in order that the impact of various positions of the crane may be compared. However, crane movement occurs in three dimensions and so this negates distance as a useful comparator between potential crane positions, as the proportions of radial, angular and vertical movement in any one distance will vary. An alternative measure of the impact of a given crane position is time, which, by including the relevant speeds, incorporates all three types of movement in one single measure.

Rodriguez-Ramos and Francis (1983), in their paper concerning crane location, assumed, albeit for two dimensional movement only, that radial and angular movement were consecutive. Putting aside situations where there is some restriction on the way in which movement can take place (e.g. obstructions) an alternative approach would be to consider that the time taken to move from one point to another is the maximum of the three individual times. Such an approach assumes that the movements of lesser duration have occurred in the time which the movement of longest duration requires; this is the approach adopted by Choi and Harris (1991). Observations in practice suggest that the true situation lies somewhere between these two extremes. On the other hand, Leung and Tam (1999), in their study on hoisting times in high rise construction, suggest that simultaneous movement occurs when loads are being lifted up, but consecutive movement occurs when the crane hook is returning to ground level. However, in this case the emphasis is upon high rise construction when the hoisting times dominate.

However, it is also necessary to consider the relationship between time and distance, and, while the relationship

$$time = \frac{distance}{velocity}$$

is valid, there are other considerations which have to be taken into account. These may be listed as:

initial acceleration and final deceleration;
type of load (if any);
wind speed;
operator experience and skill; and
delays.

Initial acceleration and final deceleration should be taken into account in the calculation of time. However, they have been disregarded as again observations in practice suggest their effect in not important. Their inclusion makes the computation process more cumbersome without any necessary gain in the accuracy of the overall outcome. Further, their omission applies to all movements and so should not have an undue influence.

The type of load and prevalent wind speed will both influence the speed of movement which can be achieved. The movement of large loads, rather than heavy loads, will be slower, particularly when wind conditions are adverse. The influence of wind speeds was discussed in Chapter 4 and it is assumed that the crane does not work above a certain wind speed. However, below this acceptable level, no reduction in working velocities is assumed in respect of either wind speed or large loads. In the case of wind speeds it is impossible to predict the precise speed prevailing at any one time, and, while it may be possible to predict the occurrence of large loads, it is difficult to assess the impact of such loads.

Operator experience and skill is the one factor which is likely to have the largest influence on whether the time taken to move between points approaches the two extremes discussed previously. As there is no way of quantifying this factor it is not possible to include its effect in the model. However, as with many other factors which influence the time to move between facilities, its influence is global and its omission unlikely to have undue impact.

Delays may be disregarded as they will occur independently of the position of the crane.

After due consideration of these factors, and observations of cranes in use, it was decided to base the time value, which the model uses to compare the impact of various crane locations within the site, as the average of the maximum and minimum theoretical times, plus an allowance for raising and lowering the load at the beginning and end of each movement. This approach is not dissimilar to that proposed by Golafshani and Aplevich (1995), who originally suggested that the minimum time should be used, but found that in practice this needed to be increased to prevent large load swings from occurring.

The maximum time for moving between two facilities A and B may be defined as:-

$$(T_{\max})_{AB} = (T_r)_{AB} + (T_a)_{AB} + (T_v)_{AB} \quad .... \quad \textit{Equation 5.2}$$

and the minimum time for moving between two facilities A and B may be defined as:-

$$(T_{\min})_{AB} = \mathrm{MAX}[\,(T_r)_{AB}, (T_a)_{AB}, (T_v)_{AB}\,] \quad .... \quad \textit{Equation 5.3}$$

where $(T_{max})_{AB}$ = maximum time to move FROM facility A TO facility B

$(T_{min})_{AB}$ = minimum time to move FROM facility A TO facility B

$(T_r)_{AB}$ = time to execute the radial movement FROM facility A TO facility B

$$= \frac{\text{radial distance from A to B (metres)}}{S_{rad}\,[\text{radial speed (metres/second)}]}$$

$(T_a)_{AB}$ = time to execute the angular movement FROM facility A TO facility B

$$= \frac{\text{angular distance from A to B (degrees)}}{S_{ang}\,[\text{angular speed (r.p.m.)}] \times 6}$$

where 6 = conversion factor to the appropriate units

$$= \frac{\text{360 (revolutions to degrees)}}{\text{60 (minutes to seconds)}}$$

$(T_v)_{AB}$	=	time to execute the vertical movement FROM facility A TO facility B
	=	$\dfrac{\text{vertical distance from A to B (metres)}}{S_{hoist}\ \text{[hoisting speed (metres/second)]}}$
		where hoisting speed corresponds to raising speed (S_{hoist}) or lowering speed (S_{lower}) as appropriate

All the above times are initially calculated in seconds and must be converted to the appropriate units (hours) at some point in the calculations.

The purpose of incorporating an allowance for raising and lowering the load at the beginning and end of each movement is to imitate that which happens in practice. Observations indicate that generally loads are lifted up before any other movement occurs and that the final movement is one of lowering the load into position. Further, if loads were being moved from two facilities of equal height it is unlikely that such movement would occur at that height but at a greater height, to suit the circumstances. Therefore, an allowance for raising and lowering the load an additional three metres has been incorporated into the time calculation.

Therefore

$$(T)_{AB} = \frac{(T_{\min})_{AB} + (T_{\max})_{AB}}{2} + \frac{3}{S_{raise}} + \frac{3}{S_{lower}}$$

where	$(T)_{AB}$	=	time to move FROM facility A TO facility B
	S_{raise}	=	raising speed (metres/second)
	S_{lower}	=	lowering speed (metres/second)

This calculation must be repeated for every set of facilities between which movement occurs. To obtain the overall time, each value of individual movement must then be multiplied by the number of movements which occur between each set of facilities.

5.4 Model hardware and software

To facilitate the modelling process, four computer programs have been written to represent the manual computation processes, which have been described in the previous section. These programs have been written in Turbo Basic. In each case compiled executable versions of the programs have been provided. This offers two main advantages to the user. Firstly, no knowledge of the programming language is required, as the programs may be run directly from the operating system (MSDOS). Secondly, compiled programs run more quickly than uncompiled programs, as it is not necessary to convert the program statements to machine code on each run.

A brief description of each program is provided below. Figure 5.17 shows how the four programs interact. To facilitate disk and file management each program creates files with a unique file extension. This aids the user in identifying which types of file are in existence and is used by the programs to ensure that data are read to and from the correct files. All the programs are menu driven and written in such a way that the user may input only viable data.

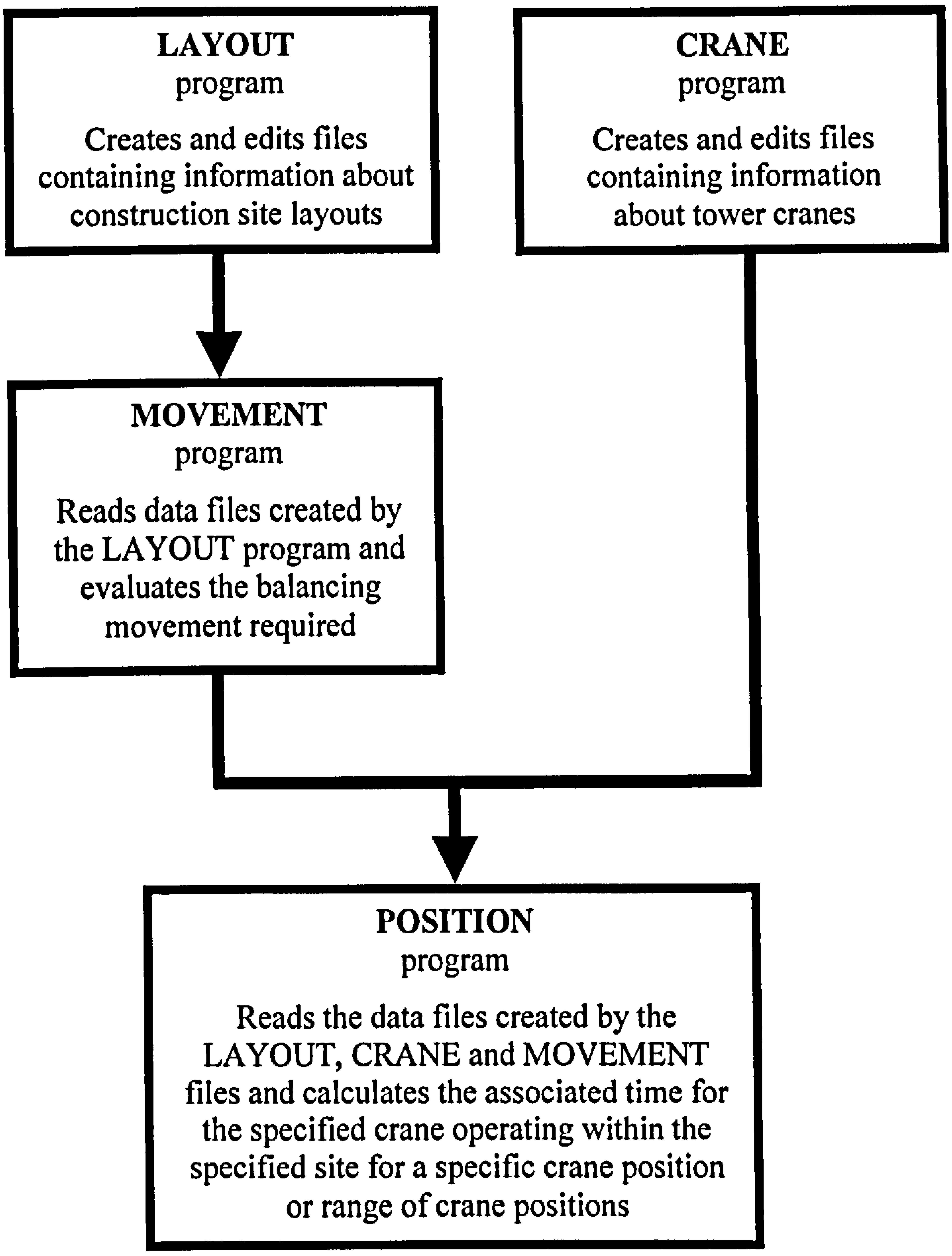


Figure 5.17 **Interaction of computer programs**

Program name - **LAYOUT**

File extension created - .LAY

Main program function

- to create and edit data files containing information about construction site layouts.

Brief program description

- the Main Menu of the program has seven options, which allow the user to create a new data file, retrieve an existing data file, view, edit, print or save the data and end the program. The data required by the program are listed in Chapter 3 (Table 3.2). An example of the output produced by the print option is provided in Table 5.1. The same data are used in the example of the MOVEMENT program (Figure 5.3) and it should be noted that, although 6 facilities exist in this example, details of them all are not shown in Figure 5.1.

Table 5.1 **The LAYOUT program**
An example of the print out

```
************************
* SITE LAYOUT DATA *
************************

Site Layout -  LAYOUT1
File Name -  LAYOUT1


Details of 4 boundary points have been entered

Boundary point (1)

X co-ordinate -   0.00 metres
Y co-ordinate -   0.00 metres
.

Details of 6 facilities have been entered

Facility (1) - CONCRETE BATCHER

This facility occurs at ground level

X co-ordinate -  10.00 metres
Y co-ordinate -  40.00 metres
.

MOVEMENT OF MATERIALS

FROM Facility 1     CONCRETE BATCHER
TO   Facility 2     STEELYARD

No movement of materials between these facilities

MOVEMENT OF MATERIALS

FROM Facility 1     CONCRETE BATCHER
TO   Facility 3     STRUCTURE

Total load    -     400.00 tonnes
Average load  -     0.5 tonnes
Maximum load  -     1.0 tonnes
.
```

Program name - **CRANE**

File extension created - .CRA

Main program function

- to create and edit data files containing information about tower cranes.

Brief program description

- the Main Menu of the program has seven options, which allow the user to create a new data file, retrieve an existing data file, view, edit, print or save the data and end the program. The print option offers the user a further option of a print out of the load capacity at one metre intervals between the minimum and maximum radius. The data required by the program is listed in Chapter 4 (Table 4.7) and depends upon the type of jib employed by the crane. An example of the output produced by the print option is provided in Table 5.2.

Table 5.2 **The CRANE program**
An example of the print out

****
* TOWER CRANE DATA *
****

Crane description	-	LIEBHERR 3150HC
Crane type	-	SADDLE JIB
File name	-	L3150HC
Minimum radius	-	5.55 metres
Radius when load begins decreasing	-	46.20 metres
Corresponding lifting capacity	-	60000.00 kg
Maximum radius	-	80.00 metres
Corresponding lifting capacity	-	32000.00 kg
Dist. from c.l. to jib articulation	-	1.80 metres
Underhook height	-	80.90 metres
Maximum slewing speed	-	0.50 rpm
Maximum trolleying speed	-	1.13 m/s
Maximum raising speed	-	1.27 m/s
Maximum lowering speed	-	1.27 m/s

Radius (metres)	Load capacity (kg)
5.55	60000.00
6.55	60000.00
7.55	60000.00
.	.
.	.
45.55	60000.00
46.55	59493.33
47.55	58088.43
.	.
.	.
77.55	33189.62
78.55	32694.89
79.55	32212.88

Program name - **MOVEMENT**

File extension created - .MOV

Main program function

- to read the data files created by the LAYOUT program and to evaluate the balancing movement required.

Brief program description

- the Main Menu of the program has five options, which allow the user to retrieve an existing LAYOUT data file, calculate the balancing movement required, print and save the total movement between facilities and end the program. The user does not enter data directly but the program retrieves the data file created by the LAYOUT program and uses the relevant data in its calculations. An example of the output produced by the print option is provided in Table 5.3. In the example given there is only one optimum solution. However, if more than one solution existed all solutions would be provided.

Table 5.3

The MOVEMENT program
An example of the print out

****
* SITE MOVEMENT DATA *
****

File Name - LAYOUT2

** ORIGINAL MOVEMENT MATRIX **

TO

FROM	1	2	3	4	5	6
1		100	200	200	200	300
2	0		0	0	0	300
3	200	200		0	0	0
4	0	0	0		100	0
5	0	100	0	100		0
6	200	0	200	0	200	

Number of optimum solutions = 1

SOLUTION - 1

TO

FROM	1	2	3	4	5	6
1		100	200	200	200	300
2	100		0	0	0	300
3	200	200		0	0	0
4	200	0	0		100	0
5	300	100	0	100		0
6	200	0	200	0	200	

Program name - **POSITION**

File extension created - not applicable

Main program function

- to read the data files created by the LAYOUT, CRANE and MOVEMENT files and to calculate the associated time for the specified crane operating within the specified site for a specific crane position or a range of crane positions.

Brief program description

- the Main Menu of the program has four options. The first option (which must be executed before any other option) allows the user to retrieve the data files created by the LAYOUT, CRANE and MOVEMENT files and the final option allows the user to end the program. The remaining two options allow the user to choose between one and multiple potential positions of the crane. Selecting either of these options gives the user a further five options, to enter a position, or range of positions, for the crane, to calculate the associated time (or times) to execute all movements, to print the results, to return to the Main Menu or to end the program.

An example of the output produced by the print option is given in Table 5.4. For each facility the maximum load to be lifted, the distance from the proposed crane position and the maximum lifting capacity of the crane at the position of the facility are provided to aid the user should the crane and its proposed position be unsuitable. The time to execute all movements between facilities is only provided when both the crane position and capacity are satisfactory. If this is not the case, one of the following messages is given to the user:

THIS FACILITY COINCIDES WITH THE POSITION OF THE CRANE

THIS FACILITY IS BEYOND THE REACH OF THE CRANE

THE CRANE IS TOO NEAR THIS FACILITY

THE LOAD CAPACITY AT THIS FACILITY IS EXCEEDED

THE HEIGHT AT THIS FACILITY EXCEEDS THE CRANE'S HEIGHT *(luffing jib)*

THE HEIGHT AT THIS FACILITY EXCEEDS THE CRANE'S UNDERHOOK HEIGHT *(saddle jib)*

The minimum, maximum and average times to execute all movements are provided to reflect the variation, which occurs when more than one optimum solution, exists. When a range of positions have been entered the above information is provided for all specified positions.

Table 5.4 **The POSITION program**
An example of the print out

```
******************************************
* CRANE POSITION AND LOCATION DATA *
******************************************

        Crane data file          -    L3150HC
        Site layout data file    -    LAYOUT2

        Crane description        -    LIEBHERR 3150HC
        Crane type               -    SADDLE JIB

Miinimum radius                       -    5.55 metres
Radius when load begins decreasing    -    46.20 metres
Corresponding lifting capacity        -    60.00 tonnes
Maximum radius                        -    80.00 metres
Corresponding lifting capacity        -    32.00 tonnes

                 No. facilities  -    6

        Facility (1)             -    BRICK DELIVERY POINT

                 X co-ordinate   -    5.00 metres
                 Y co-ordinate   -    5.00 metres
                                 .              .

**** PROPOSED CRANE POSITION ****

                 X co-ordinate   -    25.00 metres
                 Y co-ordinate   -    25.00 metres

Maximum load to be lifted                 -    1.00 tonnes
Distance from proposed crane position     -    28.28 metres
Maximum lifting capacity                  -    60.00 tonnes

CRANE POSITION AND CAPACITY SATISFACTORY

Time to execute all movement between facilities

        Minimum time    -    2.64 hours
        Maximum time    -    2.64 hours
        Average time    -    2.64 hours
```

5.5 Summary

The modelling process to assess the impact of a given crane at a given position, or range of positions, within a given construction site, may only commence when data concerning both the crane and the construction are available; the nature of these data has been discussed in the preceding chapters.

Four stages in the modelling process have been identified. Firstly, it is necessary to compute the balancing movement between facilities which must occur in order to satisfy the requirement that the total number of movements towards a given facility is matched by an equal number of movements away from that facility. This does not strictly depend on the interaction of the construction site and crane data, as it relies on the characteristics of the construction site only. Nevertheless, it is considered to be part of the modelling process, as the magnitude of such movement is determined on the basis of the values of explicit and implicit movement entered into the model.

Secondly, an initial check on crane lifting capacity is required. This has been discussed previously in Chapter 4, but such a check cannot be executed until details about both the crane and construction site are known. It is necessary to ensure that facilities are located within the crane's working radii, i.e. neither too near the crane nor beyond the reach of the crane, and that the crane has sufficient load lifting capacity with respect to the maximum load required to be lifted at each facility. It is also necessary to ensure that the crane's jib is of adequate height and, in respect of a luffing jib crane, this will depend upon the distance from the crane to each facility.

The next consideration is the assessment of any obstructions which may impinge upon the construction site, which either create unserviceable areas and so prevent some facilities from being reached by the crane, or which result in a longer path having to be travelled by the crane hook, rather than the shortest route which could be followed if the obstruction was not present. Obstructions have been classified as one of three types: solid obstructions of a permanent nature (e.g. nearby buildings), non-materialised obstructions (e.g. nearby highway) and obstructions of an occasional status (e.g. the jib of another crane). In the latter case, such obstructions are considered to be outside the scope of this thesis. When a facility is located in an unserviceable area created by a solid obstruction, the situation is untenable and the modelling process cannot be completed. On the other hand, when an obstruction, of either a permanent or non-materialised nature, results in the most direct route no longer being viable, the computation process must make allowance for the additional travelling time required, either due to the crane turning through an angle greater than 180°, or by the need for the crane jib to incorporate additional trolleying and/or luffing movement to allow the obstruction to be circumvented.

The final stage in the modelling process is the computation of total time to execute all movements between facilities. The shortest time to travel between two points is the maximum of the individual components of trolleying, slewing and hoisting and the longest time is the sum of these three components. The model uses the average of these times, with an allowance for raising and lowering the load at the beginning and end of each movement. The total time to execute all movements may then be calculated by summating the time to execute each movement multiplied by the number of movements which occur in each case.

Four computer programs have been developed to execute the modelling process. Two programs are concerned with information relating to the construction site layout and crane details respectively. The third program computes the balancing movement required to ensure that the total number of movements towards any facility is matched by an equal number of movements away from that facility, and the final program reads data files created by the previous three programs and calculates the total time to execute all movements for a given position, or range of positions, of the crane.

CHAPTER 6

COMPARISON WITH OTHER MODELS

6.1 Introduction

As discussed in Chapter 1 and Chapter 2, three other authors, Rodriguez-Ramos and Francis (1983), Choi and Harris (1991) and Zhang *et al.* (1995 and 1996), have proposed models to optimize the position of tower cranes within a construction site. These models have all demonstrated certain shortcomings. While it is appreciated that no model can take into account all variables, many of which are unknown or cannot be predicted with any degree of certainty, the model described in the previous chapter is more comprehensive than the other proposed models. In each case a numerical example has been provided. Therefore, in order to illustrate the perceived inadequacies of each model, the examples have been re-worked using the model proposed in the previous chapter.

6.2 Model proposed by Rodriguez-Ramos and Francis

The model proposed by Rodriguez-Ramos and Francis (1983) is a prescriptive mathematical model with an objective function which aims to minimize the total transportation cost. However, as will be discussed in further detail in the following section, the model actually attempts to determine the optimum position of the crane hook when waiting between movements, and not the optimum position of the crane itself.

The solution algorithm uses polar co-ordinates and is based on the construction of a graph to optimize the angle of the crane hook (relative to the origin) and a mathematical algorithm to optimize the radius of the crane hook (again relative to the origin). Vertical movement is disregarded.

In respect of the angle of the crane hook, graphs are plotted for each facility showing, over the 360 ° through which the crane hook is free to locate, the angle between that facility and the crane hook at that point. As movement may take place in either a clockwise or anti-clockwise direction (assuming that there are no obstructions), two lines are drawn in each case and it is assumed that the minimum value of movement, which is always less than 180 °, is that which is adopted. These graphs are then added together, taking due account of the weighting associated with each facility, and the optimum angle is that corresponding to the minimum angle over the full 360 °.

In respect of the radius of the crane hook, a simple mathematical algorithm based on what is referred to as "median conditions" is used. In any event, the optimum radius will be the radius associated with at least one facility.

The numerical example solved by the model proposed by Rodriguez-Ramos and Francis (1983) is as follows:

"Find the optimum location of a crane servicing construction supportive facility relative to an arbitrary co-ordinate system (that is shown in Figure 6.1). Three supportive facilities are assumed:

(1) location EF_1 at $(\pi/4,6)$;

(2) location EF_2 at $(\pi,6)$; and

(3) location EF_3 at $(3\pi/2,5)$.

Also assume:

(1) $W_1 = 1$, $W_2 = 2$, $W_3 = 1$; and

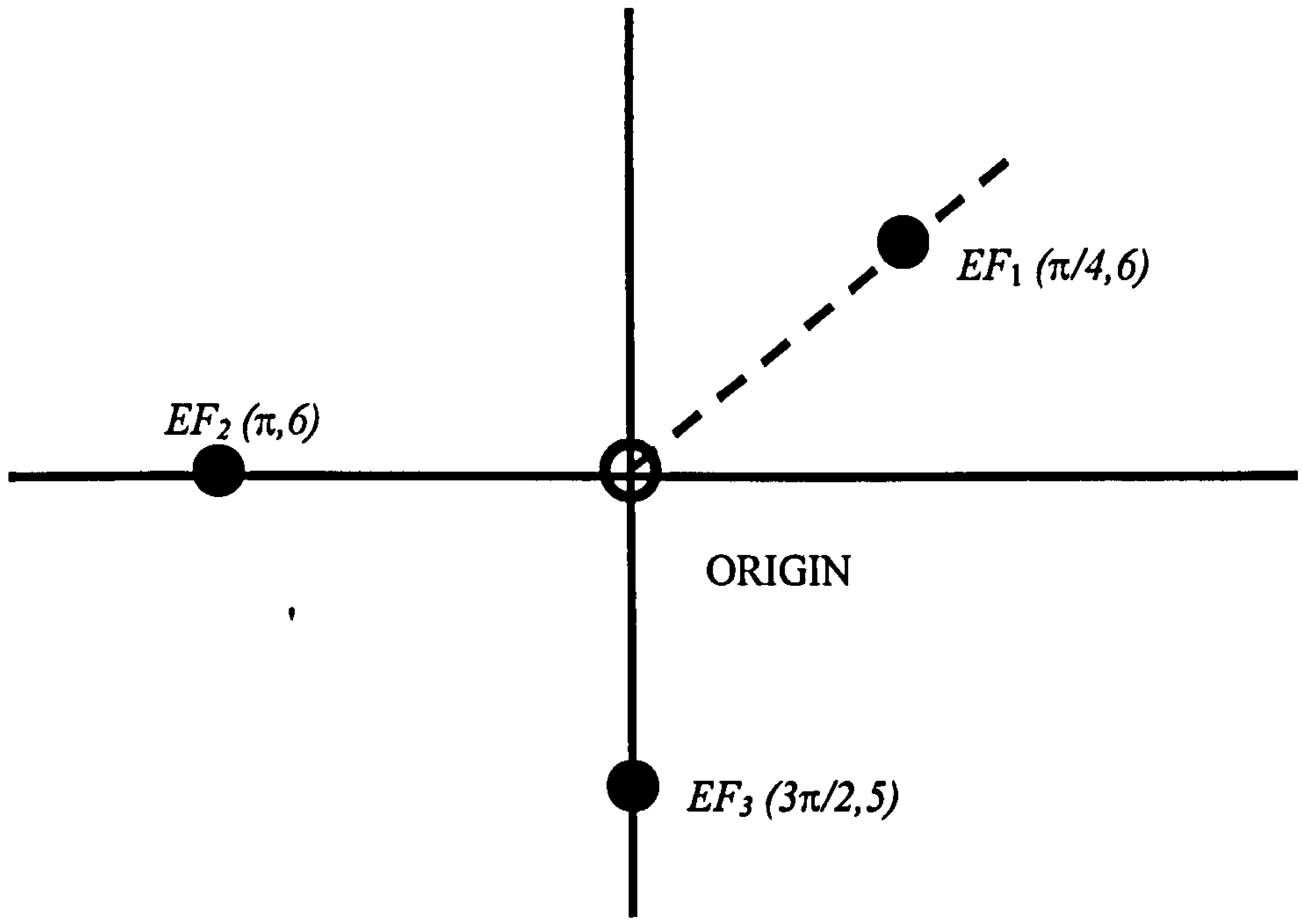
(2) $V_a = 1$, $V_r = 1$.

where W_i = transportation cost weight factor

V_a = angular velocity of the trolley

V_r = radial velocity of the trolley"

Polar co-ordinate system



Cartesian co-ordinate system

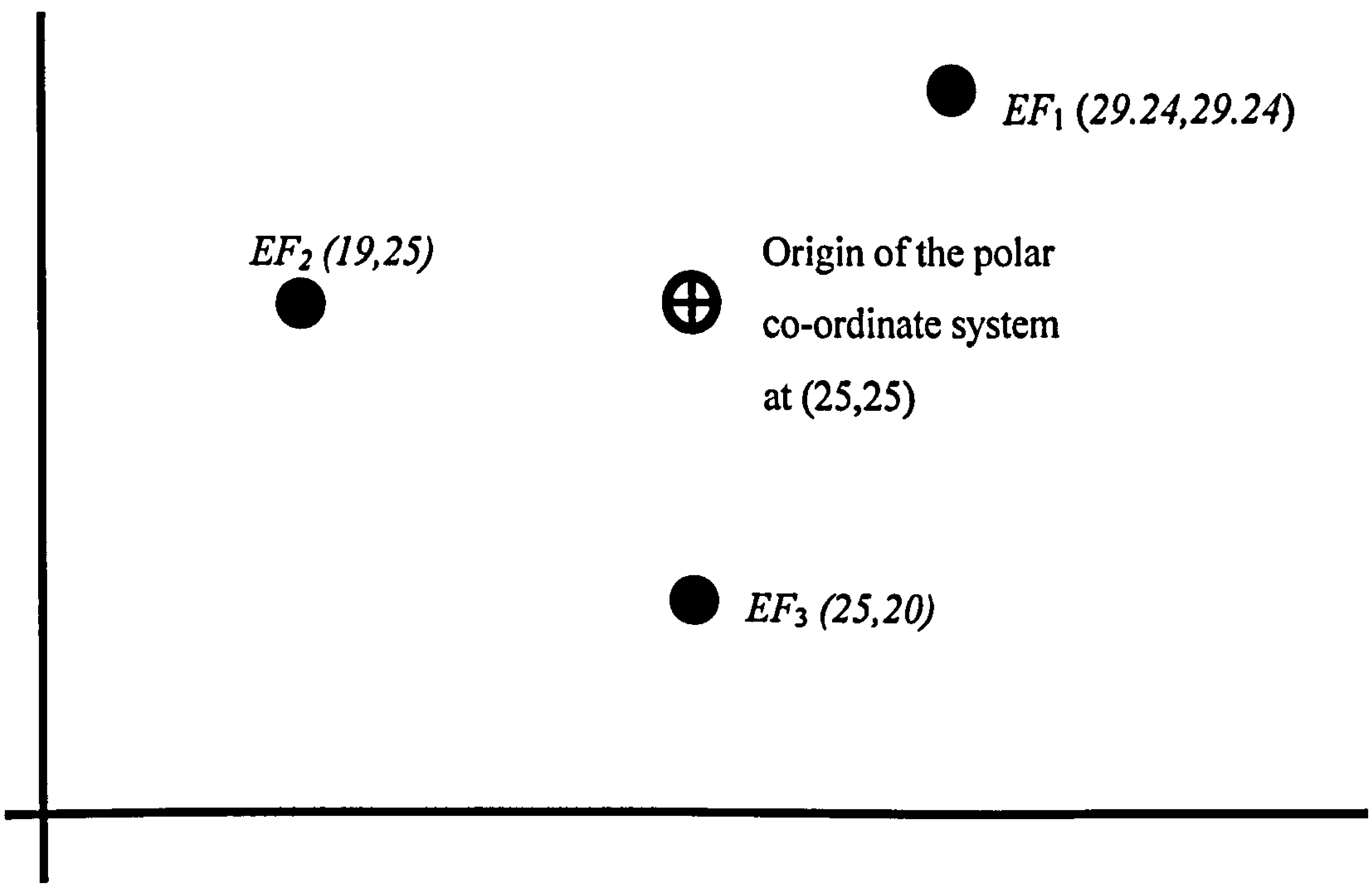


Figure 6.1 **Model and example proposed by Rodriguez-Ramos and Francis Polar and Cartesian co-ordinate systems**

Data required by the model in respect of both site layout data and crane data are detailed in Tables 3.2 and 4.7 respectively. In order that the model may be applied to the example above, these requirements, in so far as they are absolutely necessary, will be discussed below.

6.2.1 Site layout data

In the above example a polar co-ordinate system has been used. However, the model proposed in the previous chapter uses a Cartesian co-ordinate system because it was felt that facilities are usually located using a rectilinear co-ordinate system rather than a polar system. Therefore, the facility positions have been transposed to a Cartesian system, and, for convenience, and in order to avoid negative co-ordinates, the point (25,25) has replaced the polar origin. Both co-ordinate systems, and the respective position of the facilities, are illustrated in Figure 6.1.

It should be noted that no reference has been made to the height of the facilities. Further to this, no reference to this third dimension has been made in the paper which presents the model (Rodriguez-Ramos and Francis 1983). Therefore, it must be assumed, for the purposes of this exercise, that all facilities occur at ground level.

No details of the site boundary have been provided, but this is of little consequence as the site boundary merely serves to contain all facilities and the crane itself. However, some details of the boundary must be provided for the model. Therefore, it will be assumed that the site is four sided with co-ordinates at (0,0), (50,0), (50,50) and (0,50).

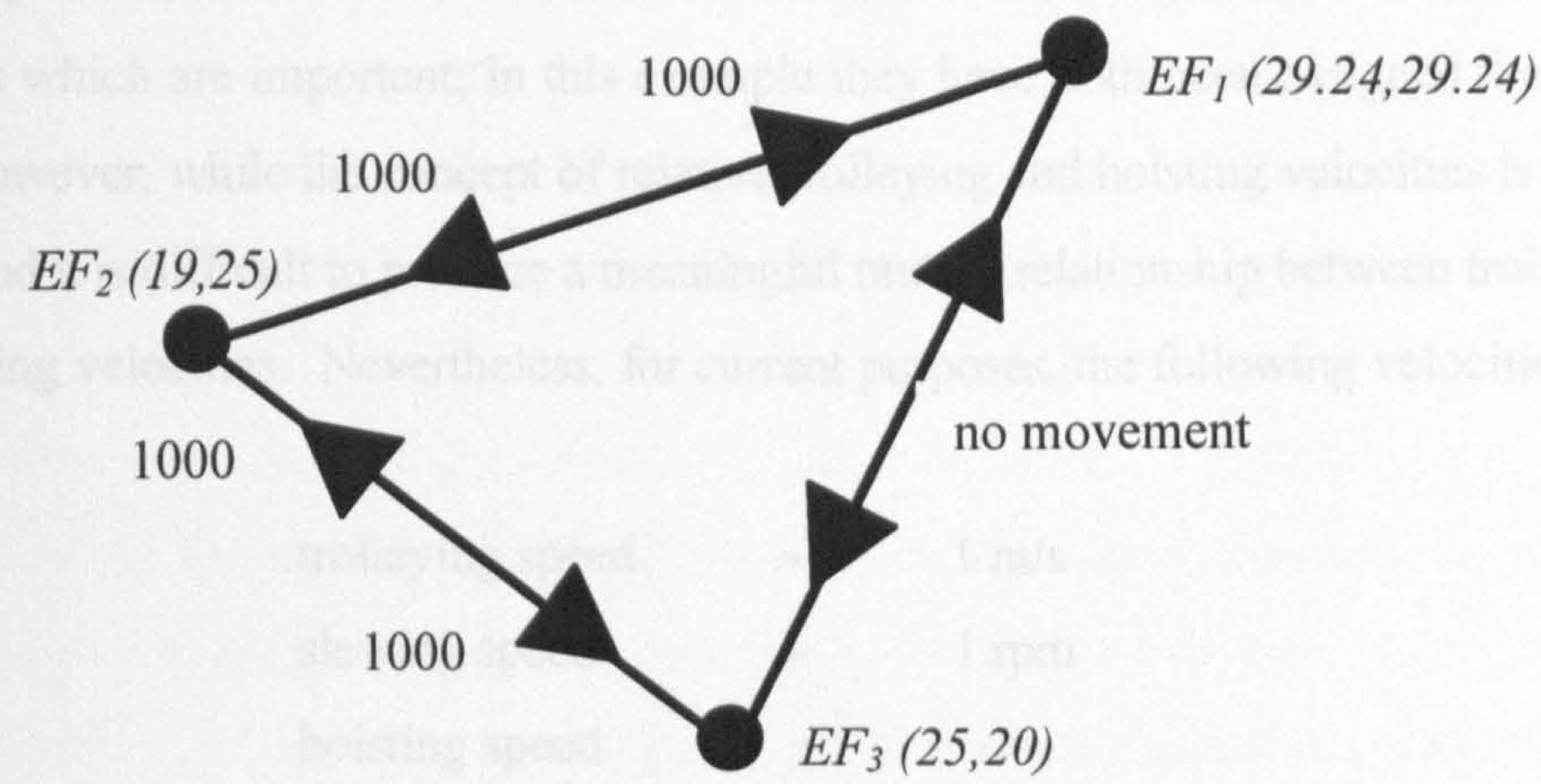
The concept of movement between facilities has been dealt with by the inclusion, in the model, of transport weight cost factors. For a facility *j* this factor is defined as "*W_j is equal to the cost per unit angular or radial travel time multiplied by the estimated number of trips or cycles made in a certain given time period between the crane's unknown location and existing supportive facility j.*" As it seems unlikely that the cost per unit angular or radial travel time will differ, the weight factors may be assumed to be an indication of the estimated number of trips between the crane's unknown position and individual facilities.

However, this approach underlies three fundamental inadequacies of the model. Firstly, it should be appreciated that the model is not attempting to locate the optimum position of the crane but the position of the crane hook when waiting between movements. The paper is somewhat misleading in this respect as the abstract states "*This paper involves the development of a mathematical prescriptive model to establish the optimal location of a crane within a construction site.*". Therefore, the solution obtained for the example provided does not relate to the position of the crane but to the optimum position of the crane hook.

Secondly, using the polar co-ordinate system, the axes have been chosen so that "*a given crane is at the origin of the polar co-ordinate system.*". This may be interpreted to mean that the initial position of the crane hook is at the origin and that the solution provides the position of the crane hook relative to this origin. It is appreciated that both models are attempting to model movement of the crane hook, as the location of the crane remains stationary, but this movement must be computed relative to the crane's position in order to determine the components of radial and angular movement relative to the position of the crane. If the position of the crane in not considered then components of movement can not be evaluated relative to this position.

Thirdly, the model only considers movement between the crane's unknown location (or crane hook position) and the facilities, but does not consider direct movement between the facilities. This would appear to be a gross simplification of the movement of the crane hook during the life of a construction project.

In order to include some value of movement between facilities in the model it can be seen that the transportation cost weight factor associated with the second facility (EF_2) is twice that associated with the other facilities. By inspection, the only way in which this condition can be satisfied is if movement of an equal magnitude occurs in both directions between the other facilities (EF_1 and EF_3) and that facility and that no movement occurs between the other facilities. For the purposes of comparison a trip value of 1000 movements between facilities has been assigned. This is illustrated diagrammatically in Figure 6.2, which also displays the number of movements in tabular form. No values of maximum load have been assigned to each facility but it will be assumed that load lifting capacity is not a restricting factor.



		FROM		
		EF_1	EF_2	EF_3
TO	EF_1		1000	0
	EF_2	1000		1000
	EF_3	0	1000	

Figure 6.2 Model and example proposed by Rodriguez-Ramos and Francis
Number of movements between facilities

6.2.2 Crane data

No details of the crane have been provided, with the exception of angular and radial velocities, which, as shown earlier, have been stated without any units. It is the relative velocities which are important; in this example they have both been assigned the same value. However, while the concept of relative trolleying and hoisting velocities is easily understood it is difficult to produce a meaningful mutual relationship between trolleying and slewing velocities. Nevertheless, for current purposes, the following velocities will be used:

trolleying speed	-	1 m/s
slewing speed	-	1 rpm
hoisting speed		
raising	-	1 m/s
lowering	-	1 m/s

Although it seems curious to express slewing speed in terms of revolutions per minute and the other speeds in term of metres per second, these values have been chosen because they more closely replicate those values suggested by crane manufacturers.

A further disparity between the two models concerns the assumption in the model proposed by Rodriguez-Ramos and Francis that angular and radial movement is consecutive. The model proposed in the previous chapter assumes that the time taken to execute movement in all three dimensions lies somewhere between the minimum time (assuming simultaneous movement) and the maximum time (assuming consecutive movement) with some allowance for the raising and lowering of the crane hook at the beginning and end of each movement. However, one benefit in this assumption that movement is consecutive is that the relative velocities of the crane are then less unimportant.

It can be appreciated that because of this disparity, and the other differences highlighted earlier, a direct comparison of the solutions provided by both models cannot be made. Nevertheless, by attempting such a comparison, the distinction between the two models is highlighted.

It will further be assumed that, in respect of height and minimum and maximum radii, the crane does not impose any restrictions on movement between facilities. This theoretical crane is annotated in the following sections as Crane1. For the purposes of comparison two further cranes are also used:

Crane2 - BPR GT 217B2 tower crane (details provided in Table 6.10)

Crane3 - Liebherr 3150 HC tower crane (details provided in Table 6.11)

A comparison of the associated velocities of all three cranes is given in Table 6.1. It should be noted that in Table 6.10 and Table 6.11, the slewing, raising and lowering velocities (speeds) are given in m/min, whereas in Table 6.1 they are given in m/s. In all cases it is assumed that height, load capacity and minimum and maximum radii do not have any undue influence. It should be noted that these three cranes offer a good range of differing relative velocities, although, as mentioned earlier, as far as the model proposed by Rodriguez–Ramos and Francis is concerned, this is inconsequential.

Table 6.1 **Model and example proposed by Rodriguez-Ramos and Francis Crane velocities used for comparative purposes**

	Crane1	Crane2	Crane3
Trolleying speed M/s	1	1	1.13
Slewing speed Rpm	1	0.8	0.5
Raising speed M/s	1	0.24	1.27
Lowering speed M/s	1	0.24	1.27

6.2.3 Model results

One advantage of the model proposed by Rodriguez-Ramos and Francis is that it is a prescriptive model rather than a descriptive one, that is, it suggests a solution and does not rely on the best guess approach. The optimum position proposed for the example given is stated as (π,6) (polar co-ordinates), or (19,25) (Cartesian co-ordinates). As can be readily appreciated, this seems to be a nonsensical answer, as it coincides with the location of EF_2. However, it must be remembered that the model proposed by Rodriguez-Ramos and Francis is not attempting to locate the optimum crane position, but the optimum position of the hook whilst waiting to move between facilities; hence, in the example given, the optimum position was determined to be directly above EF_2.

The associated times (hours) to complete the movements required are given in Table 6.2 for each crane outlined in the previous section and for a grid encompassing 36 points at 10m intervals in each direction over the assumed 50m x 50m site. In each case, the minimum and maximum values are highlighted, although it should be noted that, due to the relative coarseness of the grid used, the minimum and maximum values may very well change slightly and be located in another position.

6.2.4 Discussion

As can be seen from Table 6.2, the results for all three cranes are remarkably similar in relative terms. The co-ordinates associated with the maximum time are (20,20) in all three cases, and, although there is some disparity in the positions associated with the minimum times, it can be seen that they all occur at the perimeter of the site and that the values at the perimeter are less than those at the centre.

A plan view showing the contours of the times at each position for Crane1 is given in Figure 6.3, which demonstrates that the lesser values are at the perimeter, specifically in this case, to the north and south, and that the greater values occur at the centre, specifically clustering around the point (20,20).

Table 6.2 Model and example proposed by Rodriguez-Ramos and Francis
Re-working of the example using the Chapter 5 model
Times (hours) to complete movements for various crane locations

Crane1

Y co-ordinate						
50	14.32	13.47	13.28	13.69	13.89	14.03
40	15.72	15.14	14.95	15.12	14.84	14.82
30	16.99	17.39	21.97	17.60	16.02	15.97
20	16.57	16.96	23.50	18.15	16.32	16.15
10	15.17	15.21	15.42	14.57	14.46	15.22
0	14.03	13.99	13.92	13.44	13.31	13.95
	0	10	20	30	40	50

X co-ordinate

Crane2

Y co-ordinate						
50	35.47	35.00	34.94	35.02	35.27	35.28
40	36.85	36.81	37.10	36.92	36.28	35.98
30	38.14	38.68	46.00	39.65	37.47	37.12
20	37.70	38.59	48.07	40.76	37.71	37.35
10	36.53	36.88	37.38	36.39	35.98	36.38
0	35.37	35.47	35.26	34.98	34.73	35.05
	0	10	20	30	40	50

X co-ordinate

Crane3

Y co-ordinate						
50	13.57	14.00	14.43	14.28	13.69	13.24
40	14.21	16.13	18.38	17.75	14.79	13.80
30	15.42	16.64	32.68	20.00	16.05	14.56
20	14.97	17.53	36.43	23.48	16.60	14.88
10	14.73	16.15	18.84	16.25	14.84	13.97
0	13.62	14.20	14.42	14.04	13.34	13.00
	0	10	20	30	40	50

X co-ordinate

Figure 6.4 shows an isometric view of the same grid, with the values expressed relative to the minimum value. This portrays a very similar picture to that in Figure 6.3.

In comparing the results given by the model proposed in this thesis with the results given by the model proposed by Rodriguez-Ramos and Francis the following may be concluded.

- According to the proposed model, the optimum crane location is at the perimeter of the site and, generally, locating the crane at the site perimeter, will result in lower times to carry out all the necessary movements than if the crane was located in the centre of the site.

- The optimum position recommended by Rodriguez-Ramos and Francis is near to the position associated with the maximum time, according to the proposed model. However, this is because the model proposed by Rodriguez-Ramos and Francis is not attempting to locate the optimum crane position, but the optimum position of the hook whilst waiting to move between facilities.

- The outputs given when using the model with the three cranes described, which have a range of differing relative velocities, are very similar in relative terms.

6.3 Model proposed by Choi and Harris

The model proposed by Choi and Harris (1991) is based on symbolic model formulation and attempts to calculate the total transportation cost associated with different crane positions, suggested by the user, and assigns the optimum position as being that position associated with the least cost. The calculation is based on computing the components of radial and angular movement between facilities, which depend on the proposed crane position, and takes into account the inter-facility weightings, where these are known for anticipated movement between facilities.

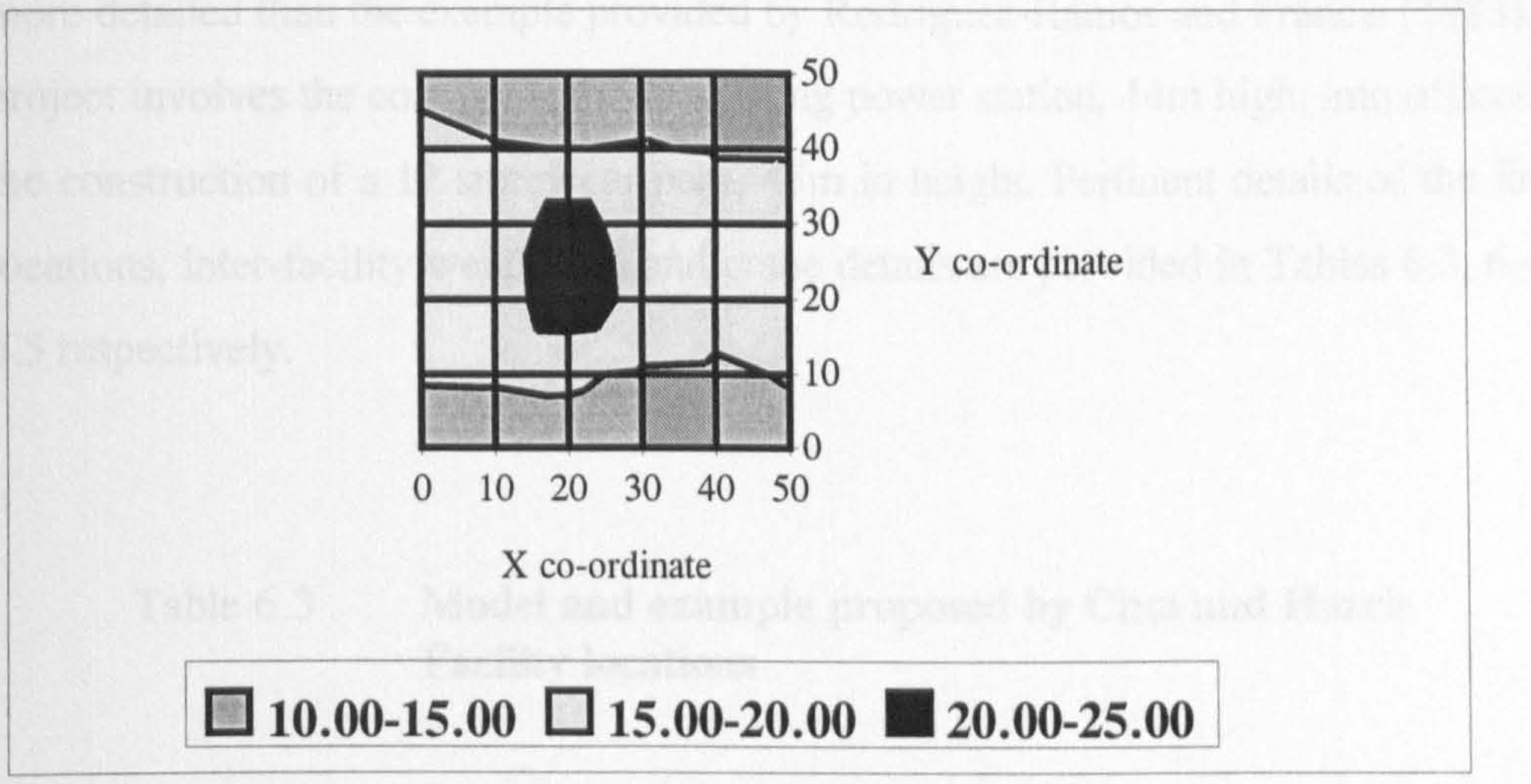


Figure 6.3 **Model and example proposed by Rodriguez-Ramos and Francis Plan view of grid of times (hours) associated with Crane1**

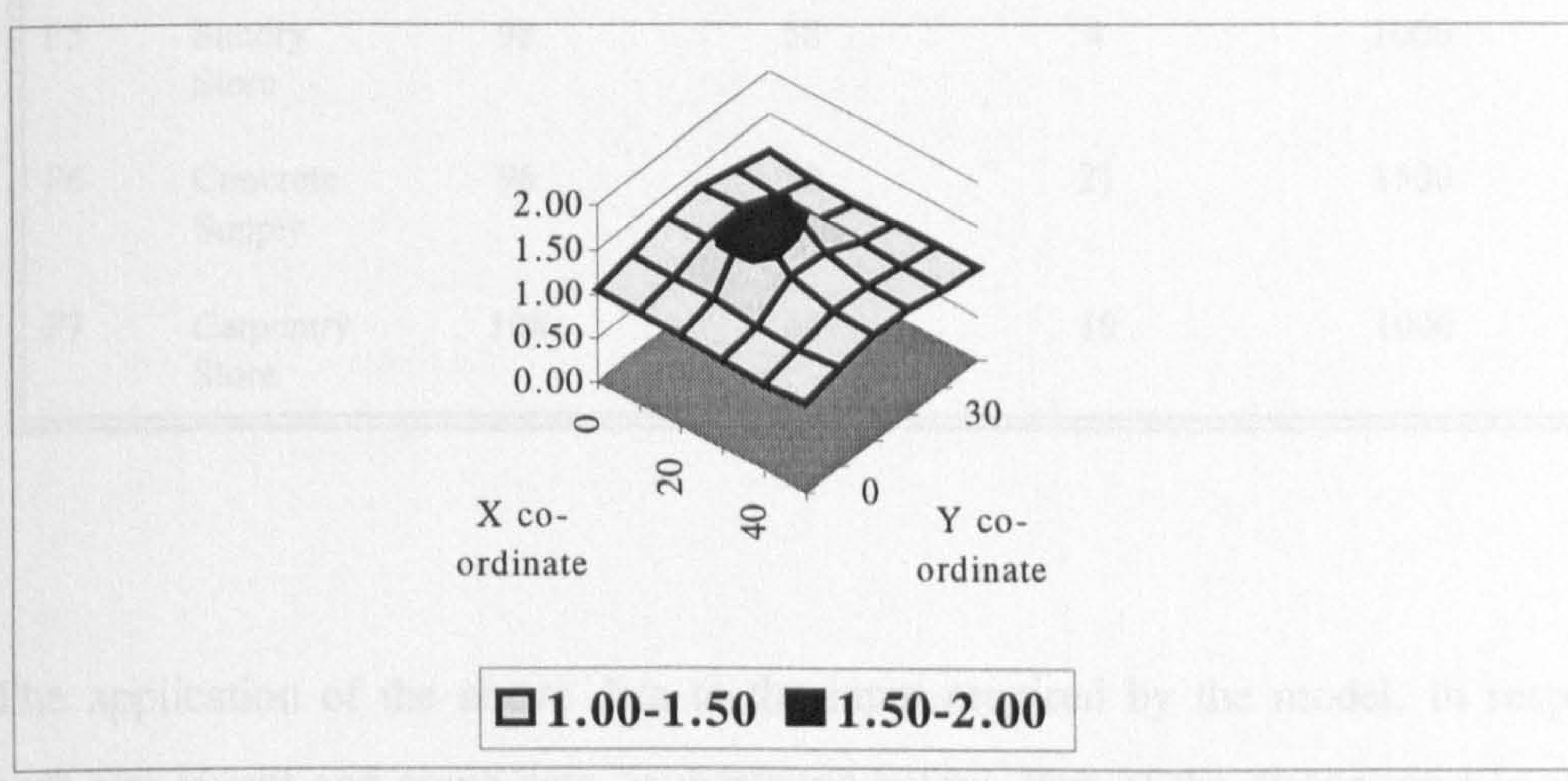


Figure 6.4 **Model and example proposed by Rodriguez-Ramos and Francis Isometric view of grid of relative times associated with Crane1**

The numerical example solved by the model proposed by Choi and Harris (1991) is based on a case study rather than a purely theoretical example and is therefore much more detailed than the example provided by Rodriguez-Ramos and Francis (1983). The project involves the conversion of an existing power station, 44m high, into offices, and the construction of a 12 storey car park, 45m in height. Pertinent details of the facility locations, inter-facility weightings and crane details are provided in Tables 6.3, 6.4 and 6.5 respectively.

Table 6.3 **Model and example proposed by Choi and Harris Facility locations**

Facility No.	Facility Name	X co-ord (m)	Y co-ord (m)	Weighting (%)	Average Load (kg)
F1	Steel Yard	28	44	35	2000
F2	Office	63	63	6	2000
F3	Carpark	74	34	4	2000
F4	Platform	88	44	20	1000
F5	Sundry Store	98	58	4	1000
F6	Concrete Supply	96	52	21	1500
F7	Carpentry Store	108	46	10	1000

The application of the above data to the input required by the model, in respect of both site layout and crane data, is discussed below. Part of the discussion has already been published in a discussion paper in response to the original publication by Choi and Harris (Emsley 1992).

Table 6.4 **Model and example proposed by Choi and Harris Inter-facility weightings**

FROM / TO	F1	F2	F3	F4	F5	F6	F7	TOTAL
F1								
F2	21%				3%	10%	6%	40%
F3	14%			20%	1%	11%	4%	50%
F4								
F5								
F6								
F7		6%	4%					10%
TOTAL	35%	6%	4%	20%	4%	21%	10%	100%

Table 6.5 **Model and example proposed by Choi and Harris Crane details**

Crane selected	=	BPR GT 217B2
Jib length	=	50 m
Underhook height	=	50 m
Angular velocity	=	360 deg/min
Radial velocity	=	30 m/min

6.3.1 Site layout data

The above example uses a Cartesian co-ordinate system, which is compatible with the model. As with the previous example, no reference is made to the height of the facilities but the author does acknowledge that this is an omission. However, it will again be necessary to assume that all facilities occur at ground level although the second, third and fourth facilities, F2, F3 and F4 representing the Office (Building), (12 Storey) Carpark and (Temporary) Platform respectively, by implication, do not exist at ground level.

No details of the boundaries have been enumerated but a scaled diagram included in the paper indicates the position of the boundary relative to the origin. Details of the boundary, scaled from the diagram, are given in Table 6.6. They are included for the completeness of the model. Figure 6.5 shows the boundary and the location of the facilities within the boundary.

Table 6.6 **Model and example proposed by Choi and Harris**
Boundary location

Boundary Point	X co-ordinate (m)	Y co-ordinate (m)
1	0	90
2	0	42.5
3	23.5	42.5
4	68	0
5	84	0
6	118.5	34
7	118.5	90

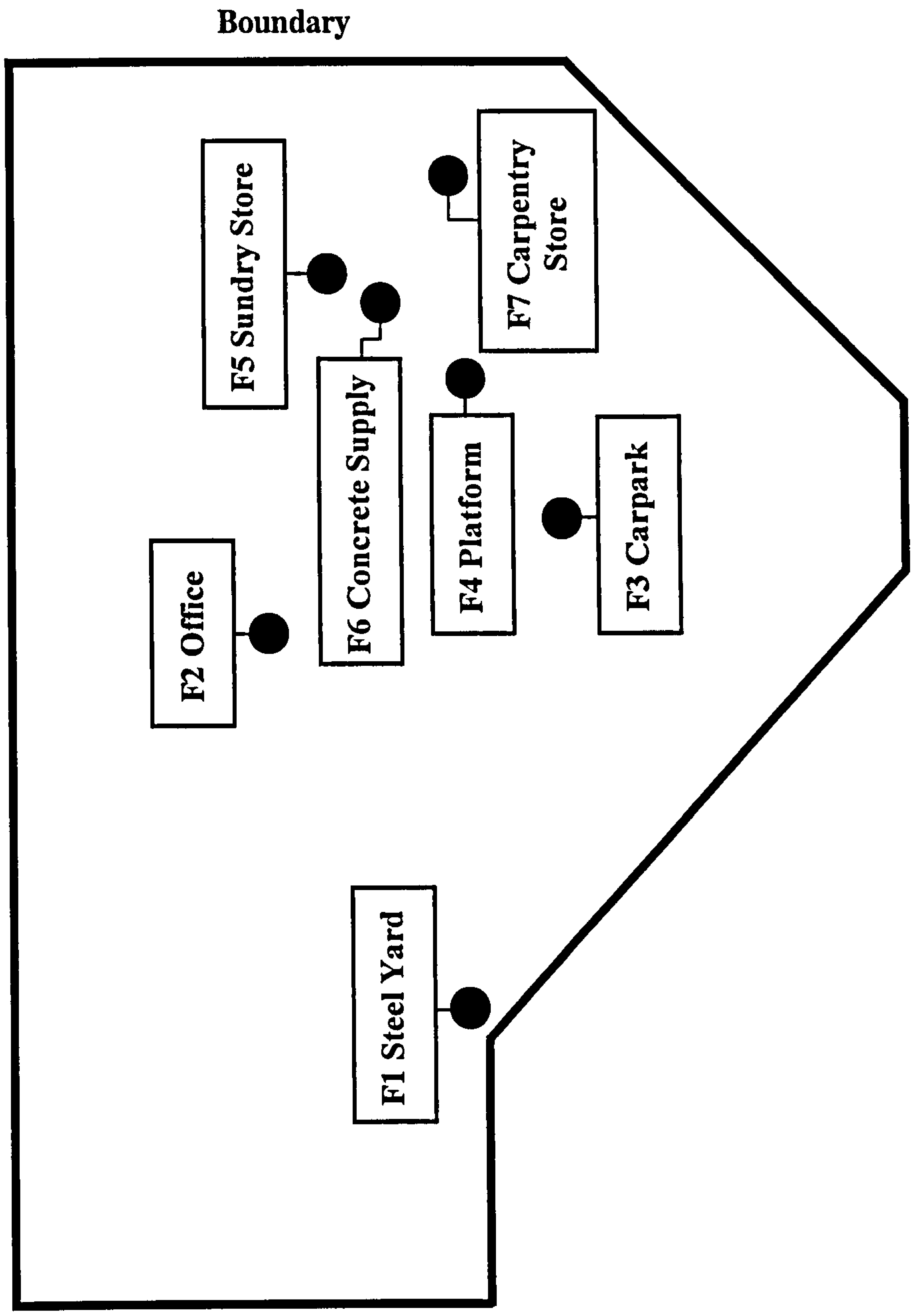


Figure 6.5 **Model and example proposed by Choi and Harris Boundary and location of facilities**

In this example, the concept of movement between facilities has been handled by the provision of inter-facility weightings. The frequencies of movements between facilities has been computed by dividing the total weight of material to be moved, from one facility to another, by the average economic lift, in order to give the total number of movements expected between facilities. Of course, in many cases, there will be no direct movement between facilities. The weightings have been obtained by expressing the values of movement as a percentage of the total movement, and in this way the inter-facility weighting may be defined as "*the percentage measurement of the expected movement frequency between two specific facilities.*" This approach is similar to that described in Chapter 3 for the evaluation of explicit movement, which is that movement which occurs when the crane is moving a load from one point to another. Choi and Harris have defined this movement as "Positive Movement" and further state that "*every lifting movement must undergo a return move ...*". This is similar to the concept of implicit movement, also defined in Chapter 3, with the distinction that implicit movement does not always occur after explicit movement. The fundamental difference between the two approaches is the inclusion, in the model described in Chapter 5, of balancing movement which ensures that total number of movements towards a facility is matched by the total number of movements away from that facility. However, Choi and Harris recognize the limitations of his method but state that "*for the purpose of evaluating the performance of different crane positions, the value provided is adequate enough to suggest a best crane position ....*".

Following this, it is apparent that there are three possible movement scenarios.

Movement1: All movements indicated in Table 6.4, which shows inter-facility weightings for the model proposed by Choi and Harris, are countered by return movement (implicit movement as defined by the proposed model). This is necessary because, as can be seen in Table 6.4, without the inclusion of such movement, the basic condition that the number of movements towards a facility must be matched by an equal number of movements away from that facility, is violated. For computational purposes, movements expressed in percentages have been expressed in terms of real numbers. For example, 21% in Choi and Harris's model has been replaced by 2100 movements.

Movement2 No assumption is made about return movements and the MOVEMENT program of the model is used to generate the optimum viable solution (i.e. least number of movements) so that the above condition (number of movements towards a facility must be matched by an equal number of movements away from that facility) is satisfied. In practice, this demonstrates an interesting feature of the proposed model, because, for the movements proposed, there are eleven alternative optimum solutions.

Movement3 An examination of Table 6.4 indicates that movement between Facilities 2 and 3 and Facility 7 are identical in both directions. Therefore, a viable alternative is to counter movements between all other facilites by return (or implict) movement, but assume that such movement has already occurred between these facilities.

The original and optimum movement matrices are shown in Table 6.7 for these three movement scenarios. It should be noted that, in respect of Movement2, only two of the eleven possible solutions are shown.

Table 6.7 **Model and example proposed by Choi and Harris**
Original and optimum movement matrices

Movement1

Original movement matrix

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2	*2100*				*300*	*1000*	1200
3	*1400*			*2000*	*100*	*1100*	800
4			2000				
5		300	100				
6		1000	1100				
7		1200	800				

Optimum solution

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2	2100				300	1000	1200
3	1400			2000	100	1100	800
4			2000				
5		300	100				
6		1000	1100				
7		1200	800				

Note: a) implicit movement shown in italics

b) the original numbers of movement from Facilities 2 and 3 to Facility 7 and from Facility 7 to Facilities 2 and 3 are 600 and 400 respectively in both cases; they have been doubled to account for implicit movement (see Table 6.4)

Movement2

Original movement matrix

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2						1000	600
3						1100	400
4			2000				
5		300	100				
6		1000	1100				
7		600	400				

Optimum solution 1

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2				2000	400	1000	600
3	3500					1100	400
4			2000				
5		300	100				
6		1000	1100				
7		600	400				

Optimum solution 11

	TO						
FROM	1	2	3	4	5	6	
1		2100	1400				
2	10			1990	400	1000	600
3	3490			10		1100	400
4			2000				
5		300	100				
6		1000	1100				
7		600	400				

Movement3

Original movement matrix

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2	*2100*				*300*	*1000*	600
3	*1400*			*2000*	*100*	*1100*	400
4			2000				
5		300	100				
6		1000	1100				
7		600	400				

Optimum solution

	TO						
FROM	1	2	3	4	5	6	7
1		2100	1400				
2	2100				300	1000	600
3	1400			2000	100	1100	400
4			2000				
5		300	100				
6		1000	1100				
7		600	400				

Note: a) implicit movement shown in italics

As mentioned earlier, no reference is made to the height of facilities. However, for the purposes of comparison it was decided to also include scenarios where facilities F2, F3 and F4 do not occur at ground level. The height of the office and carpark were mentioned by Choi and Harris as being 44m and 45m respectively and the height of the platform has been assumed to be 20m. The assumed heights of these facilities, for the purpose of comparison, are as shown in Table 6.8.

Table 6.8 **Model and example proposed by Choi and Harris**
Proposed facility heights

Facility	Description	Height (m)
F2	Office	44
F3	Carpark	45
F4	Platform	20

Therefore, combining the three movement scenarios described earlier with the concept of all facilities occurring at ground level or, more realistically, some facilities not occurring at ground level, produces six possible combinations of layouts, as shown in Table 6.9.

Table 6.9 **Model and example proposed by Choi and Harris**
Movement and facility level combinations

Layout	Movement scenario	Level of facilities
1	Movement1	Ground level
2	Movement1	F2,F3,F4 not at ground level
3	Movement2	Ground level
4	Movement2	F2,F3,F4 not at ground level
5	Movement3	Ground level
6	Movement3	F2,F3,F4 not at ground level

Again no values of maximum load have been assigned to each facility but it will be assumed that this is not a limiting factor (and for the purposes of comparison that the maximum load equates to the average load given in Table 6.3).

A similar disparity between the models concerning simultaneous or consecutive components of movement also occurs. In this case, Choi and Harris have assumed that the minimum time to execute movement is valid and so movements occur simultaneously with the movement of longest duration equating to the time used in the model.

6.3.2 Crane data

The data provided for the crane is incomplete when compared with the requirements given in Table 4.7. However, the complete data required for the model can be obtained from the manufacturer's data sheet and are given in Table 6.10 (see also Table 4.3). However, comparing these data with those in Table 6.5, highlights a problem, namely that the angular and radial velocities cited by Choi and Harris are not the same as those given by the manufacturer, who gives a range of velocities for trolleying (radial velocity), slewing (angular velocity) and hoisting.

Choi and Harris use a slewing (angular) velocity of 360 deg/min or 1rpm, while the manufacturer specifies a maximum velocity of 0.8rpm, which is the value given in Table 6.10. Further, Choi and Harris use a radial (trolleying) velocity of 30m/min, whilst the manufacturer specifies three alternative values of 7.5m/min, 30m/min or 60m/min. The value given in Table 6.10 has been chosen to be the maximum one of 60m/min (or 1m/s). The hoisting (raising and lowering) velocities are disregarded by Choi and Harris, as their model considers two dimensions only. Examination of the manufacturer's data sheet shows that the position in respect of this velocity is complicated, as there are three possible speeds of operation for the standard arrangement, depending upon the arrangement of the ropes used for hoisting. An optional arrangement gives a further four choices. It was decided to select the velocity associated with one of the arrangements for the intermediate speed of operation, namely 14.5 m/min (or 0.24m/s).

For the purposes of comparison, four cranes have been used, each with different sets of trolleying, slewing and hoisting velocities.

- Crane1 - that proposed by Rodriguez-Ramos and Francis.
- Crane2a - the BPR GT 217B2 tower crane (proposed by Choi and Harris) full details of which are given in Table 6.10, as mentioned above.
- Crane2b - the BPR GT 217B2 tower crane with the trolleying and slewing velocities suggested by Choi and Harris, but with hoisting velocities of 0.24m/s. (Note that it is impossible to run the model proposed here with zero values of hoisting velocities, as this will result in the time to complete all movements to be infinitely long).
- Crane3 - Liebherr 3150 HC tower crane, details of which are provided in Table 6.11.

A summary of the velocities for these cranes is provided in Table 6.12.

6.3.3 Model results

Choi and Harris have identified four possible crane positions. These are as stated in Table 6.13.

An attempt was made to run the model with the site layout and crane data provided for the potential positions given in the above table. However, because the model proposed by Choi and Harris give little consideration to the physical constraints imposed by the crane, it was found that none of the proposed positions were suitable.

Table 6.10 **Model and example proposed by Choi and Harris BPR GT 217B2 tower crane data**

General Information	Crane description	-	BPR GT 217B2
Crane Type	Saddle Jib		
Load Capacity	Minimum Radius	-	12.9m
	Corresponding Load Capacity	-	8000kg
	Radius at which load capacity begins to decrease	-	12.9m
	Maximum Radius	-	50.0m
	Corresponding Load Capacity	-	1400kg
	Distance from centre line of tower to point of jib articulation	-	1.23m
Speeds	Trolleying speed	-	60m/min
	Slewing speed	-	0.8rpm
	Hoisting speed		
	raising	-	14.5m/min
	lowering	-	14.5m/min
Heights	Underhook height	-	50m

Note:- i) Two versions of the 50m jib crane are available. It has been assumed that the 8000kg capacity crane has been used.

ii) The underhook height of 50m has been assumed.

Table 6.11 **Model and example proposed by Choi and Harris Liebherr 3150 HC tower crane data**

General Information	Crane description	-	Liebherr 3150 HC
Crane Type	Saddle Jib		
Load Capacity	Minimum Radius	-	5.55m
	Corresponding Load Capacity	-	60000kg
	Radius at which load capacity begins to decrease	-	46.2m
	Maximum Radius	-	80.0m
	Corresponding Load Capacity	-	32000kg
	Distance from centre line of tower to point of jib articulation	-	1.80m
Speeds	Trolleying speed	-	68m/min
	Slewing speed	-	0.5rpm
	Hoisting speed		
	- raising	-	76m/min
	lowering	-	76m/min
Heights	Underhook height	-	80.9m

Table 6.12 **Model and example proposed by Choi and Harris Crane velocities used for comparative purposes**

	Crane1	Crane2a	Crane2b	Crane3
Trolleying speed m/s	1	1	0.5	1.13
Slewing speed Rpm	1	0.8	1	0.5
Raising speed m/s	1	0.24	0.24	1.27
Lowering speed m/s	1	0.24	0.24	1.27

Table 6.13 **Model and example proposed by Choi and Harris Proposed crane positions**

Crane Position	X co-ordinate (m)	Y co-ordinate (m)
C1	63	55
C2	63	49
C3	68	49
C4	68	43

Details of the problems encountered are given in Table 6.14 and also displayed graphically in Figure 6.6, which shows that only crane position C3 is within the feasible area for locating the crane (as far as the jib length is concerned); although the crane's load capacity is exceeded in that position in respect of facility F7. For details of the calculation of load capacity refer to Equation 4.2 and Table 4.3.

Table 6.14 **Model and example proposed by Choi and Harris**
Problems encountered with crane positions

Crane Position	Facility	Distance to this Facility (m)	Load Capacity at this Radius (kg)	Comments
C1 (63,55)	F2 (63,63)	8.0	n/a	Crane too near F2
C1 (63,55)	F7 (108,46)	45.89	1591	Load capacity exceeded
C2 (63,49)	F7 (108,46)	45.10	1632	Load capacity exceeded
C3 (68,49)	F1 (28,44)	40.31	1918	Load capacity exceeded
C3 (68,49)	F7 (108,46)	40.11	1928	Load capacity exceeded
C4 (68,43)	F1 (28,44)	40.01	1935	Load capacity exceeded
C4 (68,43)	F3 (73.34)	10.30	n/a	Crane too near F3
C4 (68,43)	F7 (108,46)	40.11	1928	Load capacity exceeded

However, it is unexpected that such a situation should occur as the paper implies, although does not specifically state, that a crane of the type specified was located in one of the positions given and used to move materials of the loads stated.

It can be seen that two problems occur; load capacity is exceeded at certain facilities and, in some cases, the crane is too near a facility. The first problem can be overcome by reducing the load to be lifted at each facility, but the second problem can only be solved by the use of a different crane. However, in order to demonstrate the model, the program was run with checks concerning load capacity and operating radii by-passed.

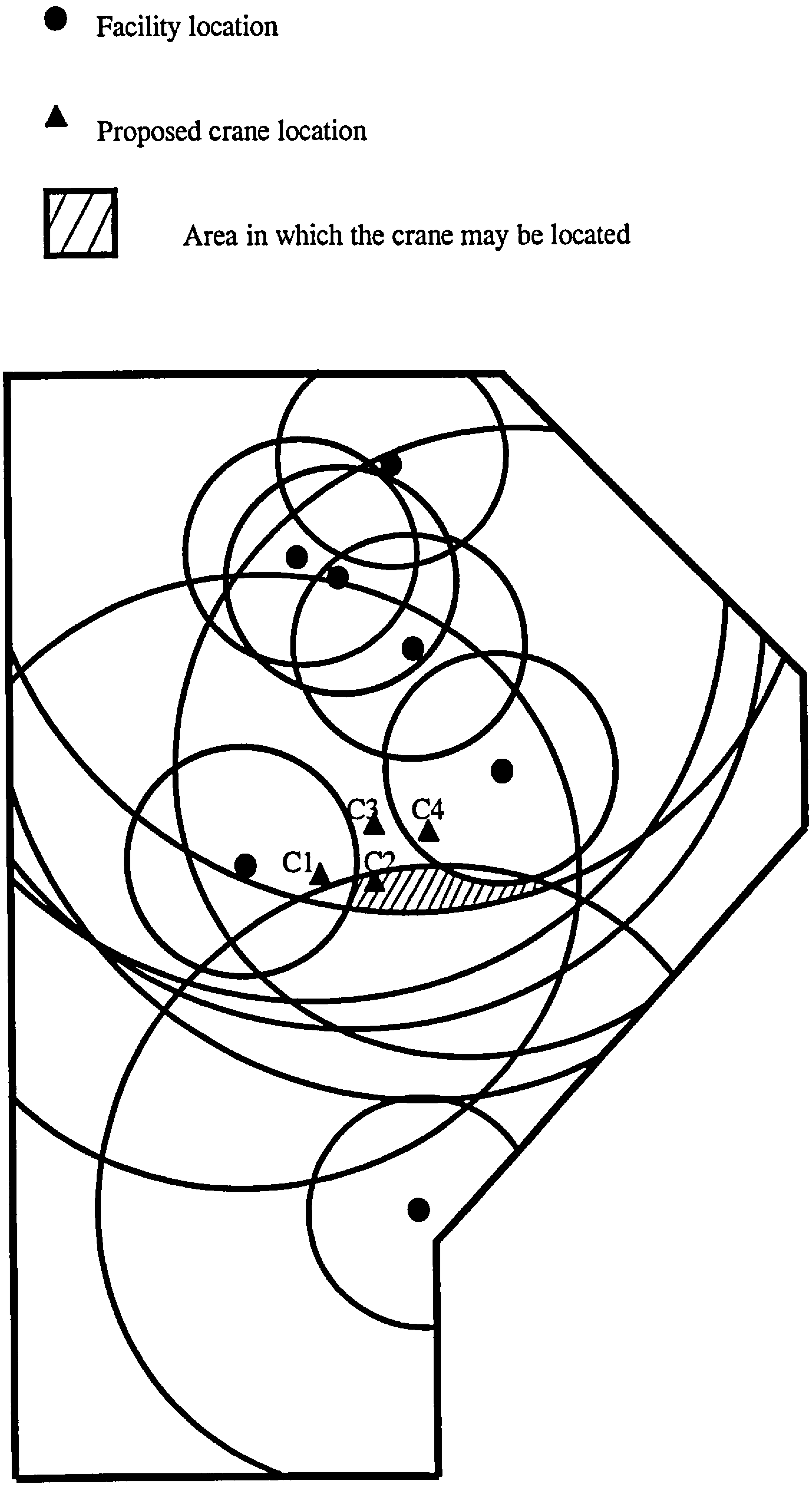


Figure 6.6 **Model and example proposed by Choi and Harris**
Determination of area in which crane is free to locate

The results obtained by Choi and Harris are provided in Table 6.15. These may be compared with the results obtained by the model, which are tabulated in Table 6.16, for each crane type and layout as defined; for each combination the minimum times are highlighted. In the case of Layout2 and Layout5 the values given are the average times for the eleven optimum movement solutions.

Table 6.15 **Model and example proposed by Choi and Harris - Model results (BPR GT 217B2 crane)**

Crane Position	Time (hrs)	Ranked Crane Position	Time (hrs)	% increase from minimum
C1	129.83	C3	119.89	-
C2	123.55	C4	122.27	1.98
C3	119.89	C2	123.55	3.05
C4	122.27	C1	129.83	8.30

It is not easy to make a direct comparison between the single set of results presented in Table 6.15 and the twenty-four sets of results presented in Table 6.16. However, by referring to the earlier discussion, the results tabulated for Crane2b (the crane specified by Choi and Harris - the BPR GT 217B2) and for Layout1, Layout3 and Layout5, are the most appropriate for the purposes of comparison. As far as the number of movements is concerned, which is reflected by the layout selected, it is difficult to make a direct comparison, as, for reasons discussed earlier, none of the proposed options directly replicate that proposed by Choi and Harris. As far as these three sets of results are concerned, it can be seen that the optimum crane position is either C2 or C3, whereas Choi and Harris state the optimum position to be C3 with C2 as the third choice position. Referring to the three specific solutions again, it can

Table 6.16 **Model and example proposed by Choi and Harris**
Model (Chapter 5) results
Time (hours) for each proposed crane position

	Crane1		Crane2a		Crane2b		Crane3	
Layout1	C1	180.80	C1	297.93	C1	390.89	C1	221.73
	C2	**173.35**	C2	**289.96**	C2	379.86	C2	**218.87**
	C3	174.59	C3	292.47	C3	**375.67**	C3	223.26
	C4	174.35	C4	291.47	C4	379.24	C4	223.64
Layout2	C1	349.19	C1	1169.72	C1	1221.74	C1	325.87
	C2	**346.18**	C2	**1166.62**	C2	1216.09	C2	**323.67**
	C3	346.45	C3	1167.34	C3	**1214.82**	C3	325.52
	C4	347.03	C4	1167.81	C4	1216.42	C4	326.85
Layout3	C1	159.61	C1	267.07	C1	341.28	C1	**208.67**
	C2	**156.23**	C2	**264.54**	C2	**333.73**	C2	209.02
	C3	160.57	C3	268.85	C3	337.00	C3	215.36
	C4	163.47	C4	270.57	C4	345.48	C4	216.88
Layout4	C1	311.81	C1	1044.33	C1	1086.91	C1	**299.76**
	C2	**310.23**	C2	**1042.85**	C2	**1083.34**	C2	299.98
	C3	311.78	C3	1044.86	C3	1084.61	C3	303.89
	C4	313.34	C4	1046.38	C4	1087.88	C4	306.18
Layout5	C1	156.15	C1	261.87	C1	338.12	C1	196.03
	C2	**150.23**	C2	**255.50**	C2	330.03	C2	**194.20**
	C3	153.17	C3	269.50	C3	**329.95**	C3	197.17
	C4	154.11	C4	259.58	C4	335.44	C4	199.07
Layout6	C1	308.65	C1	1040.38	C1	1083.75	C1	288.50
	C2	**306.52**	C2	**1038.22**	C2	**1079.54**	C2	**287.34**
	C3	307.24	C3	1039.18	C3	1080.07	C3	288.12
	C4	308.63	C4	1040.57	C4	1082.85	C4	291.23

also be seen that while the ranking of crane position changes, the times associated with all four positions are relatively similar with the maximum difference being only 5.5% (for Layout5) of the optimum time.

However, although the four crane positions proposed by Choi and Harris were selected as they were considered to be viable positions (although this was subsequently disproved), it is interesting to look at the times associated with the whole site, in order to assess if a better position, in terms of time taken to complete all movements, can be found. The results obtained by running the model for all points on a 10m x 10m grid covering the site, but contained within or along its boundaries, are given in Table 6.17, which shows, for each crane and layout combination, the minimum and maximum times and the associated co-ordinates. Again, it should be noted that, due to the relative coarseness of the grid used, the minimum and maximum values may very well change slightly and be located in another position. Comparison of Tables 6.16 and 6.17 shows that the minimum times highlighted in Table 6.16, for each of the proposed crane positions, are significantly higher than the minimum times displayed in Table 6.17, which represent, approximately, the minimum time taking into account the whole site. Generally, it can be said that the minimum time associated with the positions proposed by Choi and Harris are within one quarter and three quarters of the range between the minimum and maximum times for the site as a whole. Thereby, considerable savings in time can be achieved if the position associated with the minimum time is adopted, rather than one of the positions suggested by Choi and Harris.

Table 6.17 **Model and example proposed by Choi and Harris**
Model (Chapter 5) results
Minimum and maximum time (hours) values

		Crane1	Crane2a	Crane2b	Crane3
Layout1	*Min*	123.98 *at* (70,0)	234.41 at (70,0)	298.26 *at* (70,0)	132.37 *at* (70,0)
	Max	223.27 *at* (70,0)	331.14 *at* (90,50)	506.43 *at* (110,50)	273.05 *at* (80,40)
Layout2	*Min*	309.53 *at* (70,0)	1124.63 *at* (70,0)	1164.09 *at* (70,0)	266.01 *at* (70,0)
	Max	362.50 *at* (100,50)	1179.63 *at* (90,50)	1267.25 *at* (110,50)	372.05 *at* (80,40)
Layout3	*Min*	121.79 *at* (70,90)	221.44 *at* (70,0)	282.43 *at* (50,20)	130.33 *at* (70,90)
	Max	206.33 *at* (110,50)	307.69 *at* (90,50)	467.31 *at* (110,50)	247.42 *at* (80,40)
Layout4	*Min*	282.71 *at* (60,90)	1009.24 *at* (70,0)	1046.16 *at* (50,20)	245.68 *at* (60,90)
	Max	328.88 *at* (90,50)	1061.06 *at* (90,50)	1136.98 *at* (110,50)	332.73 *at* (80,40)
Layout5	*Min*	111.22 *at* (70,0)	210.39 *at* (70,0)	268.67 *at* (70,0)	117.89 *at* (70,0)
	Max	194.49 *at* (110,50)	295.07 *at* (90,50)	444.57 *at* (110,50)	244.84 *at* (80,40)
Layout6	*Min*	276.20 *at* (70,0)	1002.57 *at* (70,0)	1042.01 *at* (70,0)	237.10 *at* (70,0)
	Max	322.88 *at* (30,40)	1052.41 *at* (90,50)	1125.14 *at* (110,50)	334.10 *at* (80,40)

Figure 6.7 graphically displays the 10m x 10m grid used and shows the location of the positions allied with the minimum and maximum times. It can be seen that the potential crane positions associated with the minimum total movement times always occur at the boundary, or as near to the boundary as possible, while the positions associated with the maximum times are more centrally located, and are especially concentrated in the area where the facilities are located. The one exception is in respect of the maximum time associated with Crane1 and Layout6, where the maximum time is also located at the boundary (30,40).

6.3.4 Discussion

The main conclusion that can be drawn by comparing the results given by model proposed in this thesis with the results given by the model proposed by Choi and Harris is that significant savings may occur if the crane is located at the optimum position rather than at one of several pre-determined points. Such a position will normally be at or near the site boundary and it is appreciated that this would require a crane with a longer jib than if the crane was located centrally. There are cost implications associated with such decisions; this matter will be discussed in more detail in Chapter 8. Comparing the results given in Table 6.16 with those in Table 6.17, an average saving (the difference between the minimum time associated with one of the predetermined positions and the minimum time obtained over a 10m x 10m grid covering the site) of approximately 18% is achieved. The maximum saving of 60% is associated with Layout3 and Crane3, where the minimum time at C2 is 208.67 hours, compared with 130.33 hours at (70,90). It is also observed that Crane3 offers significantly better savings than the other two cranes, and that the layouts where all facilities occur at ground level, also result in a similar advantage.

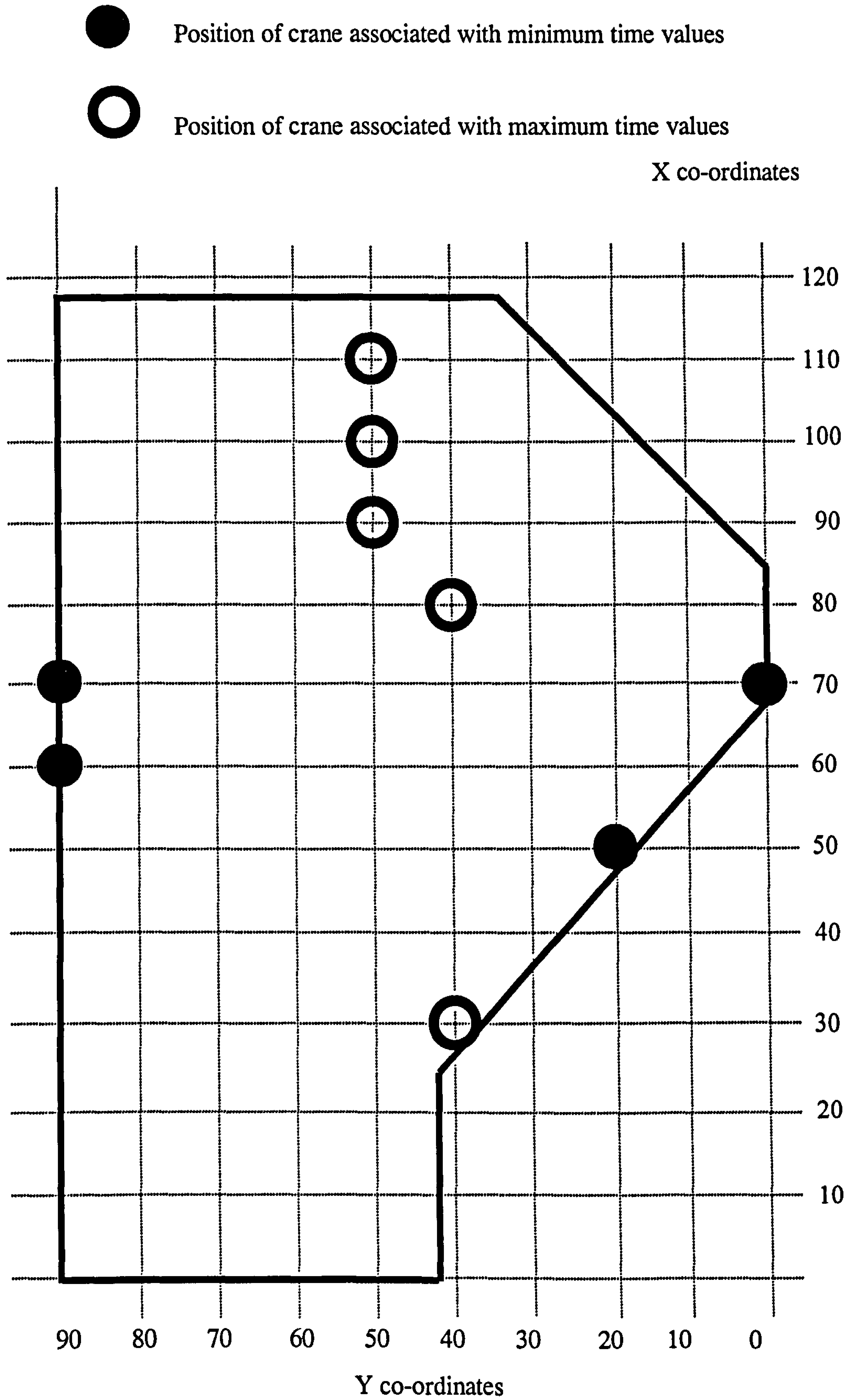


Figure 6.7 **Model and example proposed by Choi and Harris**
Location of positions allied with minimum and maximum times

Other trends, which are apparent from an inspection of Table 6.16 and 6.17, are:

- The inclusion of some facilities occurring at heights other than ground level results in a large increase in time, but the difference in minimum and maximum times is much reduced. This effect is also less noticeable as far as Crane 3 is concerned.

- As expected, Layout1 and Layout2, which encompass more movements than the other layouts, are associated with larger times.

- The times associated with Crane2b are always the greatest, followed by the times associated with Crane2a. The least times are those associated with either Crane1 or Crane3. Examining the times associated with the four positions suggested by Choi and Harris (Table 6.16) shows that Crane1 outperforms Crane3 when it is assumed that all facilities occur at ground level (Layout1, Layout3 and Layout5), and that the reverse is true when it is assumed that some of the facilities occur at heights other than ground level. This is to be expected, as Crane 3 has better hoisting speeds than Crane1. However, as far as the minimum and maximum times are concerned (Table 6.17), there seems to be no discernable pattern as far as the relative performance of the two cranes are concerned.

These matters will be investigated and discussed in more detail in the following chapter.

6.4 Model proposed by Zhang *et al.*

The model described by Zhang *et al.* (1995,1996) is a stochastic simulation model, based on re-constructing the process of supply and demand of materials handled by a tower crane on a construction site. The model attempts to reflect the influence of the intensity of material flow between service points and cites balance paths and types of request and the manner of hook movements as significant influences on the optimum crane location. The authors claim that a saving of 20 - 40% of hook horizontal travelling time, depending upon type of crane, skill of crane operator and site conditions, can be achieved by application of the model.

Zhang *et al.* highlight two assumptions made by previous models.

- The calculation of transportation time between demand and supply points depends on the geometric position of the crane only. This assumption is disregarded as it is believed that any resultant error is the same for all points. However, this is not an unjustified assumption; the calculation of transportation time between two points is a function of the position of the crane and will change if the crane's position is altered.

- The sequence of delivery between demand (D) and supply (S) is fixed and deliveries take place continuously between demand and supply points, implying that movement of the crane hook occurs continuously for each S-D pair, whereas, in reality, such movement will only take place when demand is in batch form, such as concrete handling. Zhang *et al.* acknowledge that the more likely random movement which is liable to occur in practice is difficult to predict and acknowledge the linear programming solution proposed by the author (Emsley 1992) to overcome this problem. Nevertheless, they highlight two perceived inadequacies of this solution method. Firstly, it is pointed out that the solution must be in integer form, as fractions of movements are not allowed. This problem has been acknowledged and addressed in Chapter 3 (section 3.4.5). Secondly, it is claimed that the final solution from the linear programming model represents a specific sequence of events and, when this sequence changes, the optimum solution will also change. It can only be assumed that the authors have misunderstood the rationale of the model; the model proposed in this thesis makes no assumptions about the order in which movements occur, only about the total number of movements which occur and that, globally, the total number of movements towards a facility must be matched by the total number of movements away from that facility.

The model proposed by Zhang *et al.* makes several assumptions.

- The geometric layout of all supply and demand points is known. This assumption is also made by the model proposed here.

- The crane type is predetermined. Although the crane type must be known for the model to be applied, it is quite possible, and indeed desirable, for both models to be re-run using different crane types, in order to examine their influence.

- The hook moves consecutively in the horizontal and vertical plane. A further assumption, made because the model is attempting to find the optimum crane location in the horizontal plane, is that "*the transport time for a cycle modelled in this study represents the horizontal time rather than the whole transport time for a cycle*". Therefore, vertical transport time is not modelled, although for high rise construction this is obviously a critical factor.

  Although not listed as an assumption, a related matter is that the model incorporates α, a parameter which describes the operation of the crane hook between two extreme situations: simultaneous movement when $\alpha = 0$, or consecutive movement when $\alpha = 1$. It is acknowledged that this factor depends on the skill of the operator and the spaciousness of the site. The default value is set at 0.25. Incorporation of this factor seems to negate the previous assumption that movement occurs consecutively in the horizontal and vertical planes, until further inspection reveals that this factor applies to radial and slewing components of movement in the horizontal plane only. Therefore, in essence, the model proposed by Zhang *et al.* disregards movement in the vertical dimension. This issue has been discussed earlier in Chapter 5 (section 5.3.3.4) and earlier in this chapter, in regard to the model proposed by Choi and Harris (1991), as it is believed that a more accurate model allows for some simultaneous movement in the horizontal and vertical planes, indeed in all three directions (trolleying, slewing and hoisting).

- All working areas have an approximate balance in the rate of production. This is not considered to be a relevant factor in the model proposed here.

- For each S-D pair, the total number of lifts, the number of lifts for each batch and percentage of each batch out of all lifts and the maximum load are known. Certainly, it is reasonable to assume that the maximum load must be known to ensure that a crane of sufficient capacity is selected. However, the requirement that the total number of lifts is known is an onerous assumption; the model proposed here uses the number of known movements as inputs and utilizes the linear programming technique to generate other movements to ensure that the total number of movements towards a facility is matched by the total number of movements away from that facility.

The model proposed by Zhang *et al.* is based on the construction of a series of matrices, to which are applied random generators. The first matrix, the S-D matrix, expresses the number of anticipated lifts between each supply and demand points, either as an odd job, where a single lift is requested each time, or as a batch job, where multiple lifts are requested each time. The second matrix expresses the average number of requests and the third matrix the frequency of requests in a similar format. Random numbers are then used to generate the occurrence of a request, to decide where the lift comes from and, finally, how many lifts will be repeated in one batch. In this way the occurrence of requests can be viewed as multiple Bernoulli trials. As the simulation proceeds, the transportation time is recorded and the average transport time for all requests is calculated. It is this parameter, average transport time (ATT), which is used as the objective function of the model; the optimum crane position is that associated with the smallest ATT value.

The data required by the model proposed by Zhang *et al.* include, as would be expected, such information as co-ordinates of all demand and supply points, heaviest lift at each point and crane load-radius information. It also requires input of the following:

- number of iterations. This can only be known by someone experienced in running the model, and advice should be provided to users. In addition, it would be interesting to know how the output of the model is affected by the number of iterations, although it is suggested that a steady state is reached after 10,000 simulation runs without batch requests and 15,000 simulation runs with batch requests.

- number of lifts between each S-D pair and percentages of the requests for each batch and the number of lifts in a single batch. As far as the numbers of lifts between each S-D pair is concerned, these data are required by both the model proposed in this thesis and that proposed by Zhang *et al.* However, when the model requires those data to be expressed in percentages in respect of single and batch lifts, the data collection becomes much more onerous and, in any event, such data are likely to be uncertain and unreliable.

- co-ordinates of the apex of the polygon regions. This refers to the feasible area in which the crane is free to locate and which is generally, as demonstrated in Figure 4.8, a polygon. The shape and size of this polygon may be further refined by input from site mangers in respect of the suitability of locating the crane in certain areas. Zhang *et al.* claim that "an effective algorithm is employed to find a feasible area", but no details are provided as to how this is done. However, this seems an unnecessary complication; in the model proposed in this thesis the user will be informed if, for any reason, an attempt is made to locate the crane in a position which is not feasible.

The requirement to input these data make the use of this model more onerous than the one which is developed in this thesis.

Although not of direct relevance to this thesis, it is interesting to note that Zhang *et al.* have extended their initial model to examine the optimization of a group of tower cranes (Zhang *et al.* 1999). This model requires two preliminary steps before the model described here may be applied to each crane in turn. These steps involve the allocation of what are described as task groups and task assignments to each crane, and consider factors such as feasible area, closeness and accessibility.

<u>6.4.1 Site layout data</u>

Zhang *et al.* use the same example as that used by Choi and Harris to demonstrate the model they have proposed. Table 6.18 shows the numbers of movements between facilities that have been used in order to demonstrate the model. For reasons explained above, the number of movements is expressed in absolute terms. The equivalent percentages are shown beneath the absolute values for purposes of comparison, and it can be seen that they correspond to the percentages used by Choi and Harris (Table 6.4). However, it does seem curious that the total number of movements used by Zhang *et al.* is 4683. No explanation is given for this and this, in turn, leads to rounding errors. For example, if 21% of the movements are from F1 to F2, this equates to 983 movements. Instead, 975 movements have been shown between these two facilities, which is 20.8% of the total number of movements.

However, as with the model proposed by Choi and Harris, the number of movements which is assumed to occur does not allow direct comparison with the model proposed here. The scaling factor should also be borne in mind, (i.e. 4683 movements in total, compared to 1000 used previously), although this should not influence the overall result.

Table 6.18 **Model and example proposed by Zhang *et al.***
Number of movements between facilities

FROM TO	F1	F2	F3	F4	F5	F6	F7	TOTAL
F1								
F2	975 [21%]				50 [3%]	480 [10%]	280 [6%]	1885 [40%]
F3	630 [14%]			950 [20%]	65 [1%]	493 [11%]	190 [4%]	2328 [50%]
F4								
F5								
F6								
F7		280 [6%]	190 [4%]					470 [10%]
TOTAL	1605 [35%]	280 [6%]	190 [4%]	950 [20%]	215 [4%]	973 [21%]	470 [10%]	4683 [100%]

6.4.2 Crane data

In order to demonstrate their model, Zhang *et al.* use the same crane as proposed by Choi and Harris (i.e. Crane2b). Reference is also made to a further crane, a Liebherr 330 HC, with assumed slewing and trolleying velocities of 0.6rpm and 0.83m/s (50m/min) respectively. No details of the hoisting velocities are given, as the model disregards movement in the vertical plane. However, no attempts have been made to run the model using this crane, as the relative values of the slewing and trolleying velocities are very similar to the BPR GT 2127B2 crane (Crane2a) referred to earlier.

6.4.3 Model results

The results obtained by Zhang *et al.* using the BPR GT 217B2 crane (Crane2b) for the four positions proposed by Choi and Harris are given in Table 6.19. The results are expressed in terms of the average transport time (ATT) although the units are not stated. By examination of Tables 6.15 and 6.16, it can be seen that the results more closely mirror those obtained by the model described here, rather than the model described by Choi and Harris, although, due to the different movement scenarios, it is not possible to make a full comparison.

Table 6.19 **Model and example proposed by Zhang *et al.*
Model results (BPR GT 217B2 crane)**

Crane Position	ATT	Ranked Crane Position	ATT	% increase from minimum
C1	1.209	C3	1.134	-
C2	1.146	C2	1.146	1.06
C3	1.134	C4	1.170	3.17
C4	1.170	C1	1.209	6.61

Zhang *et al.* suggest that the optimum location for the crane (i.e. the position associated with the minimum ATT) is at (60,38), which offers savings in respect of time in the order of 7%. Referring to Figure 6.7, it can be seen that this is not supported by the model proposed here, which suggests that the optimum location is one near to the boundary.

In respect of the Liebherr 330 HC crane, Zhang *et al.* discuss the results under four main headings:

- Slewing and radial velocity

It is demonstrated that the average transport time (ATT) reduces when the slewing and radial velocities are increased. As demonstrated in the previous section, this is also an obvious but valid conclusion for the model proposed here.

- Parameter α

As explained earlier, this is a measure of the co-ordination between the slewing and radial velocities. Again, the obvious conclusion has been drawn, that the average transport time reduces when the degree of co-ordination increases. This is not a relevant parameter as far as the model described here is concerned, as it is assumed that this value is fixed and cannot be adjusted by the user.

- Batch request

This is concerned with the introduction of batch requests into the model, when, rather than movements being considered as single lifts, multiple lifts are requested each time. As explained earlier, this is not considered to be appropriate to the model described here, which automatically attempts to embody both single and multiple lifts.

- Number of iterations

As it is not a simulation model, this is not an appropriate factor for the model described here.

6.4.4 Discussion

For the specific example given, the results of the model proposed by Zhang *et al.* are, as far as can be ascertained, very similar to the results obtained by the model proposed here.

However, as noted earlier, the data requirements of the model are far more onerous, and require much more knowledge about the crane's intended behaviour. On the other hand, the model proposed by Zhang *et al.* disregards vertical movement.

Examining the distribution of the ATT over the site (i.e. the criterion used to determine the optimum location), presented by Zhang *et al.*, no regular pattern emerges, but rather the distribution is characterized by local minima and maxima. The model proposed here indicates that the positions associated with the minimum values of time to complete all movements (the optimum position) are generally at the periphery of the site, and those positions associated with the maximum values of time to complete all movements (the least desirable position) are generally at the centre of the site (or at the centre of gravity of the facilities served by the crane).

Obviously, more detailed advanced knowledge about the crane's anticipated behaviour allows the model to predict the effect of its position more accurately. However, there is little point in incorporating data into the model which, by virtue of the fact that they are difficult to predict, may be inaccurate, especially if the model is very sensitive to minor changes in data values. It must also be borne in mind that any model which attempts to determine the optimum location for a fixed tower crane, can only attempt to optimize its location over the whole contract duration, and not on a day to day basis.

6.5 Summary

This chapter has compared the model proposed here with three other models proposed by other authors.

The model proposed by Rodriguez-Ramos and Francis (1973) was shown to be determining the optimum position of the crane hook when waiting between movements and not, as claimed, the optimum position of the crane hook. Therefore, it has limited value in the context of the model proposed here.

The shortcomings of the model proposed by Choi and Harris (1973) have already been published in a discussion paper (Emsley 1992). This highlighted a disregard of movement in the vertical plane and lack of consideration of balancing movement to ensure that the number of movements towards any one facility is matched by and equal number of movements away from that facility. It was also noted that the example provided required the lifting of loads at radii not possible using the proposed crane, and which were also outside its load lifting capacity.

The model proposed by Zhang *et al.* (1995 and 1996) is a stochastic simulation model. Vertical movement is disregarded and the model requires extensive input of data, which may not be known with certainty at the time the model is used (i.e. prior to construction commencing).

In conclusion, it is believed that the model proposed here utilizes the limited data about crane behaviour, which will be realistically available at the time the decision about crane location is made, and assists the decision process in respect of crane location by providing an objective assessment of the impact of each proposed position. Further discussion will be provided in Chapter 9.

CHAPTER 7

MODEL SIMULATIONS

7.1 Introduction

The model described earlier is primarily intended for use in individual situations where a particular tower crane is being located within a particular construction site. However, the model may also be used to examine a wide range of situations to see if any general principles concerning the location of tower cranes may be evinced. In order to achieve this objective a series of simulations has been carried out; this chapter describes these simulations and states the results, which have been produced.

It is possible to use the computer programs to generate an almost infinite number of scenarios. The problem is how to represent the resultant data in a compact and yet meaningful way, which can also allow any general principles to emerge. Not all the output which has been generated is presented here and the results are presented in both tabular and graphical format.

Three series of simulations have been executed, annotated for clarity by the letters A, B and C. All simulations are based on a 50m by 50m grid and utilize between 1 and 4 fixed facilities and 1 moving facility. The fixed facilities are located at the corners of the grid at (5,5), (45,5), (45,5) and (5,45). The moving facility is located at 5m intervals within the grid; thus a maximum of 121 positions occur (less those positions where the moving facility coincides with a fixed facility). The crane used throughout is modified so that reach and load lifting capacity are not limiting factors. Hence, the radii have been extended (at both ends of the range) and the load lifting capacity made artificially large, with an arbitrary maximum load assigned to each facility.

All the series of simulations are based on a series of 10 layouts utilizing the 50m by 50m grid referred to above. These layouts are displayed in Figure 7.1, which shows, in each case, a total of 1000 movements from the fixed facilities to the moving facility (which in this case is shown as being centrally located). However, the total number of movements considered in each case will be 2000 as, although implicit movement is not specified, it must occur in order to satisfy the balancing movement requirement. This is also verified by running the movement program which, in each case, determines that the optimum solution, to minimize the total number of movements, is to counter the explicit movement with an equal number of implicit movements.

The distinguishing characteristics of each series of simulations is briefly described below. More details are provided in the following sections, which consider each series individually.

Series A - for each of the 10 layouts the moving facility is assumed to be centrally located (at (25,25)). The times to complete all the movements are examined on a 10m by 10m grid. All fixed facilities occur at ground level and the moving facility occurs at a height of 30m. Four different sets of crane speeds are used.

Series B - as Series A above, but the effect of varying the height of the central facility is investigated.

Series C - as Series A above, but with the moving facility located at 5m intervals within the grid, thus giving 121 different positions for the moving facility. Only one set of crane speeds is used.

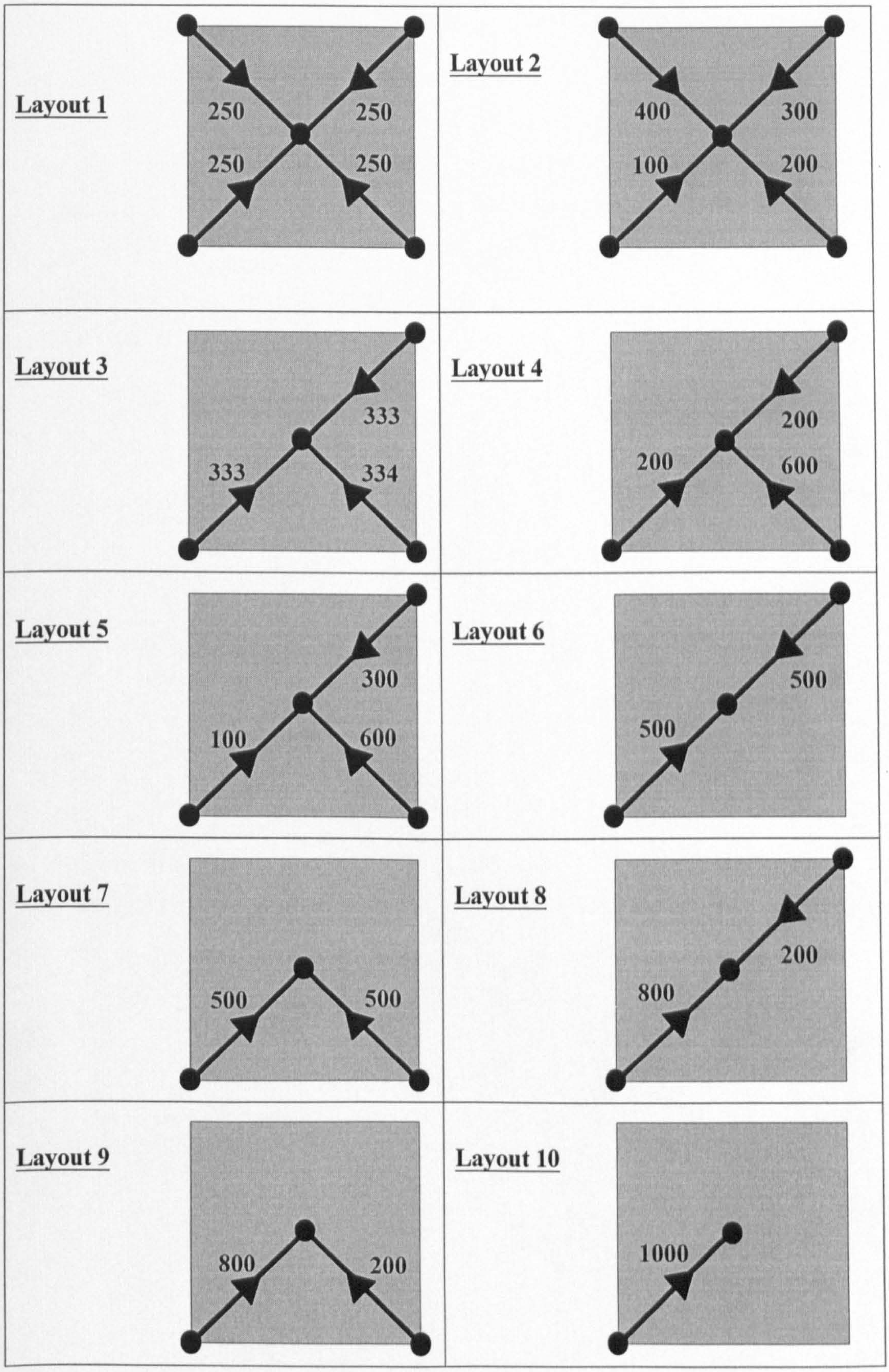


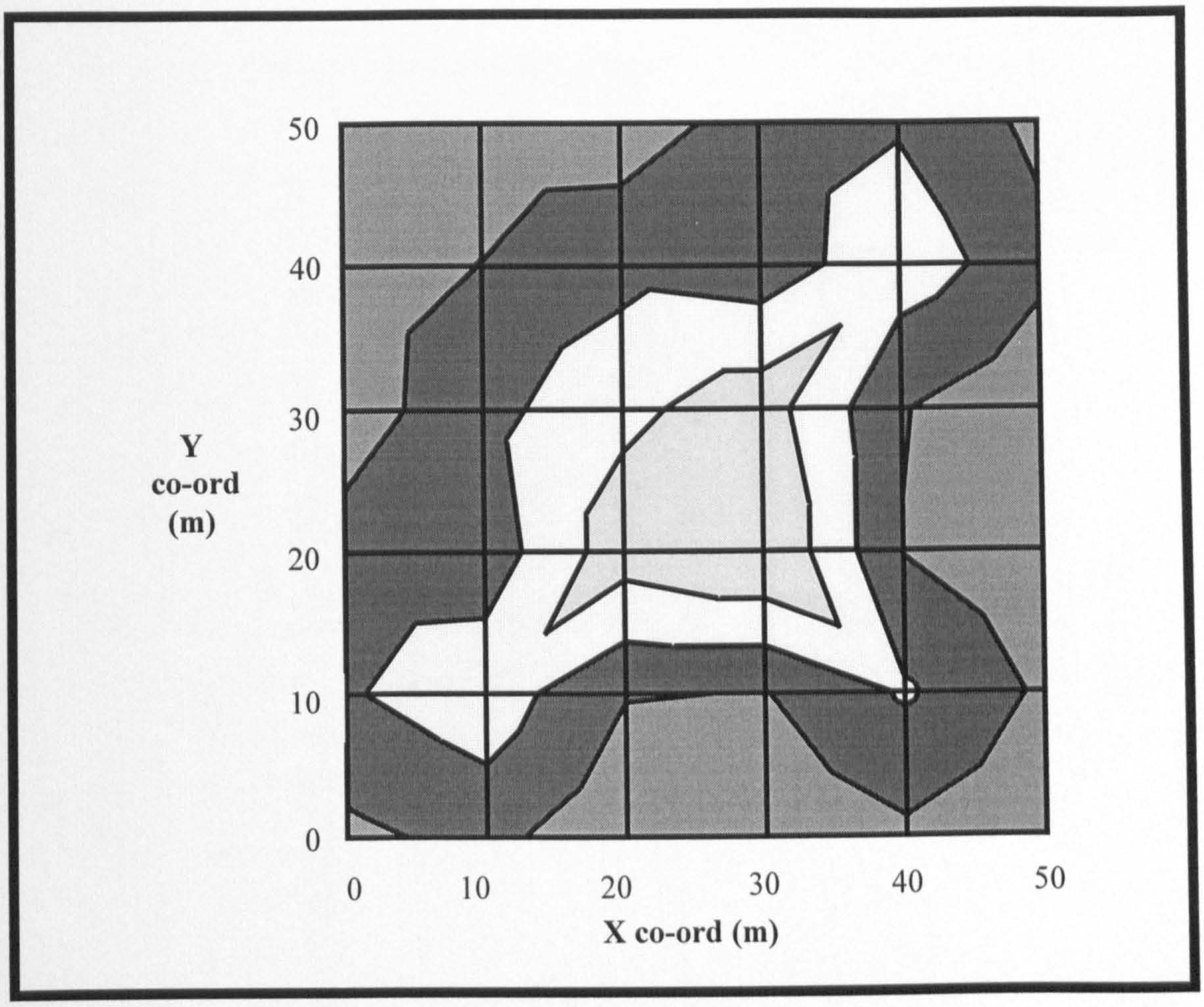
Figure 7.1 **Layouts showing different movement scenarios**

7.2 Series A simulations

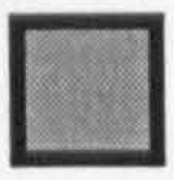
The 10 layouts chosen are shown in Figure 7.1. In each case the moving facility occurs at the centre of the 50m by 50m grid (i.e. at (25,25)), as shown. The fixed facilities are located at (5,5), (45,5), (5,45) and (45,45) as appropriate and it is assumed that these facilities occur at ground level with the moving facility at a height 30m above ground level. In each case the total number of movements allocated is 2000 and it is assumed that explicit movement between each fixed facility and the moving facility is counteracted by implicit movement of the same magnitude. Because of the simplicity of these movements, no linking or balancing movements are necessary. Four different sets of crane speeds are used, which are those also used when comparing the model proposed here with that proposed by Choi and Harris (1991); the four cranes are referred to as Crane1, Crane2a, Crane2b and Crane3 and details of their relative velocities are tabulated in Table 6.12. As mentioned previously, the load–lifting characteristics of these cranes have been artificially modified so that none of the cranes used impose any restrictions in respect of reach and load lifting capacity. It is assumed that speed is constant throughout and no allowance is made for acceleration and deceleration.

Initially, the times required to complete all the movements are tabulated on a grid at 10m intervals (i.e. 36 positions in total); this has the advantage of avoiding the position of any of the facilities. The results are tabulated in Appendix D, which, for each layout and for each crane, shows the times to complete the total number of movements for each position of the crane on the grid. The minimum and maximum times are also highlighted and a surface contour plot provided for each grid. However, it should be appreciated that as the grid used in respect of proposed crane position is relatively coarse (at 10m intervals), then the true position associated with the minimum and maximum times may not have been accurately ascertained; nevertheless when the minimum time occurs in the corner of the grid, which is a common occurrence, then this is likely to be the accurate position associated with the minimum time.

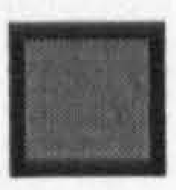
An example of a surface plot is given in Figure 7.2 for Layout 3 and Crane1, which, as expected, exhibits symmetry about a line running from the top left hand corner (0,50) to the bottom right hand corner (50,0). This reflects the symmetry of the distribution



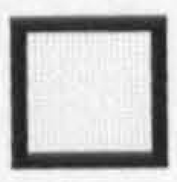
The key is:



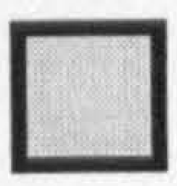
0% - 25% of the range from minimum value to maximum value



25% - 50% of the range from minimum value to maximum value



50% - 75% of the range from minimum value to maximum value



75% - 100% of the range from minimum value to maximum value

Figure 7.2 **Series A simulations**
Surface contour plot for Layout 3 Crane1

of the number of movements and, referring to Appendix D, it can be seen that all layouts which have symmetry in the distribution of movements illustrate the same symmetry in the distribution of times to complete all movements.

As there is a large variation in the absolute values of times associated with each crane, the contours of the surface plot have been based on the range between minimum and maximum time. Thus the plots do not provide for direct comparison between layouts, or between cranes within each layout, but allow comparison of the distribution trends. Generally, the two trends which can be assimilated from these plots are:

- The minimum times are distributed at the perimeter of the layout and the maximum times are concentrated at or near the central areas of the layout. This will be discussed in more detail in the following sections.

- The distribution of times associated with Crane2b are more skewed towards the 75% - 100% end of the range than those distributions associated with the other cranes, whilst the distribution of times associated with Crane3 are more skewed towards the 0% - 25% end of the range. Examining the velocities associated with each crane (Table 6.12) shows that Crane3 has higher velocities in respect of trolleying, raising and lowering than the other cranes (although a lesser value of slewing speed). On the other hand, Crane2b has the least values of trolleying, raising and lowering speeds (although the maximum value of slewing speed). Therefore it may be tentatively concluded that crane velocities not only influence the absolute values of time to complete all movements but that the distribution is likely to be more favourable (i.e. skewed to the lower end of the range) for cranes with higher speeds.

7.2.1 Minimum and maximum times to complete all movements

An overview of the results is given in Table 7.1, which shows the minimum and maximum times to complete all the movements and the corresponding co-ordinates (in parentheses), at which the minimum and maximum times occur, for each layout and for each crane, although, as mentioned earlier, the true position associated with the

Table 7.1 **Series A simulations**
Model results

Layout	Crane1		Crane2a		Crane2b		Crane3	
	Minimum Time (hours)	Maximum Time (hours)	Minimum Time (hours)	Maximum Time (hours)	Minimum Time (hours)	Maximum Time (hours)	Minimum Time (hours)	Maximum Time (hours)
	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's
1	26.20	29.86	89.76	94.15	93.62	99.20	22.44	31.62
	(0,0) (0,50) (50,0) (50,50)	(20,20) (20,30) (30,20) (30,30)	(0,0) (0,50) (50,0) (50,50)	(20,20) (20,30) (30,20) (30,30)	(0,20) (0,30) (20,0) (20,50) (30,0) (30,50) (50,20) (50,30)	(20,20) (20,30) (30,20) (30,30)	(0,0) (0,50) (50,0) (50,50)	(20,20) (20,30) (30,20) (30,30)
2	25.50	30.24	89.47	94.85	91.58	99.27	22.31	34.49
	(30,50)	(20,30)	(0,0) (50,50)	(20,30)	(30,50)	(20,30)	(0,0) (50,50)	(20,30)
3	25.65	30.52	89.28	95.14	91.97	99.25	22.22	34.47
	(0,50) (50,0)	(30,20)	(0,50) (50,0)	(30,20)	(30,0) (50,20)	(30,20)	(0,50) (50,0)	(30,20)
4	24.78	31.22	88.82	96.15	90.10	99.36	22.31	39.08
	(20,0) (50,30)	(30,20)	(20,0) (50,30)	(30,20)	(20,0) (50,30)	(30,20)	(0,0) (50,50)	(30,20)
5	24.63	31.22	88.74	96.15	89.50	99.36	22.31	34.54
	(50,30)	(30,20)	(50,30)	(30,20)	(50,30)	(30,20)	(0,0) (50,50)	(30,20)
6	24.55	30.06	88.33	94.43	90.64	99.29	21.80	34.54
	(0,50) (50,0)	(10,10) (20,20) (30,30) (40,40)	(0,50) (50,0)	(10,10) (20,20) (30,30) (40,40)	(0,50) (50,0)	(10,10) (20,20) (30,30) (40,40)	(0,50) (50,0)	(10,10) (20,20) (30,30) (40,40)
7	24.82	30.96	89.03	95.77	89.50	99.32	22.44	37.35
	(20,0) (30,0)	(20,20) (30,20)	(20,0) (30,0)	(20,20) (30,20)	(20,0) (30,0)	(20,20) (30,20)	(0,0) (0,50) (50,0) (50,50)	(20,20) (30,20)
8	23.99	31.38	88.02	96.38	88.54	99.43	21.80	41.42
	(0,30) (30,0)	(10,10) (20,20)	(0,30) (30,0)	(10,10) (20,20)	(0,30) (30,0)	(10,10) (20,20)	(0,50) (50,0)	(10,10) (20,20)
9	23.80	31.74	87.95	96.91	87.67	99.44	22.05	42.54
	(30,0)	(20,20)	(30,0)	(20,20)	(30,0)	(20,20)	(0,50) (50,0)	(20,20)
10	23.12	32.26	87.23	97.68	86.45	99.52	21.80	46.01
	(0,30) (30,0)	(10,10) (20,20)	(0,30) (30,0)	(10,10) (20,20)	(0,30) (30,0)	(10,10) (20,20)	(0,50) (50,0)	(10,10) (20,20)

minimum and maximum times may not have been accurately ascertained.

Inspection of Table 7.1 highlights two noteworthy features. Firstly, for each crane, the range of times associated with the minimum times is very small, regardless of layout. This also applies to the range of maximum times (with the exception of Crane3). Secondly, there are significant differences in the outputs associated with each crane.

The range of minimum times for each layout are as follows for each crane:

Crane1	23.12 – 26.20 hours	(13.3% increase)
Crane2a	87.23 – 89.76 hours	(2.9% increase)
Crane2b	86.45 – 93.62 hours	(8.3% increase)
Crane3	21.80 – 22.44 hours	(2.9%increase)

The rank order of the minimum times for each layout are given in Table 7.2 for each crane, with the least minimum time being ranked as 1. The times (hours) are given in parentheses.

Table 7.2 demonstrates that that the rank order is different for each crane. However, the lowest minimum time is always associated with Layout 10 and the highest minimum time is always associated with Layout 1. Inspection of the layouts in Figure 7.1, indicates that Layout 10, with the lowest minimum time, is the most compact, with all movements occurring between 2 facilities only, whilst Layout 1, with the highest minimum time, is the most diverse, with movement distributed evenly between the central facility and the four outer facilities. Between these two extremes it is difficult to rank the other layouts in terms of the diversity of the distribution of movements, although general trends can be seen in Table 7.2. For example, Layouts 8 and 9 could be described as being more compact than Layout 2, and these are always associated with a lesser minimum time, thus corroborating the principal that lower minimum times occur when the movement between facilities is compact or compressed.

Table 7.2 **Series A simulations**
Rank order of minimum times

<table>
<tr><th>Rank Order</th><th>Crane1</th><th>Crane2a</th><th>Crane2b</th><th>Crane3</th></tr>
<tr><td>1</td><td>10
(23,12)</td><td>10
(87.23)</td><td>10
(86.45)</td><td rowspan="3">6, 8, 10
(21.80)</td></tr>
<tr><td>2</td><td>9
(23.88)</td><td>9
(87.95)</td><td>9
(87.67)</td></tr>
<tr><td>3</td><td>8
(23.99)</td><td>8
(88.02)</td><td>8
(88.54)</td></tr>
<tr><td>4</td><td>6
(24.55)</td><td>6
(88.33)</td><td rowspan="2">5, 7
(89.50)</td><td>9
(22.05)</td></tr>
<tr><td>5</td><td>5
(24.63)</td><td>5
(88.74)</td><td>3
(22.22)</td></tr>
<tr><td>6</td><td>4
(24.78)</td><td>4
(88.82)</td><td>4
(90.10)</td><td rowspan="3">2, 4, 5
(22.31)</td></tr>
<tr><td>7</td><td>7
(24.82)</td><td>7
(89.03)</td><td>6
(90.64)</td></tr>
<tr><td>8</td><td>2
(25.50)</td><td>3
(89.28)</td><td>2
(91.58)</td></tr>
<tr><td>9</td><td>3
(25.65)</td><td>2
(89.47)</td><td>3
(91.97)</td><td rowspan="2">1,7
(22.44)</td></tr>
<tr><td>10</td><td>1
(26.20)</td><td>1
(89.76)</td><td>1
(93.62)</td></tr>
</table>

The range of maximum times for each layout are as follows for each crane:

Crane1	29.86 – 32.26 hours	(8.0% increase)
Crane2a	94.15 – 97.68 hours	(3.7% increase)
Crane2b	99.20 – 99.52 hours	(0.3% increase)
Crane3	31.62 – 46.01 hours	(45.5%increase)

The rank order of the maximum times for each layout are given in Table 7.3 for each crane, with the least maximum time being ranked as 1. The times (hours) are again given in parentheses.

Table 7.3 **Series A simulations**
Rank order of maximum times

Rank Order	Crane1	Crane2a	Crane2b	Crane3
1	1 *(29.86)*	1 *(94.15)*	1 *(99.20)*	1 *(31.62)*
2	6 *(30.06)*	6 *(94.43)*	3 *(99.25)*	3 *(34.47)*
3	2 *(30.24)*	2 *(94.85)*	2 *(99.27)*	2 *(34.49)*
4	3 *(30.52)*	3 *(95.14)*	6 *(99.29)*	5,6 *(34.54)*
5	7 *(30.96)*	7 *(95.77)*	7 *(99.32)*	
6	4,5 *(31.22)*	4,5 *(96.15)*	4,5 *(99.36)*	7 *(37.35)*
7				4 *(39.08)*
8	8 *(31.38)*	8 *(96.38)*	8 *(99.43)*	8 *(41.42)*
9	9 *(31.74)*	9 *(96.91)*	9 *(99.44)*	9 *(42.54)*
10	10 *(32.26)*	10 *(97.68)*	10 *(99.52)*	10 *(46.01)*

As with the rank order for minimum times (Table 7.2), Table 7.3 also demonstrates that the rank order is different for each crane, although it may be argued that there is more consistency between cranes in respect of the maximum times. However, the lowest maximum time is always associated with Layout 1 and the highest maximum time is always associated with Layout 10. This is the converse to the ranking which occurs in respect of minimum time, implying that the range between the minimum and maximum times will be the least when the minimum time is at its maximum (i.e. Layout 1) and the most when the minimum time is at its minimum (i.e. Layout 10). This is confirmed in Table 7.4 which shows the percentage increase (%) between minimum and maximum times (expressed as a percentage (%) of the minimum time) for the rank order for minimum times, as given in Table 7.2; Table 7.4 shows that the range of percentage increase (%) is very closely inversely correlated, in terms of order, with the rank order of minimum times. This is confirmed by the correlation coefficients which have been calculated for each crane in respect of the correlation between percentage increase (%) between minimum and maximum times and both the rank order (i.e. 1 to 10, taking the

Table 7.4 **Series A simulations**
Percentage increase (%) between minimum and maximum times

Rank Order (minimum times)	Crane1		Crane2a		Crane2b		Crane3	
1	10	39.4%	10	12.0%	10	15.1%	10	111.1%
2	9	33.4%	9	10.2%	9	13.4%	8	90.0%
3	8	30.8%	8	9.5%	8	12.3%	6	58.4%
4	6	22.4%	6	6.9%	7	11.0%	9	92.9%
5	5	26.8%	5	8.4%	5	11.0%	3	55.1%
6	4	26.0%	4	8.3%	4	10.3%	5	54.8%
7	7	24.7%	7	7.6%	6	9.5%	4	75.2%
8	2	18.6%	3	6.6%	2	8.4%	2	54.6%
9	3	19.0%	2	6.0%	3	7.9%	7	66.4%
10	1	14.0%	1	4.9%	1	6.0%	1	40.9%

average ranking where layouts are ranked equally) and minimum time (hours); these correlation coefficients are displayed in Table 7.5, which shows that percentage increase (%) is highly negatively correlated with both of these measures, except for Crane3, which is moderately correlated.

In respect of the significant increase in times associated with Crane2a and Crane2b, it can be seen, in Table 6.12, that these cranes have identical hoisting speeds, which are much reduced compared to Crane1 (24%) and Crane3 (19%). This confirms the importance of the hoisting speeds in selecting a crane to minimize crane usage time.

Table 7.5 **Series A simulations**
Correlation between percentage increase (%) and rank order and minimum time

	Crane1	Crane2a	Crane2b	Crane3
Percentage(%) increase vs. rank order	-0.93	-0.92	-0.99	-0.64
Percentage (%) increase vs. minimum time	-0.98	-0.93	-1.00	-0.66

7.2.2 Co-ordinates associated with minimum and maximum times

The co-ordinates associated with the minimum and maximum times to complete all movements are displayed in Table 7.1.

As mentioned previously, there is not always a unique set of co-ordinates (i.e. a single point) associated with either the minimum or maximum times. However, as several of the layouts exhibit symmetry, this would be expected, and, where there is more than one set of co-ordinates associated with the minimum and maximum times, they are symmetrically arranged.

Again, as mentioned previously, the co-ordinates associated with the minimum time are always on the perimeter of the layout, whilst those associated with the maximum times are always located internally, regardless of the layout.

Whilst the co-ordinates associated with the minimum time are not consistent for each layout, the co-ordinates associated with the maximum time are identical for each layout. Due to the variation associated with the location of the minimum times it is not possible to develop a technique to predict the location where the minimum time will occur, although the location (or locations) is always on the site perimeter.

Adopting a finer grid, based on 1m increments, confirms that the location of the minimum times are those indicated in Table 7.1

However, investigation of the position associated with the maximum time indicates that the *centre of gravity of the movement matrix* may be a reasonable predictor of the position at which the maximum time occurs. The *centre of gravity of the movement matrix* is calculated in a similar way to the centre of gravity of a plane figure, by taking moments about an axis and using the number of movements from that point and the associated distance to that point from the axis. For Layout 1, the centre of gravity of the movement matrix obviously occurs at (25,25). For Layout 2 it is calculated as follows (see Figure 7.1):

In respect of the x axis (taking moments about the y axis)

$$2000\bar{x} = (100 \times 5) + (400 \times 5) + (200 \times 45) + (300 \times 45) + (1000 \times 25)$$

$$\bar{x} = 25\text{m}$$

In respect of the y axis (taking moments about the x axis)

$$2000\bar{y} = (100 \times 5) + (200 \times 5) + (300 \times 45) + (400 \times 45) + (1000 \times 25)$$

$$\bar{y} = 29\text{m}$$

The centre of gravity co-ordinates of the movement matrix for each layout are summarised in Table 7.6.

It is also possible to use a finer grid, based on 1m increments, to ascertain a truer value of the maximum time and a more accurate position. Table 7.7 shows the maximum times and their corresponding locations, which were originally determined using a 10m grid and which are tabulated in Table 7.1, and provides a comparison with both the position of the centre of gravity of the movement matrix and the corresponding time, and the maximum time obtained through examination of the times using a finer gird and the corresponding locations. Note that for Layouts 1 and 6 the centre of gravity of the movement matrix is calculated as occurring at (25,25), but this point cannot be used as it coincides with the central facility; instead those co-ordinates closest to this point, and giving the maximum times, have been used instead.

Table 7.6 **Series A simulations**
Centre of gravity co-ordinates of the movement matrix

Layout	Centre of gravity co-ordinates
1	(25,25)
2	(25,29)
3	(28.34,21.66)
4	(31,19)
5	(33,21)
6	(25,25)
7	(25,15)
8	(19,19)
9	(19,15)
10	(15,15)

As can be seen in Table 7.7, using a grid based on 1m increments, rather than 10m increments, enables the maximum time to be accurately ascertained, both in terms of value and position where this value occurs. With one exception (Layout 2 Crane 3), the location of the position associated with the maximum time is still identical within each Layout, regardless of the crane selected, even when this fine grid is used. The use of the centre of the gravity of the movement matrix gives an approximate estimate of the position where the maximum value occurs. As a general rule this is a more accurate measure when the movement is more widely dispersed (i.e. the maximum number of facilities), which is likely to be the situation in real life, than when it is more compact (i.e. less facilities).

Table 7.7 **Series A simulations**
Comparison of maximum times obtained from different methods

Layout	Crane1			Crane2a			Crane2b			Crane3		
	Max. Time (hrs)/Co-ords			Max. Time (hrs)/Co-ords			Max. Time (hrs)/Co-ords			Max. Time (hrs)/Co-ords		
	5m grd	C of G	1m grd	5m grd	C of G	1m grd	5m grd	C of G	1m grd	5m grd	C of G	1m grd
1	29.86	31.57	31.57	94.15	95.93	95.93	99.20	102.37	102.37	31.62	33.94	33.94
	(20,20) (20,30) (30,20) (30,30)	(24,24) (24,26) (26,24) (26,26)	(24,24) (24,26) (26,24) (26,26)	(20,20) (20,30) (30,20) (30,30)	(24,24) (24,26) (26,24) (26,26)	(24,24) (24,26) (26,24) (26,26)	(20,20) (20,30) (30,20) (30,30)	(24,24) (24,26) (26,24) (26,26)	(24,24) (24,26) (26,24) (26,26)	(20,20) (20,30) (30,20) (30,30)	(24,24) (24,26) (26,24) (26,26)	(24,24) (24,26) (26,24) (26,26)
2	30.24	31.19	32.44	94.85	95.13	97.00	99.27	101.00	103.27	34.49	34.71	36.90
	(20,30)	(25,29)	(25,26)	(20,30)	(25,29)	(25,26)	(20,30)	(25,29)	(25,26)	(20,30)	(25,29)	(24,26)
3	30.52	31.44	32.80	95.14	95.52	97.50	99.25	100.96	103.48	24.37	35.73	37.55
	(30,20)	(28.34, 21.66)	(26,24)	(30,20)	(28.34, 21.66)	(26,24)	(30,20)	(28.34, 21.66)	(26,24)	(30,20)	(28.34, 21.66)	(26,24)
4	31.22	30.58	33.84	96.15	95.50	98.43	99.36	98.13	103.48	39.08	38.35	42.04
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
5	31.22	29.75	33.84	96.15	93.95	98.82	99.36	97.07	104.40	34.54	35.95	42.01
	(30,20)	(33,21)	(26,24)	(30,20)	(33,21)	(26,24)	(30,20)	(33,21)	(26,24)	(30,20)	(33,21)	(26,24)
6	30.06	31.63	31.68	94.43	96.01	96.04	99.29	102.43	102.60	34.54	35.93	35.93
	(10,10) (20,20) (30,30) (40,40)	(24,24) (26,26)	(24,24) (26,26)	(10,10) (20,20) (30,30) (40,40)	(24,24) (26,26)	(24,24) (26,26)	(10,10) (20,20) (30,30) (40,40)	(24,24) (26,26)	(24,24) (26,26)	(10,10) (20,20) (30,30) (40,40)	(24,24) (26,26)	(24,24) (26,26)
7	30.96	28.83	33.57	95.77	92.94	98.45	99.32	95.60	104.29	37.35	33.82	40.45
	(20,20) (30,20)	(25,15)	(25,24)	(20,20) (30,20)	(25,15)	(25,24)	(20,20) (30,20)	(25,15)	(25,24)	(20,20) (30,20)	(25,15)	(25,24)
8	31.38	30.75	33.89	96.38	95.75	98.89	99.43	98.17	104.45	41.42	40.86	43.63
	(10,10) (20,20)	(19,19)	(6,6)	(10,10) (20,20)	(19,19)	(6,6)	(10,10) (20,20)	(19,19)	(6,6)	(10,10) (20,20)	(19,19)	(6,6)
9	31.74	28.67	34.62	96.91	93.64	98.45	99.44	94.13	105.11	42.54	37.24	45.41
	(20,20)	(19,15)	(24,24)	(20,20)	(19,15)	(24,24)	(20,20)	(19,15)	(24,24)	(20,20)	(19,15)	(24,24)
10	32.26	28.33	35.40	97.68	93.17	100.82	99.52	91.67	105.80	46.01	42.54	48.77
	(10,10) (20,20)	(15,15)	(6,6)	(10,10) (20,20)	(15,15)	(6,6)	(10,10) (20,20)	(15,15)	(6,6)	(10,10) (20,20)	(15,15)	(6,6)

7.2.3 Times to complete all movements for crane positions based on a radial grid

For the purposes of comparison, six sets of radii, measured from the central point (25,25) and ranging from 2.00m to 35.36m, have been used to generate 40 potential crane positions. These radii and corresponding crane positions are tabulated in Table 7.8 and displayed graphically in Figure 7.3

Table 7.8 **Series A simulations**
Proposed crane positions and corresponding radii
(measured from the central facility)

Radius	Co-ordinates		Co-ordinates	
1 2.00m	A	(27,25)	B	(26.41,26.41)
	C	(25,27)	D	(23.59,26.41)
	E	(23,25)	F	(23.59,23.59)
	G	(25,23)	H	(26.41,23.59)
2 10.00m	A	(35,25)	B	(32.07,32.07)
	C	(25,35)	D	(17.93,32.07)
	E	(15,25)	F	(17.93,17.93)
	G	(25,15)	H	(32.07,17.93)
3 18.00m	A	(43,25)	B	(37.73,37.73)
	C	(25,43)	D	(12.27,37.73)
	E	(7,25)	F	(12.27,12.27)
	G	(25,7)	H	(37.73,12.27)
4 25.00m	A	(50,25)	B	(42.67,42.67)
	C	(25,50)	D	(7.33,42.67)
	E	(0,25)	F	(7.33,7.33)
	G	(25,0)	H	(42.67,7.33)
5 30.00m	B	(46.21,46.21)	D	(3.79,46.21)
	F	(3.79,3.79)	H	(46.21,3.79)
6 35.36m	B	(0,0)	D	(50,0)
	F	(50,50)	H	(0,50)

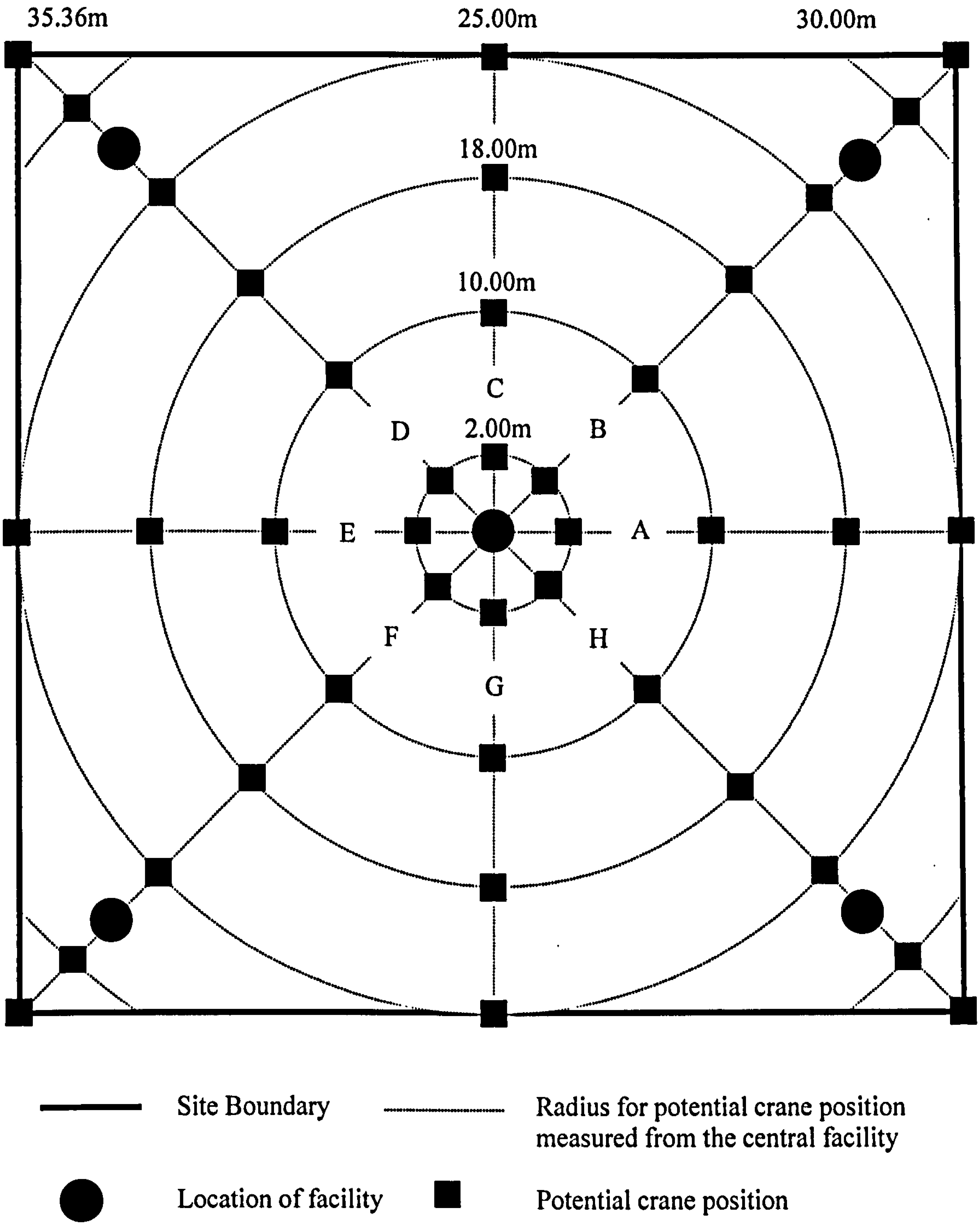


Figure 7.3 **Series A simulations**
Proposed crane positions and corresponding radii

Initially, the times associated with each proposed crane position were computed for each layout and for each crane. The average times associated with the proposed position on the same radius were then computed and found to be identical for each layout; these results are tabulated in Table 7.9

Table 7.9 **Series A simulations**
Average time (hours) to complete all movements for crane positions located at different radii

	Crane radius (m)					
Crane	2.00	10.00	18.00	25.00	30.00	35.36
1	31.37	28.92	27.34	27.37	26.50	26.20
2a	95.72	93.16	91.46	91.39	90.08	89.76
2b	102.01	97.58	94.88	95.31	95.32	94.84
3	33.47	30.04	27.65	26.80	22.82	22.44

While the average times are shown in Table 7.9, the distribution of times is not necessarily identical for each layout. By observation of the results, where symmetry exist in the layouts the spread of times is less than when there is less or no symmetry. Nevertheless, these results confirm the previous assertion made in respect of minimum times, notably that the influence of the layout is slight, but that there is a significant difference in the times associated with each crane.

7.2.4 Summary

For Series A simulations the most notable feature is that the range of minimum times to complete all movements is very similar, regardless of layout, although there are large variations of the times associated with different cranes (which is a reflection of the relative velocities). This trend is also reflected in the range of maximum times, although the range is not as compressed as that associated with the minimum times. However, the layouts associated with the least minimum time are also those associated with the largest maximum time, resulting in a larger range of times (maximum – minimum) for those layouts with the least minimum time. The range of times from minimum to maximum, can be in excess of 100%. Further, the least minimum times are associated with the layouts that are most compact or compressed in their distribution of movements, whilst those where the movements are more widely distributed are associated with the larger minimum times.

Where the movement patterns are symmetrical the distribution of times is also symmetrical, and the same symmetry can be applied to the positions at which the minimum and maximum times occur. The co-ordinates associated with the minimum times are always at the perimeter of the layout whilst those associated with the maximum are always located internally. For the scenario described by Series A, the location of the co-ordinates associated with the maximum times is virtually constant, regardless of layout. The centre of gravity of the movement matrix may be used a technique to approximately predict the location of the position associated with the maximum time. However, the location of the co-ordinates associated with the minimum time may vary between layouts, but the locations can be accurately ascertained using a coarse 10m by 10m grid.

The lack of influence of the layout is also apparent when the times to complete all movements for crane positions based on a radial grid are compared. The average times to complete all movements for all positions located on the same radius are identical, regardless of layout, although the type of crane obviously gives rise to different values. These results also support the concept of minimum times being associated with positions at or near the perimeter, as the times to complete all movements decrease as the radius increases (i.e. moves towards the perimeter).

There is an extensive variation in times to complete all movements between different crane types, with Crane1and Crane3 having significantly reduced times compared to Crane2a and Crane2b. For example, for Layout 1, the times for Crane1 range from 26.20 – 29.86 hours, whilst for Crane2b the time range is 93.62 – 99.20 hours. Generally, this difference is attributed to the hoisting speeds, which are much less for Crane2a and Crane 2b (which have identical hoisting speeds) compared to the other two cranes.

7.3 Series B simulations

In Series B simulations, the effect of varying the height of the central facility is examined, to see if the same conclusions which were reached for Series A are still valid. Series B simulations are an extension of those in series A, except that the central facility is considered to occur at heights ranging from 0m to 30m in increments of 5m; for the sake of completion, Series B also includes the scenario when the central facility is located at 30m (i.e. as in Series A). The results are tabulated in Appendix E, which give the minimum and maximum times, the range between the minimum and maximum times, expressed both as an absolute range and as a percentage increase in respect of the minimum times, and the co-ordinates of the crane associated with the minimum and maximum times.

7.3.1 Minimum and maximum times to complete all movements

The minimum times to complete all movements are summarised in Appendix E. Inspection shows that, as expected, the minimum time to complete all movements increases as the height of the central facility also increases. The range of minimum times between layouts for each crane and for each central facility height are tabulated in Table 7.10, which also shows, in parentheses, the percentage increase (%) relative to the minimum value. This table shows that the range of minimum times decreases as the height of the central facility increases, with the largest range occurring when the central facility is located at ground level. However, as real movement scenarios are likely to include some hoisting, indeed hoisting may become the dominant movement component in high rise construction, this result is encouraging in terms of the application of the model in real life (i.e. that there is very little difference in the times to complete all movements for different movement scenarios when a realistic element of hoisting is incorporated). Inspection of Table 7.10 also indicates that even if the height of the central facility was increased to, say 100m, it is unlikely that the range of minimum times would be reduced much further than the values obtained when the central facility is at a height of 30m.

Table 7.10 **Series B simulations**
Range of minimum times to complete all movements

Central Facility height	Crane1	Crane2a	Crane2b	Crane3
0m	9.57 – 14.69 (53.5%)	21.50 – 25.62 (19.2%)	20.13 – 32.96 (63.7%)	12.22 – 14.36 (17.5%)
5m	10.96 – 16.08 (46.7%)	29.36 – 32.76 (11.6%)	28.58 – 39.51 (38.2%)	13.32 – 15.46 (16.1%)
10m	12.35 – 17.47 (41.5%)	40.94 – 43.46 (6.2%)	40.16 – 48.20 (20.0%)	14.41 – 16.55 (14.9%)
15m	14.79 – 19.20 (29.8%)	52.51 – 55.04 (4.8%)	51.73 – 58.90 (13.9%)	15.51 – 17.65 (13.8%)
20m	17.56 – 21.28 (21.2%)	64.08 – 66.61 (3.9%)	63.30 – 70.47 (11.3%)	17.41 – 19.15 (10.0%)
25m	20.34 – 23.58 (15.9%)	75.66 – 78.18 (3.3%)	74.88 – 82.05 (9.6%)	19.60 – 20.79 (6.1%)
30m	23.12 – 26.20 (13.3%)	87.23 – 89.76 (2.9%)	86.45 – 93.62 (8.3%)	21.80 – 22.44 (2.9%)

The maximum times to complete all movements are also summarised in Appendix E. Inspection shows that as expected, and as in line with that which occurs in respect of the minimum times, the maximum time to complete all movements increases as the height of the central facility also increases. The range of maximum times between layouts for each crane and for each central facility height are tabulated in Table 7.11, which also shows, in parentheses, the percentage increase (%) relative to the least maximum value. This table also shows that the range of maximum times decreases as the height of the central facility increases, with the largest range occurring when the central facility is located at ground level. Inspection of Appendix E also shows that the range between minimum and maximum times, in both absolute terms and percentage increase (%) relative to the minimum value, is consistently larger when the central facility height decreases. For example, for Layout 10, the percentage increases (%) between minimum and maximum values, relative to the minimum value are as follows:

Table 7.11 **Series B simulations**
Range of maximum times to complete all movements

Central Facility height	Crane1	Crane2a	Crane2b	Crane3
0m	20.30 – 23.93 (17.9%)	32.34 – 38.65 (19.9%)	41.90 – 45.32 (8.2%)	25.04 – 39.43 (57.5%)
5m	21.69 – 25.32 (16.7%)	38.13 – 44.44 (16.5%)	47.69 – 51.10 (7.2%)	26.14 – 40.53 (55.0%)
10m	23.08 – 26.71 (15.7%)	47.85 – 51.38 (7.4%)	54.28 – 56.89 (4.8%)	27.23 – 41.62 (52.8%)
15m	24.47 – 28.10 (14.8%)	59.43 – 62.96 (6.1%)	64.48 – 64.80 (0.5%)	28.33- 42.72 (50.8%)
20m	25.86 – 29.48 (14.0%)	71.00 – 74.53 (5.0%)	76.06 – 76.38 (0.4%)	29.42 – 43.82 (48.9%)
25m	27.65 – 30.87 (11.6%)	82.57 – 86.10 (4.3%)	87.63 – 87.95 (0.4%)	30.52 – 44.92 (47.2%)
30m	29.86 – 32.26 (8.0%)	94.15 – 97.68 (3.7%)	99.20 – 99.52 (0.3%)	31.62 – 46.01 (45.5%)

Crane1: 39.53% – 150.05%

Crane2a: 11.98% - 79.77%

Crane2b: 15.12% - 125.14%

Crane3: 111.06% - 222.67%

where the lower value represents the percentage increase (%) for a central facility height of 0m and the higher value represents the percentage increase (%) for a central facility height of 30m. This range of times demonstrates the importance of selecting the optimum crane location.

Inspection of the data in Appendix E, in respect of the rank order between layouts for both the minimum and maximum times, shows there is again a variation between cranes. However, there is also a variation in the rank order between different central facility heights for most cranes. These variations are mostly relatively minor; in some instances there may be only one variation between the seven different central facility heights, whilst in other cases there may be more variations. However, the general trend remains that the layout associated with the most compressed and compact movement

(Layout 10) is always that associated with the least minimum time (and conversely the greatest maximum time) and the layout associated with the most diverse movement (Layout 1) is always that associated with the greatest minimum time (and conversely the least maximum time).

Surface contour plots for Layout 3 Crane1 are shown in Figure 7.4 for varying central facility heights. The same key is used as previously (see Figure 7.2) where the contours are based on dividing the range between the minimum and maximum time into 4 equal ranges. Although this does not strictly allow for direct comparisons to be made, nevertheless, Figure 7.4 demonstrates the general trends in respect of the distribution of times as the crane position varies and shows that that these trends are very similar, regardless of the height of the central facility. As expected, varying the height of the central facility also maintains the symmetry of the distribution.

7.3.2 Co-ordinates associated with minimum and maximum times

The co-ordinates associated with the minimum and maximum times to complete all movements are tabulated in Appendix E.

Generally, it can be seen that for the majority of combinations of cranes and layouts, the co-ordinates at which the minimum and maximum times occur is constant for each central facility height, and that the co-ordinates associated with the maximum times demonstrate more consistency than those associated with the minimum times. Where there is discrepancy between the co-ordinates at differing central facility heights, it is difficult to give any rational explanation about why this should be the case. However, regardless of the crane, layout or central facility height, the co-ordinates at which the minimum times to complete all movements occur are always at the perimeter (and often at the corner), whilst those associated with the maximum time are always located internally.

In respect of the minimum times to complete all movements, the coarse 10m by 10m grid used is still considered to be an accurate way to determine the minimum value and

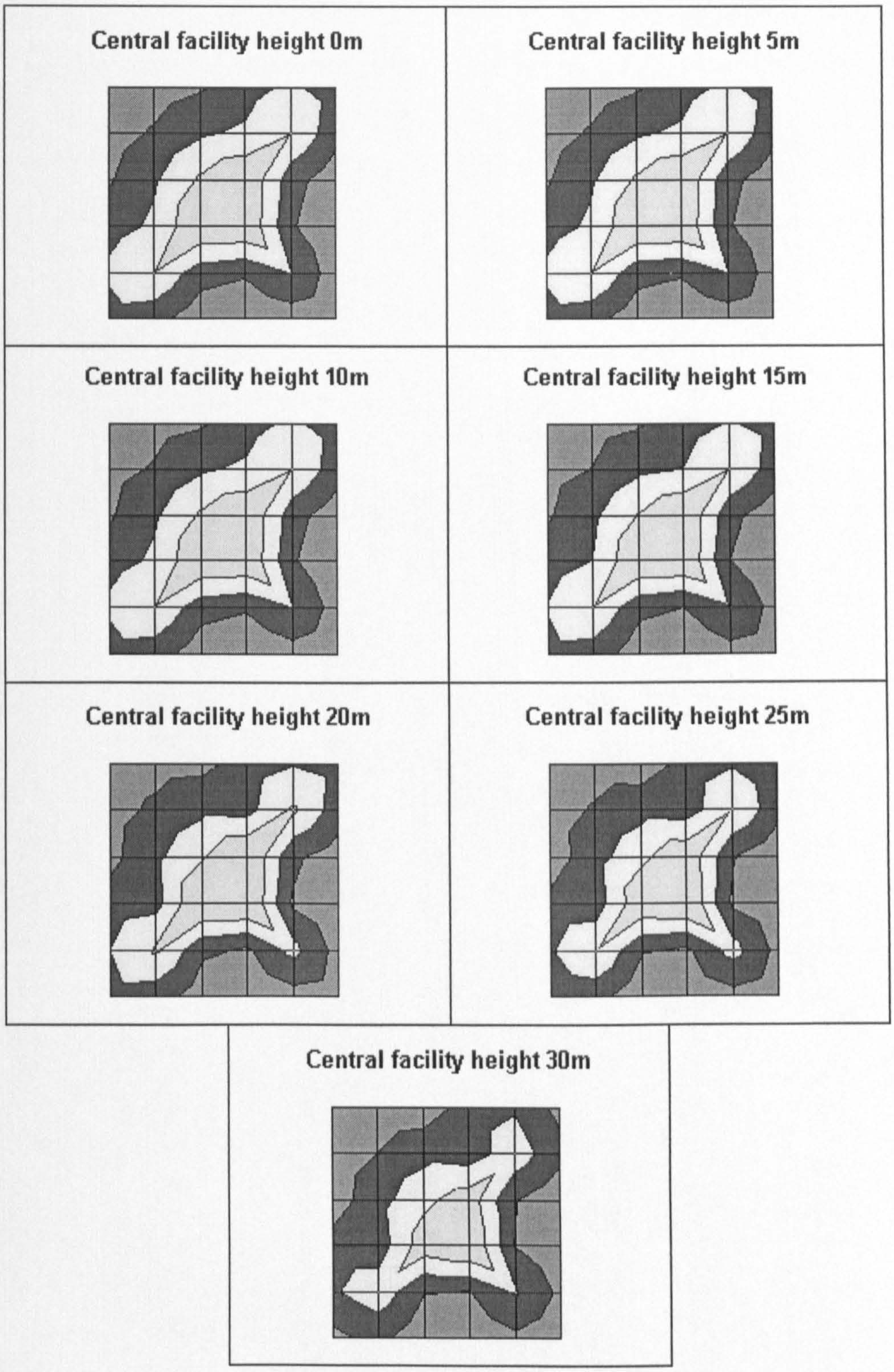


Figure 7.4 **Series B simulations**
Surface contour plots for Layout 3 Crane1
for varying central facility heights

the associated co-ordinates. However, due to the symmetry of the movement distribution, there may be more than one set of co-ordinates associated with the minimum time and, when two or more sets of co-ordinates are positioned closely together (i.e. 10m apart), then it is possible that the point at which the minimum value occurs may not have been accurately ascertained. Such a situation arises for the following layout, crane and central facility height combinations:

Layout 1	Crane1	Central facility heights: 0 – 25m
Layout 1	Crane2a	Central facility height: 5m
Layout 7	Crane1	Central facility height: 0 – 30m
Layout 7	Crane2a	Central facility height: 0 – 30m
Layout 7	Crane2b	Central facility height: 0 – 30m .

Using a finer 1m grid between the two closely positioned points for the scenarios above does confirm that there is variation in times to complete all movements at the intermediate points. For example, for Layout 7, Crane1 with a central facility height of 10m, the initial investigations showed that the minimum time of 14.41 hours to complete all movements occurred when the central facility was located at (20,0) and (30,0) (see Appendix E). In fact, the true minimum value occurs at (25,0) and is 14.36 hours. This is a 0.3% decrease in the value originally determined and investigations verify that this is the typical order of variation which exists between the minimum value which is produced when a coarse 10m grid is used, compared to that which is obtained when a finer 1m grid is used. Interestingly, in respect of Layout 1, an average 0.3% increase in times, as opposed to an increase, occurs at the mid-point. However, as the variations are so small it may be concluded that the coarse grid has accurately determined the location of the co-ordinates associated with the minimum time.

In respect of the co-ordinates associated with the maximum times to complete all movements, there is very little change as the height of the central facility varies. In fact, the only changes are associated with Crane2b, at central facility heights 0 –10m, for all layouts, apart from Layout1, and, in each case, if the co-ordinates associated with the central facility heights 15 – 30m were used, this only results in an average reduction in maximum times of 5%. Therefore, the use of the centre of gravity of the movement matrix as a predictor for the location of the point where the maximum time to complete all movements occurs is unaffected by central facility height.

Table 7.12 shows the range of maximum times for Layout 4 for each central facility height between 0m and 30m in increments of 5m , which have been obtained using the original 10m grid, the centre of gravity of the movement matrix ((31,19) in this case) and the maximum time determined using a finer1m grid. The associated co-ordinates are shown in parentheses, but, for this particular layout are virtually constant; when the 10m grid is used, the maximum time occurs at (30,20) in all but 4 cases (Crane2b, central facility heights 0 – 15m) and, when the 1m grid is used, the maximum times are found to always occur at (26,24). In terms of rank order, the time ascertained using the 10m grid is always the lowest and that obtained using the 1m, grid is always the highest.

7.3.3 Summary

Overall, the trends which occur when varying central facility heights are considered are very similar to those which occur when the central facility height of 30m was considered in isolation.

Obviously, the overall times to complete all movements reduce as the central facility height also reduces. However, the range between the minimum and maximum times increases as the central facility height reduces. The most notable difference between the extremes of central facility height (i.e. when the central facility is considered to be at ground level (0m) and 30m) is that there is significantly more variation between layouts, with the more compact layouts giving reduced minimum times to complete all movements. This means that the layout has more influence when the central facility is lower, but, when cranes are used in high rise construction, which is likely to be the case in reality, the selection of layout assumes less importance. However, the range of times, from minimum to maximum, can be in excess of 200%, demonstrating the importance of selecting the optimum crane position. The extensive variation in times between cranes, referred to in respect of Series A simulations, is still in evidence.

Table 7.12 **Series B simulations**
Comparison of maximum times obtained from different methods for Layout 4 for varying central facility height

Central Facility Height	Crane1			Crane2a			Crane2b			Crane3		
	Max. Time (hrs)/Co-ords			Maxi. Time (hrs)/Co-ords			Max. Time (hrs)/Co-ords			Max. Time (hrs)/Co-ords		
	10m grd	C of G	1m grd	10m grd	C of G	1m grd	10m grd	C of G	1m grd	10m grd	C of G	1m grd
0m	22.00	21.25	25.15	35.41	34.64	38.61	43.97	38.36	49.42	32.50	31.77	35.44
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(20,30)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
5m	23.39	22.63	26.54	41.20	40.43	44.39	49.75	44.15	55.21	33.60	32.87	36.53
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(20,30)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
10m	24.78	24.02	27.93	49.86	49.20	52.53	55.54	51.89	61.00	34.70	33.97	37.63
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(20,30)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
15m	26.17	25.41	29.32	61.43	60.78	64.10	64.35	63.41	69.68	35.79	35.06	38.72
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(20,30)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
20m	27.56	26.80	30.71	73.00	72.35	75.67	76.21	74.99	81.25	36.89	36.16	39.82
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
25m	29.27	28.63	32.10	84.58	83.93	87.25	87.79	86.56	92.83	37.98	37.25	40.92
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)
30m	31.22	30.58	33.84	96.15	95.50	98.43	99.36	98.13	103.48	39.08	38.35	42.04
	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)	(30,20)	(31,19)	(26,24)

Movement distributions, as expected, exhibit the same symmetry as Series A. The co-ordinates of the times associated with the minimum times are always located at the perimeter (and often the corner) of the site, whilst those associated with the maximum time are still located internally. A coarse 10m grid may be used to determine the values and location of the set (or sets) of co-ordinates associated with the minimum time, whilst the maximum times, although of less importance, may only be determined accurately by the use of a finer 1m grid.

7.4 Series C simulations

In Series C simulations, the effect of moving the moving facility, which previously was located at the centre of the grid, is examined. Whilst the fixed facilities remain at the corners of the grid, the moving facility is, in turn, located at 5m intervals within the grid, giving a maximum of 121 positions (less those where the moving facility coincides with a fixed facility). For each of these arrangements, which includes those described in Series A simulations, the times to complete all movements are examined on a 10m by 10m grid. This is repeated for each of the 10 layouts shown in Figure 7.1, but only Crane3 is used for this set of simulations and it is assumed that the moving facility located at a height of 30m, with all other facilities being located at ground level.

The results are tabulated in Appendix F, which, for each layout, shows the minimum times to complete all movements (assessed on a 10m by 10m grid) when the central facility is positioned on a 5m by 5m grid as shown. As mentioned previously, the 10m by 10m grid used to assess the crane location associated with the minimum time is relatively coarse, but as demonstrated in section 7.2, the use of such a grid is sufficient to indicate an accurate location for the position of the crane associated with the minimum time. A contour plot of the minimum times is also included, highlighting the lowest and highest minimum times and their corresponding positions, as well as a diagrammatic representation of each layout, showing the number of movements and the location of the moving facility and the corresponding crane position associated with the least minimum time. Note that where more than one set of moving facility co-ordinates is associated with any layout, only one solution (and the corresponding crane position) is depicted graphically.

7.4.1 Range of minimum times to complete all movements

In examining the contour plots in Appendix F, caution is needed as the contours are based on the range between the lowest and highest minimum values and, therefore, do not provide for direct comparison between layouts. Nevertheless the general trend that can be observed is that the dominant range is within 0% - 25% of the range from the lowest minimum time to the highest minimum time, although the trend becomes less pronounced in layouts where the movements are more compact (Layouts 8,9,10).

A summary of the results is presented in Table 7.13, which, for each layout, shows the range of minimum times obtained, ranging from the lowest minimum time to the highest minimum time. In each case, the moving facility and crane co-ordinates associated with these times are included and, for purposes of comparison, the minimum time (and associated crane co-ordinates) are also included when the moving facility is centrally located.

Examining Table 7.13 shows that the range of minimum times (from lowest to highest) is least for Layout 1 (15.4%) where the movement is most diverse, and increases to a maximum of 58.4% (for Layout7), although Layout 10, which is most compact in terms of movement distribution, also exhibits a large range (57.3%). There is also more variability in the minimum times, but this is due to the fact that comparisons are not being made on a like for like basis, as the co-ordinates associated with the lowest and highest minimum times are different in each case, unlike the scenario when the moving facility is centrally located and the magnitude of the variability in minimum times is low. What is perhaps unexpected is that locating the moving facility centrally never results in the least minimum time; this is surprising for Layouts 1 and 6, where the movement scenario is evenly distributed about the centre position. However, the explanation for this is probably that the least minimum time is also influenced by the crane position and the expected symmetry is distorted by the crane location (which inevitably is in a corner position, as far as these layouts are concerned).

Table 7.13 **Series C simulations**
Range of minimum times for each layout

		Layout									
		1	2	3	4	5	6	7	8	9	10
Lowest minimum time	Time (hrs)	21.91	20.68	19.88	19.36	18.80	19.50	18.48	17.76	17.47	16.44
	Moving facility co-ordinates	(20,20) (20,30) (30,20) (30,30)	(30,35)	(30,15)	(40,10)	(45,10)	(30,40) (40,30)	(10-40,0) (10-15,5) (35-40,5)	(5,10) (10,5)	(10,5)	(0,5) (5,0) (5,10) (10,5)
	Crane co-ordinates	(0,0) (0,50) (50,0) (50,50)	(0,0)	(0,50)	(0,50)	(0,30)	(0,50) (50,0)	(20,50) (30,50)	(0,50) (50,0)	(30,50)	(0,0) (10,50) (50,10) (50,50)
Minimum time with central facility at (25,25)	Time (hrs)	22.44	22.31	22.22	22.31	22.31	21.80	22.44	21.80	22.05	21.80
	Crane co-ordinates	(0,0) (0,50) (50,0) (50,50)	(0,0) (50,50)	(0,50) (50,0)	(0,0) (50,50)	(0,0) (50,50)	(0,50) (50,0)	(0,0) (0,50) (50,0) (50,50)	(0,50) (50,0)	(0,50) (50,0)	(0,50) (50,0)
Highest minimum time	Time (hrs)	25.28	26.32	27.86	27.06	26.84	25.60	29.27	24.19	25.95	25.86
	Moving facility co-ordinates	(0,0) (0,50) (50,0) (50,50)	(20,0)	(0,50)	(0,50)	(0,20)	(0,50) (50,0)	(25,50)	(50,50)	(40,50)	(50,50)
	Crane co-ordinates	(0,0) (0,50) (50,0) (50,50)	(50,50)	(0,0) (50,50)	(0,0) (50,50)	(50,50)	(0,50) (50,0)	(0,0) (50,50)	(0,50) (50,0)	(0,50)	(0,50) (50,0)

Table 7.13 also demonstrates that the minimum time when the moving facility is centrally located is closer to the lowest minimum time when movement is more diverse (Layout 1) and there is more disparity between these times when the movement distribution is more compact (Layout 10).

Table 7.14 shows the minimum time associated with four randomly selected positions for the moving facility, and also provides a comparison between the lowest minimum time for each layout. This table demonstrates that there is also variability between the layouts in terms of the minimum times associated with each set of co-ordinates, especially when these variations are compared with those which occur when the moving facility is centrally located at (25,25), as shown in Table 7.1.

Table 7.14 **Series C simulations**
Minimum times for various co-ordinates

Layout	Minimum Time (hours)	Minimum time (hrs) with moving facility at:			
		(0,0)	(20,30)	(30,40)	(40,10)
1	21.91	25.28	21.91	22.63	23.42
2	20.68	25.71	21.73	21.23	22.91
3	19.88	22.23	22.23	22.80	20.59
4	19.36	22.26	23.25	22.94	19.36
5	18.80	23.49	23.28	21.83	19.20
6	19.50	21.69	20.06	19.50	22.13
7	18.48	19.57	24.36	25.29	19.14
8	17.76	19.20	20.06	20.53	21.46
9	17.47	18.35	21.36	22.84	20.03
10	16.44	17.52	20.06	21.21	20.62

7.4.2 Co-ordinates of moving facility and crane associated with minimum time

The co-ordinates of the moving facility and the corresponding crane positions associated with the minimum time are given in Table 7.13 and illustrated graphically in Appendix F.

As mentioned above, the minimum time when the moving facility is centrally located is closer to the lowest minimum time when movement is more diverse than when the movement distribution is more compact. To endorse this, Table 7.13 also shows that when the two minimum values are close (Layoutl), then the co-ordinates of the moving facility are located more centrally than then when there is more disparity between the two minimum values (Layout 10).

In respect of the co-ordinates of the moving facility associated with the lowest minimum time, the moving facility is generally found to be located internally; those cases where this is not so have centres of gravity of the movement matrix located towards the perimeter. On the other hand, in respect of the co-ordinates associated with the highest minimum time, the moving facility is consistently located at the perimeter. However, the increase in minimum times when the moving facility is centrally located, whilst not insignificant, is within an acceptable range of the lowest minimum values and this configuration is more likely to be representative of the scenario on site (i.e. movement of material from the perimeter to the central area).

As far as the crane position associated with the minimum times are concerned, in the majority of cases the optimum position is located at one or more of the corners, and, in any event, is always at the layout perimeter.

7.4.3 Maximum times to complete all movements

The maximum times to complete all movements are tabulated in Table 7.15, which, for each facility, gives the maximum times which correspond to the lowest minimum time, the scenario when the moving facility is centrally located, and the global maximum time. In each case, the co-ordinates of the moving facility are given (apart from the case when the moving facility is centrally located when it is implied), in addition to the corresponding crane co-ordinates. The lowest minimum time is also included for the purposes of comparison.

The main conclusions that can be reached from this analysis are:

- The maximum times corresponding to the lowest minimum times are less than those associated with other scenarios.

- The maximum times are generally associated with crane positions located internally, in direct comparison to those associated with minimum times, which are generally located on the perimeter.

- The percentage increase in times from the lowest minimum time to the overall maximum time to complete all movements are of a high magnitude, varying from a 67.3% increase, relative to the lowest minimum time, for Layout 1, to a 226.6% increase for Layout 10.

7.4.4 Summary

The main conclusion that can be drawn from Series C simulations is that although the optimum layout, in terms of location of moving facility and crane position, never occurs when the moving facility is centrally located, placing the moving facility centrally does not result in significantly large increases in minimum time; this increase is less (that is the two minimum times referred to are closer in order of magnitude) when the movement distribution is diverse, rather than compressed and compact. These results bode well for real life situations, where, generally, movement from the perimeter to the centre of the site is anticipated, and where the movement scenario is likely to be diverse rather than compressed.

Table 7.15 **Series C simulations**
Maximum times to complete all movements

Layout	Minimum Time (hours)	Maximum time corresponding to minimum time			Central facility at (25,25)		Highest overall maximum time		
		Max. time (hours)	Moving facility co-ordinates	Crane co-ordinates	Max. time (hrs)	Crane co-ordinates	Max. time (hrs)	Moving facility Co-ordinates	Crane co-ordinates
1	21.91	30.69	(20,20) (20,30) (30,20) (30,30)	(20,20) (20,30) (30,20) (30,30)	31.62	(20,20) (20,30) (30,20) (30,30)	36.65	(0,0) (0,50) (50,0) (50,50)	(0,10) (0,40)
2	20.68	32.37	(30,35)	(20,40)	34.49	(20,30)	41.15	(0,0)	(0,10)
3	19.88	31.16	(30,15)	(40,10)	34.47	(30,20)	44.08	(5,45)	(10,40)
4	19.36	26.03	(40,10)	(30,10) (40,20)	39.08	(30,20)	47.62	(5,45)	(10,40)
5	18.80	25.62	(45,10)	(40,20)	34.54	(30,20)	47.05	(5,45)	(10,40)
6	19.50	33.84	(30,40) (40,30)	(10,10)	34.54	(10,10) (20,20) (30,30) (40,40)	40.75	(0,50) (50,0)	(0,40) (10,50) (40,0) (50,10)
7	18.48	28.36 - 31.58	(0-40,0) (10-15,5) (35-40,5)	(10,0) (20,0) (30,0) (40,0)	37.35	(20,20) (30,20)	46.29	(5,5) (45,45)	(10,40) (40,40)
8	17.76	23.88	(5,10) (10,5)	(40,40)	41.42	(10,10) (20,20)	45.91	(45,50) (50,45)	(10,10)
9	17.47	21.95	(10,5)	(10,10)	42.54	(20,20)	50.28	(45,45)	(40,40)
10	16.74	18.50	(0,5) (5,0) (5,10)	(0,0) (0,10) (10,0) (10,10)	46.01	(10,10) (20,20)	54.68	(50,50)	(10,10)

On the other hand, those scenarios where the optimum configuration of crane and moving facility place the moving facility towards the site perimeter are associated with layouts where the centre of gravity of the movement matrix located towards the perimeter.

In all cases, the optimum crane position is found to be at the perimeter, and, in many cases, at one or more of the site corners; the maximum times occur when the crane is located internally. The percentage increase between the minimum and maximum times to complete all movements can be significant and may be in excess of a 200% increase relative to the minimum time.

7.5 Summary

The three series of simulations which have been described above have been carried out in order to permit investigations of the sensitivity of the variables in the model.

The ten different movement scenarios described in the introduction (section 7.1), though perhaps simple and not truly representative of real life situations, were designed to represent a range of situations with respect to patterns of movement, and this range was extended in Series C simulations, which investigated the influence of moving the "central" facility at 5m intervals within the grid. In addition, the simulations described allowed the influence of varying crane velocities (Series A simulations) and facility heights (Series B simulations) to be investigated.

The most important aspects to be investigated were the positions and values associated with the minimum and maximum times to complete all movements. The position associated with the minimum time represents the optimum crane location, whilst the position associated with the maximum time represents the least desirable position. The relative values of the minimum and maximum times indicate the importance of attempting to locate the crane at, or near, the optimum position.

Conclusions from this chapter are summarized in Chapter 9.

CHAPTER 8

DISCUSSION

8.1 Introduction

This chapter will focus upon discussing three particular aspects that have arisen from the application of the model which has been developed.

Firstly, the results of the simulations which have been carried out in the previous chapter clearly indicate that the optimum crane position is one which occurs on the perimeter of the site, and indeed is often located in a corner. This clearly has implications in respect of the length of jib which would be suitable to reach all facilities, and contrasts with the situation which would have arisen had it been shown that the optimum crane position was centrally located. Evidently, if the optimum position is to be utilized, a longer jib length than would be necessary were the crane centrally located will be required and this has financial implications in respect of either the purchase cost, or, more commonly, the hire rate, for the crane selected. The discussion will therefore focus upon comparing the costs of cranes with different jib lengths with the potential savings that can be made by locating the crane in its optimum position, and concludes with a crude break-even analysis.

Secondly, as mentioned previously, the model which has been developed is a prescriptive model which does not give the user the optimum solution to the problem of crane location, but merely allows him/her to experiment on a "what-if" basis. However, by inputting the solutions obtained from the simulations to a neural network, the user may then use the neural network to obtain the optimum solution directly. A limited application of a neural network is described in order to illustrate this potential application.

Finally, means of validating the model developed and the output obtained are described. Firstly, a postal questionnaire, which was distributed to 108 construction companies in the United Kingdom, in order to obtain practitioners' response to the results obtained in the previous chapter and from Section 8.2, and hence validate the results obtained, is described. The results obtained are presented and some statistical analyses which have been carried out are described. This is supplemented by some telephone interviews with practitioners regarding the data requirements of the model and a brief investigation into the ease of use of the software which has been developed.

8.2 Crane jib length

In order to examine whether the potential benefits of placing a crane at the site perimeter can outweigh the expense associated with hiring (or purchasing) a crane with a longer jib length, it is necessary to obtain some data concerning the cost (hire rate per week) of different crane jib lengths. Although many inquires were made (via mail) such information proved to be fairly illusive. However, the necessary information concerning Wolffkran cranes was ultimately provided by Hewden Tower Cranes. These data are tabulated in Table 8.1 (for saddle jib cranes only), which also shows the comparison between the actual costs and those predicted using Equation 8.1.

Table 8.1 **Weekly hire cost of Wolffkran cranes**

Crane type	Radius (m)	Actual Hire cost (£/week)	Predicted Hire cost (£/week)
WK45EC	36	445	447
WK100EC	45	610	609
WK135EC	50	720	728
WK200EC	60	1070	1075
WK280EC	70	1620	1631

The data in Table 8.1 are displayed graphically in Figure 8.1, which shows that the relationship between cost (£/week) and radius (m) may be modelled by a third order polynomial equation of the form:

$$\text{Cost} = 0.0129\,(\text{radius})^3 - 1.2758\,(\text{radius})^2 + 57.611(\text{radius}) - 575.44$$

……Equation 8.1

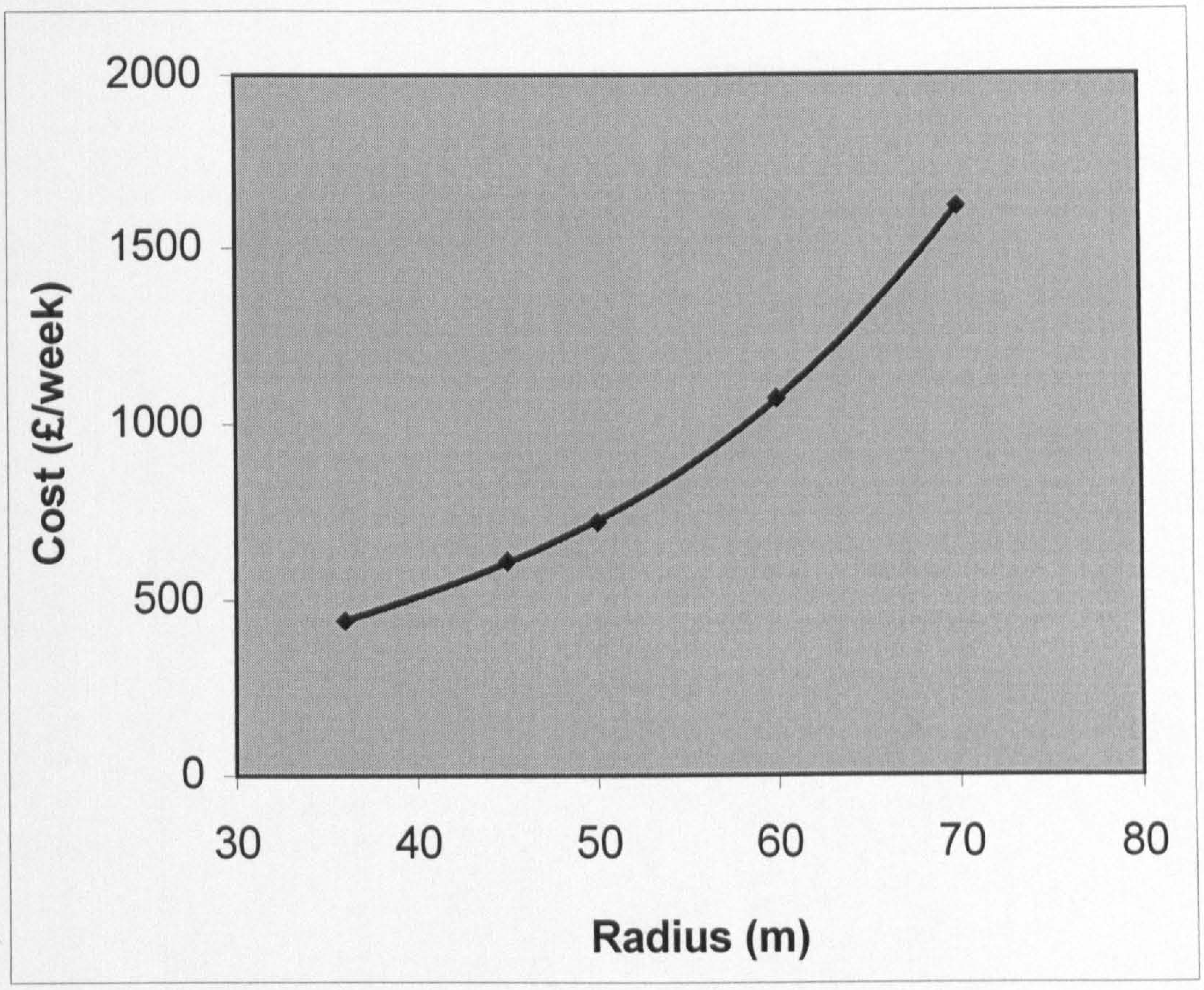


Figure 8.1 **Graph of weekly hire cost of Wolffkran cranes**

It is now necessary to generate some data in respect of the times taken to carry out movements of materials for crane located in different positions and hence requiring cranes of varying jib length. Using the layouts generated for the simulations carried out in the previous chapter (Figure 7.1), and assuming that movement of materials takes place from the fixed facilities at the corners (at (5,5), (45,5), (45,45) and (5,45)) to the moving facility, which is assumed to be centrally located at (25,25), potential crane positions for a range of radii are tabulated in Table 8.2; these positions give rise to six sets of radii, ranging from 29.73m to 63.64m, which is an appropriate range for the type of crane used in this exercise (available radii range from 36m to 70m, as shown in Table 8.1.). The data in Table 8.2 are very similar to those in Table 7.8 (section 7.2.3); the co-ordinates associated with axes A, C, E and G are identical but those associated with B, D, F and H are slightly modified. However, in this case, the radii are measured

Table 8.2 **Proposed crane positions and corresponding radii (measured from corner facilities)**

Radius	Co-ordinates		Co-ordinates	
1 29.73m	A	(27,25)	B	(26.02,26.02)
	C	(25,27)	D	(23.98,26.02)
	E	(23,25)	F	(23.98,23.98)
	G	(25,23)	H	(26.02,23.98)
2 36.06m	A	(35,25)	B	(30.50,30.50)
	C	(25,35)	D	(19.50,30.50)
	E	(15,25)	F	(19.50,19.50)
	G	(25,15)	H	(30.50,19.50)
3 42.94m	A	(43,25)	B	(35.36,35.36)
	C	(25,43)	D	(14.64,35.36)
	E	(7,25)	F	(14.64,14.64)
	G	(25,7)	H	(35.36,14.64)
4 49.24m	A	(50,25)	B	(39.82,39.82)
	C	(25,50)	D	(10.18,39.82)
	E	(0,25)	F	(10.18,10.18)
	G	(25,0)	H	(39.82,10.18)
5 58.28m	B	(46.21,46.21)	D	(3.79,46.21)
	F	(3.79,3.79)	H	(46.21,3.79)
6 63.64m	B	(0,0)	D	(50,0)
	F	(50,50)	H	(0,50)

to or from the corner facilities (as this represents the maximum distance that a crane located at one of these positions would be required to reach). Figure 8.2 shows how the co-ordinates are computed (for the 42.94m radius) and it can be seen that, due to the symmetry of the layout, each potential position along each axis is measured from one or two of the four corner positions. For example, Axis A is measured from the corner facilities at (5,5) and (5,45), whilst Axis B is measured from (5,5) only.

For the purposes of comparison, it is now necessary to compute data concerning the time taken to complete certain movements when the crane is located at each position identified in Table 8.2. The scenarios described in Series A simulations in Chapter 7 have initially been used for this purpose – based on 1000 explicit movements (countered by 1000 implicit movements) distributed in 10 layouts (Figure 7.1) with the central facility located at 30m and the corner facilities located at ground level.

The average times associated with the same position on each radius were again found to identical for each layout (refer to section 7.2.3, where a similar exercise was previously carried out). These results are given in Table 8.3 which gives the predicted cost (£/week) for each jib length, based on Equation 8.1, and then, for each crane and for each radius:

- the average time to complete all movements;
- the time factor, which is obtained by dividing the time to complete all movements for the minimum radius (29.73m) by the time taken to complete all movements for the specific radius and which is a measure of the change in time to complete all movements as the radius changes; and
- the adjusted cost, which is the average time divided by the time factor. Ultimately, plotting the adjusted cost for each radius will highlight the radius where the optimum balance between the cost of hire and potential savings by using a longer jib is achieved.

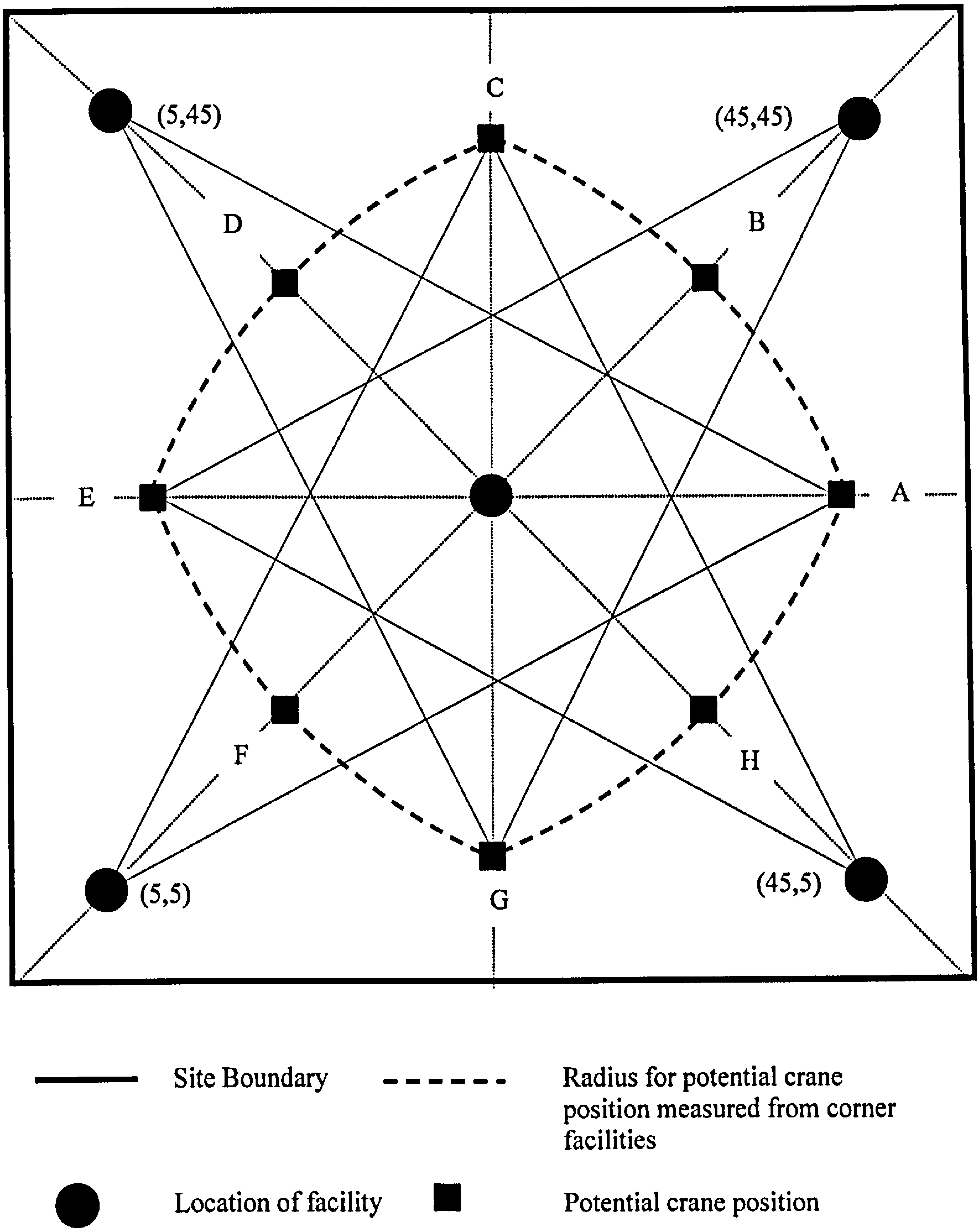


Figure 8.2 **Proposed crane positions for a 42.94m jib length**

Table 8.3. shows that for each crane the optimum radius (i.e. crane jib length) is the shortest and that any benefits achieved by using a longer jib length are outweighed by the additional costs incurred. However, it is appreciated that this assertion is based on using average times for each potential crane jib length and that this assertion may not be valid if the situation is examined in more detail by looking at the data for one specific position and one specific layout. Inspection of the data used to construct Table 8.3 shows that the scenario offering most potential is Crane 3, Layout 10 and Axis F and data for this and three other specific scenarios are shown in Table 8.4. However, the same conclusion can still be drawn, although for the specific case mentioned there is a reduction in times to complete all movements of over 50% when the time associated with the smallest radius is compared with the time associated with the largest radius.

Table 8.3 **Average time to complete all movements for crane positions located at different radii and adjusted costs of crane hire**

Crane radius (m)		29.73	36.06	42.94	49.24	58.28	63.64
Predicted cost (£/week)		349	448	567	708	1002	1249
Crane 1	Average time (hrs)	31.46	29.23	27.29	27.25	26.50	26.20
	Time factor	1.00	1.08	1.15	1.15	1.19	1.20
	Adjusted cost (£)	349	416	492	613	844	1040
Crane 2a	Average time (hrs)	95.81	93.48	91.42	91.29	90.08	89.76
	Time factor	1.00	1.02	1.05	1.05	1.06	1.07
	Adjusted cost (£)	349	437	541	675	942	1170
Crane 2b	Average time (hrs)	102.18	98.16	94.71	95.02	95.32	94.84
	Time factor	1.00	1.04	1.08	1.08	1.07	1.08
	Adjusted cost (£)	349	430	526	659	935	1159
Crane 3	Average time (hrs)	33.59	30.45	27.67	26.76	22.82	22.44
	Time factor	1.00	1.10	1.21	1.26	1.47	1.50
	Adjusted cost (£)	349	406	467	564	681	834

The only variable which has not been investigated is height of the central facility (or, more specifically, the relative height of the facilities). In the foregoing it was assumed that the height of the central facility was 30m, with all other facilities being located at ground level. The data for each crane for Layout 10 and for Axis F are shown in Table 8.5 for central facility heights of both 0m and 15m, which shows the same overall results as previously.

Table 8.4 **Time to complete all movements for specific cranes located at different radii and adjusted costs of crane hire**

Crane radius (m)		29.73	36.06	42.94	49.24	58.28	63.64
Predicted cost (£/week)		349	448	567	708	1002	1249
Crane 3 Layout 10 Axis F	Time (hrs)	48.38	44.57	44.44	47.88	23.10	23.08
	Time factor	1.00	1.09	1.09	1.01	2.09	2.10
	Adjusted cost (£)	349	413	521	701	478	596
Crane 1 Layout 5 Axis H	Time (hrs)	33.83	30.90	28.24	29.85	26.77	26.53
	Time factor	1.00	1.10	1.20	1.13	1.26	1.32
	Adjusted cost (£)	349	401	473	625	793	946
Crane 3 Layout 1 Axis B	Time (hrs)	33.93	31.35	29.37	29.36	22.82	22.44
	Time factor	1.00	1.08	1.16	1.16	1.49	1.51
	Adjusted cost (£)	349	414	491	613	674	826
Crane 2b Layout 2 Axis D	Time (hrs)	103.04	98.82	95.02	97.00	96.06	95.68
	Time factor	1.00	1.04	1.08	1.06	1.07	1.08
	Adjusted cost (£)	349	430	523	666	934	1160

8.2.1 Discussion

As mentioned earlier, the simulations which have been carried out in the previous chapter have clearly indicated that the optimum position is one associated with the perimeter of the site, and therefore if advantage is to be taken of any potential time saving this may offer, then it is necessary to utilize a crane with a longer jib length than

Table 8.5 **Time to complete all movements for Layout 10 and Axis F for different central facility heights and adjusted costs of crane hire**

Crane radius (m)		29.73	36.06	42.94	49.24	58.28	63.64
Predicted cost (£/week)		349	448	567	708	1002	1249
Crane 1 Height 0m	Time (hrs)	23.05	21.29	19.66	21.42	19.05	19.05
	Time factor	1.00	1.08	1.17	1.08	1.21	1.21
	Adjusted cost (£)	349	414	484	658	828	1032
Crane 1 Height 15m	Time (hrs)	27.22	25.46	23.83	25.59	23.22	23.21
	Time factor	1.00	1.07	1.14	1.06	1.17	1.17
	Adjusted cost (£)	349	419	496	666	855	1065
Crane 2a Height 0m	Time (hrs)	35.69	33.93	32.30	34.06	29.61	29.60
	Time factor	1.00	1.05	1.10	1.05	1.21	1.21
	Adjusted cost (£)	349	426	513	676	831	1036
Crane 2a Height 15m	Time (hrs)	61.28	59.52	57.89	59.64	56.47	56.47
	Time factor	1.00	1.03	1.06	1.03	1.09	1.09
	Adjusted cost (£)	349	435	536	689	923	1151
Crane 2b Height 0m	Time (hrs)	47.89	41.47	38.22	41.73	45.32	45.32
	Time factor	1.00	1.16	1.25	1.15	1.06	1.06
	Adjusted cost (£)	349	388	453	617	948	1182
Crane 2b Height 15m	Time (hrs)	67.70	64.17	60.91	64.42	64.33	64.32
	Time factor	1.00	1.06	1.11	1.06	1.05	1.05
	Adjusted cost (£)	349	425	510	674	954	1187
Crane 3 Height 0m	Time (hrs)	29.34	27.79	26.36	27.91	16.51	16.50
	Time factor	1.00	1.06	1.11	1.08	1.78	1.78
	Adjusted cost (£)	349	424	509	654	564	702
Crane 3 Height 15m	Time (hrs)	32.63	31.08	29.65	31.19	19.80	19.79
	Time factor	1.00	1.05	1.10	1.05	1.65	1.65
	Adjusted cost (£)	349	427	515	677	608	758

would be necessary were the crane located centrally. Such a decision, though, has cost implications in respect of the need to hire or buy a crane with a longer jib length. Therefore, it is necessary to compare the increased costs associated with the need to utilize a longer jib length with the potential savings which may accrue by placing the crane in the optimum position. However, the difficulty in attempting to perform such a break even analysis, albeit at a fairly crude level, is plotting the impact of the increased crane jib length and the potential savings to a common scale. The impact of increased jib length can only really be measured in monetary terms (in this case in terms of weekly hire rate) whilst the potential savings are initially measured in terms of time, and without detailed knowledge of the many factors, such as the number of workers involved, conversion to a monetary scale is difficult. Therefore, the method of reducing the cost of all other jib lengths, apart from the shortest, in proportion to the percentage potential time savings, was adopted.

Examination of the results of the analyses (Tables 8.3, 8.4 and 8.5) show that there is not necessarily a consistent reduction in times to complete all movements, although the general assumption that the smaller jib lengths result in longer times to complete all movements than when a longer jib length is adopted is valid. Such variation is attributable to the relative crane velocities and the distribution of the movement patterns. However, the results of the analyses demonstrate that, without question, for the scenarios described it is financially prudent to use the smallest length of jib (i.e. the cheapest) available. However, it should be pointed out that these analyses are based on one supplier's data set only and should other data be available that indicate that the disparity in costs between different jib lengths is less than assumed here, then these results may not necessarily be valid. Another possible limitation is that predicted costs have been used based on the third order polynomial equation that was derived to enable such costs to be predicted, depending on the radius. In practice only a limited range of jib lengths are manufactured and they are not available on a continuous scale, as assumed here. It is also possible that other scenarios, other than those described by the layouts used here, may arise, and this may lead to different results, although in practice the most likely scenario is one where materials dispersed at points around the perimeter are moved towards the centre of the site (as described by Layouts 1 – 10).

It has to said that it was initially expected that the gradient of the curve which plots potential time savings against jib length would be of sufficient magnitude to counter the opposite effect of the increased cost associated with increased jib length, and so the optimum position would occur somewhere between the minimum and maximum available jib lengths. However, as mentioned earlier this did not occur, and the shortest job length was always the clear choice. This had the advantage of eliminating the problem that not necessarily all the savings in crane time could result in overall saving in the operations in which the crane was involved. This was discussed in Chapter 2 (Section 2.6.2.1) when it was shown that although the crane may often be critical in terms of individual operations, any time savings in crane time which may occur do not necessarily reduce the overall operation by the same amount. On the other hand, this could be considered to confirm the choice of the shortest jib length as the most economic decision.

8.3 Neural networks

Neural networks (sometimes referred to as Artificial Neural Networks or ANN's) have been defined as "systems that can learn"(Boussabaine 1996). If a set of input and output data belonging to a particular problem is introduced to the neural network as a training set, then subsequently the neural network can predict outcomes for new data for the same problem.

A brief introduction to neural networks will be provided; it is beyond the scope of this research to provide an in-depth discussion of the fundamentals of neural networks. A brief overview of previous applications of neural networks in the field of construction management follows and, finally, the application of neural networks to the crane location problem is described through a limited example.

8.3.1 Background introduction

Neural networks loosely mimic the structure and behaviour of the human brain (Moselhi 1998). Neural network technology mimics the human brain's own problem solving process by applying knowledge gained from past experience to new problems or situations. Neural networks look for patterns in what are referred to as "training" sets of data, learn these patterns and develop the ability to correctly classify new patterns to make forecasts and predictions (NeuroShell2® 1993).

Several neural network paradigms have been evolved, but it is generally considered that that the Back Propagation (or feed-forward) type of network is most suitable for pattern recognition and forecasting class of problems (Moselhi 1998). Such a network structure has a minimum of three layers: an input layer, one or more hidden layers and an output layer (NeuroShell2® 1993), with each layer containing a number of nodes. The nodes in the input layer represent the influencing factors or variables of the specific problem and the nodes in the output layer represent the solution of this problem. The number of hidden layers and the number of nodes in each layer are determined by trial and error, according to the complexity of the problem (Elhag and Boussabaine 1998 and 1999). All nodes are connected to each other by connection wires and each connection has an associated weight which is a reflection of the strength between each set of nodes (Adul-Hamid 1996). The components of a three layer neural network are illustrated in Figure 8.3.

The pattern of connectivity or the network topography specifies how each node is connected to other units in the network. The strength of each connection is represented by a number (weight), which represents the knowledge that is encoded in the network. As the network learns, the numerical values of the weights may change, according to the new information that is circulating in the network.

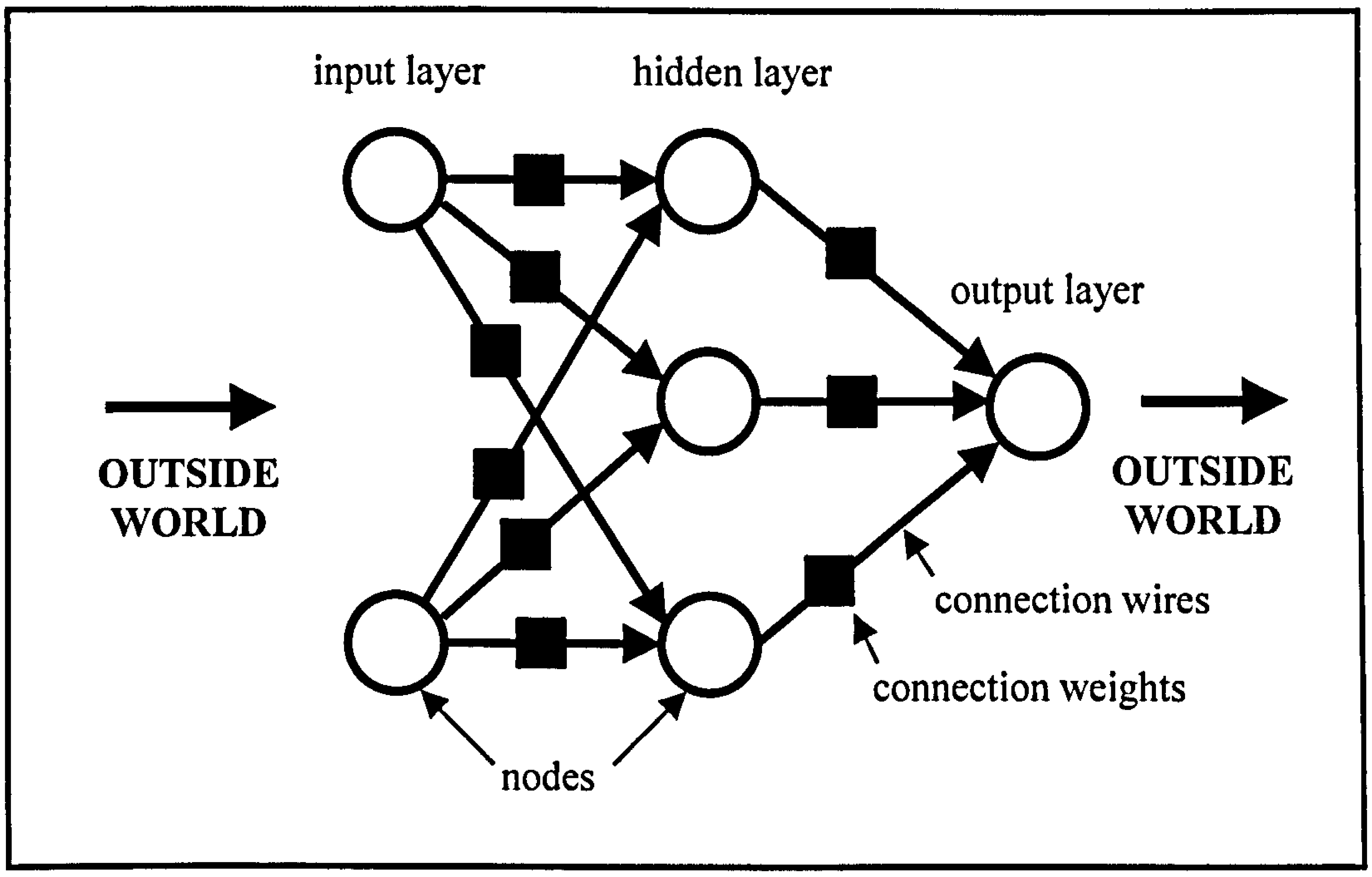


Figure 8.3 **Three layer Back Propagation neural network**
(Source: Boussabaine, 1996)

To train a Back Propagation network, a set of input and output data belonging to a particular problem is used (Adul-Hamid 1996). During training, the input layer broadcasts a pattern to the output nodes. The system is then asked to calculate an output value. The hidden nodes broadcast their results to all output nodes and each output node generates a weighted sum and passes it to the output node to generate an actual value. The result is compared with the output, originally input into the network. The difference yields the system output error. If the error is too large to be acceptable, the output nodes calculate the derivatives of the error with respect to the weights, and the result is sent back through the system to all the hidden nodes and the weights of the connections are adjusted and the process is repeated until an acceptable error is produced.

Whilst the three layer Back Propagation type of network is claimed to be used in 95% of working neural network applications (NeuroShell2® 1993) many other types of architecture exist. One such example (and which is used in the example provided later in this chapter) is General Regression neural networks. This type of network can fit multi-dimensional surfaces to multi-dimensional input and so is particularly suited to continuous function approximation. A General Regression neural network is a three layer network that contains one hidden neuron for each training pattern and which works by measuring how far a given sample pattern is from patterns in the training set in *N* dimensional space, where *N* is the number of inputs in the problem. When a new pattern in presented to the network, the input pattern is compared in *N* dimensional space to all of the patterns in the training set to determine how far in distance it is from those patterns. The output that is predicted by the networks is a proportional amount of all the outputs in the training set. The proportion is based on how far the new pattern is from the given patterns in the training set (NeuroShell2® 1993).

8.3.2 Construction management applications

Whilst the use of neural networks has found widespread utilization in commercial applications, such as the detection of credit card fraud and the optimization of marketing strategies, the same can not yet be said of the application of neural networks in the field of construction management (Boussabaine 1996).

Several authors have described some of the earlier applications of neural networks to construction management related problems, giving examples of applications and highlighting areas of potential future development (Andersen and Gaarslev 1996, Boussabaine 1996 and Moselhi 1998). Areas where some developments have taken place, albeit often by way of a limited example to exemplify their potential, and those which are considered suitable for future development include:

- cost estimating;
- competitive bidding and mark-up estimation;
- predicting construction duration;
- predicting project cash flow and budget performance;
- production simulation; and

- time series forecasting.

This list is not definitive and is merely intended to serve to highlight those areas which have already attracted interest from researchers and practitioners.

Cost estimating is an area which has demonstrated considerable potential in respect of the application of neural networks and one which has been addressed by several authors. Siqueira and Moselhi (1998) described the development of a neural network-based decision support system for cost estimating of low-rise buildings. Only thirty–six data sets were used and the main purpose was to investigate the accuracy of neural networks in determining a cost estimate. It was found that neural networks and in particular General Regression neural networks outperformed other methods, including other types of neural network models and regression analysis. Duff *et al.* (1998) described a feasibility study to determine whether a model to determine the comparative costs of projects carried out using different procurement routes could be developed. Thirty-nine cost significant variables were identified and data from forty-six projects were collected, including, in addition to construction costs, client costs. Neural networks were shown to be an appropriate tool for the modelling process and the next phase is now being carried out (Harding *et al.* 1999a and 1999b) with the objective of collecting five hundred data sets, achieved through substantial industrial collaboration. Similarly, Elhag and Boussabaine (1998 and 1999) have developed a neural network model to predict tender prices for newly constructed office buildings. Thirty six data sets and thirteen input variables were used in the model development, which attempted to compare neural networks and regression analysis. It was concluded that there was no significant difference in the accuracy achieved by both techniques.

A related topic to cost estimation is that of the mark-up (percentage) which contractors apply to their initial cost estimation when submitting a competitive tender. Moselhi *et al.* (1981) used the example of optimum mark-up estimation (that is a percentage increase which will be competitive enough to allow a contractor to win the job but sufficiently high to enable a profit to be made) to demonstrate the application of neural networks. The data used were simulated purely for the purposes of demonstrating the technique. More recently Li (1996) described an experiment to predict the mark-up based on factors such as need for work and number of bidders, which are thought to influence the selection of the optimum mark. The experiments were based on data generated by students on a construction project course in an Australian university, who were participating in a simulated "bid-game" (Harris and McCaffer 1983). It was concluded that the neural network-based model captured the intuition of cost estimators and performed better than regression-based models. Both these applications also demonstrated that simulated data can be used in neural network models.

Predicting construction duration is an other application which has demonstrated potential in respect of the application of neural network models. Adul-Hamid (1996) identified twenty-two variables that influenced construction duration and developed a neural network model using the Back Propagation paradigm based on thirty-six data sets to predict construction duration. A very similar model was developed by Bhokha and Ogunlana (1999), also using a Back Propagation network. The emphasis was on the forecasting of duration at the design stage, so only eleven variables were used, but a larger data set of one hundred and thirty-six buildings were used in the model development.

Budget performance is another area of considerable interest to construction managers. Chua *et al.* (1997) described the development of a model to enable budget predictions to be made and various management strategies to be evaluated. Eight key determining factors were identified and data from seventy five construction projects were collected. It was concluded that the model could perform well, even when presented with incomplete data sets.

The estimation of construction productivity involves consideration of the complex inter-reaction between environment and management related factors; thus this is thought to be a problem where the application of a neural network approach may prove to be profitable. Chao and Skibniewski (1993) described the development of a neural network model to estimate excavator capacity and efficiency. Although it is suggested that the task to be considered must be broken down into several simpler modules, enabling example input-output data to be collected and used in network training, data in the example provided are generated by a computer simulation programme. Nevertheless, test results showed that sufficiently accurate production estimates can be achieved with a limited data collection effort. A similar approach was adopted by Shi (1999) who developed a model to predict earthmoving production.

Neural networks have also demonstrated potential in respect of time series prediction. An example of such an application is provided by Coulibaly and Anctil (1998) who used such a technique for real-time forecasting of potential energy requirements for a hydropower reservoir, by using data from the past fifty-four years to predict the requirements for the next four years.

8.3.3 Application to the crane location problem: an example

This section will provide a presentation of the application of neural networks to the problem of crane location. In particular, it will use the data from Series C simulations, described in Chapter 7, to demonstrate the potential of such a technique. It should be stressed that this example is for illustrative purposes only and is restrictive in two main aspects.

- Only the data from Series C simulations are used and there is no attempt to use any data from a wider description of the problem. Therefore the neural network could only be used in the limited circumstances described by this set of simulations and could not be generally applied to all situations.

- There are only very limited attempts to make adjustments to the settings used by the neural network (such as number of nodes on the hidden layer, learning rate etc.) and so the final output may not necessarily be the optimum which could be achieved.

8.3.3.1 Methodology

In order to build the neural network, the software used (NeuroShell2®) requires the following seven steps to be executed (NeuroShell2® 1993).

1. *Import the data into the neural network software.*

The data, containing both the input and output variables, may be imported from a spreadsheet. Alternatively, the data may be entered directly into a spreadsheet facility contained within the software, although this is necessarily more limited than a dedicated spreadsheet. There is provision for the conversion of alphanumeric data into number format and the creation of If/Then/Else type rules, neither of which are appropriate here.

The variables in the input and output layers are shown in Table 8.6.

Table 8.6 **Neural network input and output variables**

Input variables	Output variables
Number of movements from fixed facility 1	Minimum time
Number of movements from fixed facility 2	Minimum time: X co-ordinate
Number of movements from fixed facility 3	Minimum time: Y co-ordinate
Number of movements from fixed facility 4	Maximum time
Moving facility: X co-ordinate	Maximum time: X co-ordinate
Moving facility: Y co-ordinate	Maximum time: Y co-ordinate

It was decided to create seven different networks; all the networks use all six input variables and the first network uses all the output variables, with the remaining six networks using only one output variable (each selected in turn).

In addition three different notations in respect of the optimum co-ordinate system were investigated.

- Cartesian co-ordinates – with the origin at the bottom left of the grid and maximum values of 50m in respect of both the X and Y axes;
- polar co-ordinates – with the origin at the centre (25,25) and with the angle measure anti-clockwise from a line subtended between (25,25) and (50,25); and
- perimeter co-ordinates – with the first value representing the distance around the perimeter, measured from (0,0) and moving in an anti-clockwise direction, and the second value measuring the distance in from the perimeter, measured at right angles to the perimeter.

The purpose of these investigations was to overcome any difficulties which may arise due to the nature of the data. Many of the co-ordinates associated with the minimum time are located at the perimeter and, in many instances, at the corners. The concern is that the network, faced with multiple entries such as (0,0) and (50,50) may determine an optimum co-ordinate of (25,25).

There are approximately 121 x 10 x 4 = 4840 data sets for each network. 121 represents the number of combinations of moving facility co-ordinates (based on a 50m grid at 5m intervals in both directions). 10 represents the number of layouts (refer to Figure 7.1). The factor of 4 is included because, in some instances, there is more than one set of co-ordinates associated with either the minimum or maximum time. If, in the worst case scenario, there are four sets of such co-ordinates for any one position of the moving facility for any one network, then these data are entered four times with the co-ordinates changed each time. If there are two sets of such co-ordinates then there will be two sets of data entered twice. If there is only one set of co-ordinates (the most likely occurrence), then the data set is entered four times. Therefore, this factor is a device to represent the relative weighting of each data set. In practice, there are actually 4773 data sets, as some are missing where the moving facility coincides with one of the fixed facilities.

2. *Define the inputs and outputs and set the minimum and maximum values of each variable.*

This is necessary so that the data can be scaled into the range 0 to 1 and can be done automatically by inspection of the data which have been entered.

3. *Extract the test set.*

The default value is 10% selected randomly.

4. *Design the network architecture.*

NeuroShell2® provides several different architectures (NeuroShell2® 1993): Back Propagation, Kohonen, Probabilistic Neural Networks (PNN) and General Regression Neural Networks (GRNN).

Initially, the Back Propagation network architecture was selected. By default NeuroShell2® selects a three layer Back Propagation network using standard connections. The input layer has 6 nodes and the output layer has either 6 or 1 node (depending on the number of output variables). The number of nodes in the hidden layer is set at 71 and 68 respectively. The learning rate, momentum and initial weights are set at 0.1, 0.1 and 0.3 respectively. These are all variables which influence the way in which weights leading to an output node are modified during the learning process. Changing these variables, in particular the number of nodes in the hidden layer, did not enable any better network to be produced than those which arose from using the default values.

The Back Propagation network with jump connections and the recurrent type of Back Propagation network (more suitable for time series data) were not investigated. The Kohonen architecture (suitable for data without correct outputs in the sample patterns) and the Probabilistic Neural Network (PNN) (where output values must be either 0 or 1) were also disregarded.

However, General Regression neural networks were also investigated. Such a network is a three layer network that contains one hidden layer for each training pattern. There are no training parameters such as learning rate and momentum, but there is a smoothing factor that is used when the network is applied to new data, and which determines how tightly the network matches the predictions to data in the training patterns. Again, using the default values (which varied for each network) was found to give the optimum results.

5. Run (train) the network and hence learn.

The problem with any type of neural network training is achieving a balance between over-learning, when the network memorises the patterns which are presented to it and cannot interpolate smoothly between them, or under-learning, when the network will not be able to generalise when presented with data not used in training.

When using a Back Propagation architecture, NeuroShell2® uses a device which trains on the training set and computes an average error factor, which continues to get smaller as training proceeds. However, it periodically reads the test data set and also computes an average error for this data set; this error, whilst initially decreasing will, at the optimum point, begin to get larger. NeuroShell2® identifies this optimum point and then saves the network.

When using a General Regression architecture, the network is essentially trained after one pass of the training pattern. NeuroShell2® then tests a range of smoothing factors (which determine how tightly the network matches its predictions to the data in the training patterns) and selects the one that results in the lowest mean squared error for all outputs over all test patterns.

6. Apply to file.

This procedure processes a data file through a trained neural network in order to produce the network's classifications or predictions for each pattern in the file. For each output the following statistical data are computed:

- *R squared*, a statistical indicator usually applied to regression analysis. Its value can range from 0 to 1 and it indicates what proportion of the variation in the actual output values predicted by the network may be explained by changes in the values of input data (and hence how much of the variation is unexplained);
- mean squared error, where the squared error is $(\text{actual} - \text{predicted})^2$;
- mean, minimum and maximum absolute error, where the absolute error is |actual- predicted|; and
- correlation coefficient r, which is a measure of the correlation of the strength of the relationship between the actual versus predicted values, and which can range from –1 to +1. It is not believed that this coefficient is a good measure of the performance of neural network models (NeuroShell2® 1993).

The values of *R squared* for each network and each output variable are shown in Table 8.7, where the annotation '1-6' indicates that the output variables were considered separately in six separate networks. Other statistical data are not included as, for example, comparing error values between the minimum times (which are fairly closely clustered) with values of co-ordinates (which have a much greater range) is perceived to be of little value. In examining Table 8.7, it should be noted that when the outputs are considered separately, the values associated with the minimum and maximum times are the same for each network type, regardless of whether Cartesian, polar or perimeter co-ordinates have been used, due to the fact that the associated input data are identical in all cases.

Examining the data in Table 8.7, it can be seen that the values of *R squared* associated with the minimum and maximum times are generally good (ranging from 0.7984 to 0.9998) whilst those associated with the co-ordinates are more variable (ranging from 0.0000 to 0.9916). In respect of the minimum and maximum times, this is to expected, as because the data are simulated data the problem is not so much 'noise' within the data, but the difficulty in being able to accurately model the multi-dimensional surface produced by the data. The (occasional) poor values of *R squared* associated with the co-ordinates highlights the difficulty, mentioned earlier, of the likelihood of the network averaging out co-ordinates when many of them are located

Table 8.7 **Values of *R squared* for each network and for each output variable**

		Minimum time			Maximum time		
		Time (hrs)	X Co-ord	Y Co-ord	Time (hrs)	X Co-ord	Y Co-ord
Back Propagation	Cartesian	0.8763	0.6673	0.6259	0.8246	0.6915	0.7033
	Cartesian 1-6	0.8636	0.6266	0.3431	0.8663	0.6417	0.6485
	Polar	0.8365	0.3316	0.4645	0.8270	0.3622	0.0000
	Polar 1-6	0.8636	0.1265	0.2402	0.8663	0.6417	0.6485
	Perimeter	0.8352	0.5258	0.0158	0.7984	0.3960	0.4193
	Perimeter 1-6	0.8636	0.4056	0.0073	0.8663	0.4028	0.0096
General Regression	Cartesian	0.9994	0.9309	0.9390	0.9984	0.9814	0.9831
	Cartesian 1-6	0.9998	0.9283	0.9380	0.9996	0.9840	0.9583
	Polar	0.9998	0.9916	0.9487	0.9995	0.9749	0.9725
	Polar 1-6	0.9998	0.6545	0.9480	0.9996	0.9840	0.9220
	Perimeter	0.9960	0.9383	0.8272	0.9895	0.5613	0.9220
	Perimeter 1-6	0.9998	09498	0.8895	0.9996	0.4395	0.9657

at the perimeter, and in many instances at a corner, resulting in the network suggesting an internal position as the optimum position, Further, on the basis of the results in Table 8.7, there is no significant improvement obtained by using another co-ordinate system other than Cartesian; it may be argued that, in many cases, the values of *R squared* associated with the Cartesian co-ordinate system are better than those associated with other co-ordinate systems.

The two other notable results are that there appear to be no immediate benefits in considering each output separately, rather than considering all outputs together, and there is a marked (albeit not statistically significant) improvement in values of

R squared when the General Regression network is compared with the Back Propagation network; when the General Regression networks are considered in isolation, *R squared* ranges from 0.9960 to 0.9998 in respect of minimum and maximum times and from 0.6545 to 0.9916 in respect of co-ordinates.

7. *Execute the trained network*

Once the network has been trained it is necessary to use the Dynamic Link Library (DLL) server to enable the network to be accessed for predictive purposes. Execution of the trained network is the process of feeding an array of inputs to the network and receiving back the appropriate array of outputs. A Predict function can then be used in other software (such as a spreadsheet) which gives the predicted output for the specified input.

<u>8.3.3.2 Results</u>

Firstly, a fairly crude attempt was made to identify the 'best' network. The networks created using Back Propagation architecture and polar and perimeter co-ordinates were discounted because of the relatively low values of *R squared* associated with these networks. Also, an initial comparison of the actual and predicted values using these networks showed that they were not good predictors. For the remaining networks, a comparison was made between the actual minimum and maximum times and their associated co-ordinates for the existing layouts (See Figure 7.1) when the moving facility was located at (20,10) and those values which are predicted by the network. Table 8.8 tabulates this information in respect of minimum times and Table 8.9 in respect of maximum times. In both cases, the predicted values closest to the actual values are shown in bold text. The position of (20,10) for the moving facility was chosen more or less at random; the central position of (25,25) was not selected as, due to the symmetry associated with this position, there are often multiple sets of co-ordinates associated with the minimum and maximum times, and, as the neural networks can only predict one position, this does not provide a very satisfactory basis for comparison.

Table 8.8 **Comparison of output for minimum times**
Back Propagation and General Regression networks

Layout		Back propagation		General regression					
		Cartesian	Cartesian 1 - 6	Cartesian	Cartesian 1 - 6	Polar	Polar 1 - 6	Perimeter	Perimeter 1 - 6
	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's
1	22.63	22.49	23.05	22.65	**22.63**	22.64	**22.63**	22.69	**22.63**
	(50,0)	(23.73,50.00)	(28.05,31.54)	(1.99,50.00)	(3.39,50.00)	(25.13, 24.85)	**(25.10,25.17)**	(5.91,50.00)	(2.28,50.00)
2	23.76	22.63	23.53	23.73	**23.76**	23.75	**23.76**	23.70	**23.76**
	(50,50)	(38.60,47.02)	(41.19,20.98)	**(50.00,49.95)**	(50.00,49.91)	(24.81,24.97)	(24.85,24.88)	(50.00,49.54)	(50,00,49,93)
3	20.38	20.96	21.41	20.41	**20.38**	20.39	**20.38**	20.47	**20.38**
	(0,50)	**(0.00,50.00)**	(1.00,43.28)	(0.01,50.00)	(0.02,50.00)	(24.80,25.00)	(24.80,25..00)	(0.05,50.00)	(0.01,50.00)
4	21.08	20.44	20.87	21.09	**21.08**	21.09	**21.08**	29.12	**21.08**
	(0,50)	**(0.35,50.00)**	(3.67,48.23)	(1.33,50.00)	(2.26.50.00)	(25.17,25.09)	(24.85,24.88)	(3.93,50.00)	(1.52,50.00)
5	21.42	20.96	21.30	21.45	**21.42**	21.43	**21.42**	21.50	**21.42**
	(0,50)	**(0.00,50,00)**	(0.17,47.13)	(1.70.50.00)	(2.79,50,00)	(25.19,24.93)	(24.88,25.16)	(31.73,10.00)	(34.83,10.00)
6	19.50	20.16	20.78	19.56	**19.50**	19.52	**19.50**	19.70	**19.50**
	(0,50)	(0.00,48.48)	(2.15,34.28)	**(0.02,49.98)**	(0.06,49.97)	(24.80,25.00)	(24.81,24.98)	(0.37,50.00)	(0.05,50.00)
7	19.41	18.66	19.52	**19.41**	**19.41**	**19.41**	**19.41**	19.42	**19.41**
	(40,50)	(9.68,50.00)	(17.40,49.24)	**(39.91,50.00)**	(39.81,50.00)	(25.00,25.16)	(25.16,24.96)	(39.57,50.00)	(39.89,50.00)
8	18.48	19.32	19.04	18.57	**18.48**	18.51	**18.48**	18.72	**18.48**
	(0,50)	(0.00,49.02)	(7.15,40.16)	**(0.34,50.00)**	(0.56,50.00)	(24.83,25.10)	(24.92,25.17)	(0.93,50.00)	(0.39,50.00)
9	18.66	18.70	18.54	18.70	**18.66**	18.68	**18.66**	18.78	**18.66**
	(0,50)	(1.40,50.00)	(15.84,46.14)	**(0.24,50.00)**	(0.47,50.00)	(24.81,25.07)	(24.88,25.12)	(1.00,50.00)	(0.28,50.00)
10	17.79	18.40	17.69	**17.76**	17.70	17.72	17.70	17.88	17.70
	(0,50)	**(0.22,50.00)**	(14.99,43.46)	(0.23,49.98)	(0.43,49.97)	(24.81,25.06)	(24.85,25.10)	(1.08,50.00)	(0.29,50.00)

Table 8.9 **Comparison of output for maximum times**
Back Propagation and General Regression networks

Layout		Back propagation		General regression					
		Cartesian	Cartesian 1 - 6	Cartesian	Cartesian 1 - 6	Polar	Polar 1 - 6	Perimeter	Perimeter 1 - 6
	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)	Max. Time (hours)
	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's	Co-ord's
1	32.64	33.55	33.19	32.60	**32.64**	32.62	**32.64**	32.55	**32.64**
	(20,20)	(19.97,10.45)	(22.00,16.39)	(20.65,19.47)	**(20.08,19.88)**	(24.99,25.04)	(24.96,24.90)	(31.53,38.66)	(30.09, 16.75)
2	36.19	**36.18**	35.43	36.96	**36.18**	36.10	**36.18**	35.67	**36.18**
	(20,20)	(16.09,16.44)	(22.09, 20.91)	(20.48,19.97)	**(20.07,20.00)**	(24.98,25.04)	(24.97,24.89)	(30.23,49.33)	(30.00,38.55)
3	32.75	32.38	32.95	32.68	**32.75**	32.72	**32.75**	32.59	**32.75**
	(30,10)	(27.85,8.93)	(25.91,12.21)	(30.50,10.26)	**(30.07,10.06)**	(23.91,24.98)	(24.92,24.85)	(33.69,10.09)	(40.45,10.00)
4	35.87	34.43	34.02	35.74	**35.86**	35.82	**35.86**	35.49	**35.86**
	(30,10)	(27.12,5.05)	(29.51.11.26)	(30.19,10.00)	**(30.03,10.00)**	(24.97,25.08)	(24.90,25.13)	(30.83,10.00)	(24.40,10.00)
5	37.51	36.20	34.98	37.30	**37.50**	37.43	**37.50**	36.94	**37.50**
	(30,10)	(29.31,5.50)	(31.87,12.89)	(30.33,10.00)	**(30.55,10.00)**	(24.94,25.06)	(24.84,25.04)	(31.73,10.00)	(34.83,10.00)
6	33.83	37.78	37.48	33.88	**33.84**	33.86	**33.84**	33.98	**33.84**
	(10,10) (40,40)	(25.35,14.47)	(21.26,13.41)	(29.92,29.77)	(29.99,29.95)	(25.04,25.00)	(25.00,24.83)	(32.29,4843)	(30.12,40.25)
7	30.59	30.86	32.02	30.52	**30.59**	30.57	**30.59**	30.40	**30.59**
	(30,10)	(18.90,4.91)	(21.96,7.87)	(29.44,9.88)	**(29.93,9.97)**	(25.07,24.94)	(24.97,24.84)	(36.51,9.55)	(40.02,3.23)
8	34.49	36.09	33.79	34.21	**34.47**	34.39	**34.47**	33.76	**34.47**
	(10,10)	(13.46,5.48)	(14.20,8.70)	(10.01,9.67)	**(10.00,9.92)**	(24.90,24.94)	(24.96,24.96)	(36.64,40.86)	(40.06,33.42)
9	32.49	33.68	32.15	32.34	**32.48**	32.44	**32.48**	32.09	**32.48**
	(10,10)	(10.77,3.36)	(14.45,6.74)	(10.01,9.54)	**(10.00,9.90)**	(24.91,24.92)	(24.97,24.95)	(41.30,37.77)	(40.08,9.46)
10	34.93	35.24	33.38	34.70	**34.92**	34.85	**34.92**	34.30	**34.92**
	(10,10)	(10.13,4.56)	(10.03,6.03)	(10.00,9.61)	**(10.00,9.91)**	(24.90,24.93)	(24.97,24.96)	(41.14,43.08)	(40.07,25.66)

Comparing the actual and predicted values of minimum and maximum times shows that in 9 cases out of 10 in respect of minimum times and in all 10 cases in respect of maximum times, the networks created using the General Regression architecture, and where individual networks have been developed in respect of each output, predict the times closest to those which are determined by the model (referred to as the actual values). More specifically, in respect of the prediction of minimum times, in the 9 out of 10 cases mentioned above, the values predicted by these networks are identical to those determined by the model, with a correlation coefficient $r = 1.00$, and, even if the other case is included (that associated with Layout 10) a correlation coefficient of $r = 1.00$ (to 2 decimal places) is still obtained. Obviously, in respect of the times (either minimum or maximum), the co-ordinate system is irrelevant as the times are independent of the co-ordinate system adopted. However, when considering the networks created using the Back Propagation architecture or those created using the General Regression architecture but where all outputs are considered together, high levels of correlation between actual and predicted values are also obtained with the worst case being associated with the Back Propagation architecture using Cartesian co-ordinates and where all outputs are considered together; in this case $r = 0.95$.

Considering the same network in respect of maximum times (Table 8.9), a similar picture emerges. Comparing the actual and predicted values of times for the networks created using the General Regression architecture, and where individual networks have been developed in respect of each output, although the actual and predicted times are not consistently identical (with actual and predicted times only being identical on three occasions) the actual and predicted times are still highly correlated with a correlation coefficient $r = 1.00$ (to 2 decimal places). When considering the networks created using the General Regression architecture but where all outputs are considered together, high levels of correlation between actual and predicted values are also obtained. However, those networks created using the Back Propagation architecture and Cartesian co-ordinates and where all outputs are considered together have relatively low correlation coefficients with $r = 0.71$ (all outputs considered together) and $r = 0.55$ (outputs considered separately).

The situation in respect of the co-ordinates associated with the minimum and maximum times is not so precise. Firstly, considering the co-ordinates associated with the minimum times, there is no one particular combination of architecture and co-ordinate system that consistently produces the best prediction. In one case, the network created using General Regression architecture and polar co-ordinates and where all outputs were considered separately, produces the predicted sets of co-ordinates most closely aligned to the actual values. However, the predicted value may be considered as inaccurate, compared to the actual value. In four cases, the networks created using Back Propagation architecture and Cartesian co-ordinates and where all outputs were considered together produce the predicted sets of co-ordinates most closely aligned to the actual values; and in each case the predicted values may be considered as highly accurate (within 0.35m). In five cases, the networks created using General Regression architecture and Cartesian co-ordinates and where all outputs were considered together produce the predicted sets of co-ordinates most closely aligned to the actual values; in four cases the predicted values may be considered as highly accurate (within 0.34m), whilst the remaining one is only moderately so (within 1.0m). However, when considering the combination of architecture and co-ordinate system, for the four cases mentioned previously, while the predicted sets of co-ordinates are not the most accurate, they may still be considered as moderately accurate (within 1.7m).

In respect of the sets of co-ordinates associated with the maximum times, the situation is much simpler. With the exception of Layout 6, where there are two sets of co-ordinates associated with the maximum time, the network created using General Regression architecture and Cartesian co-ordinates and where all outputs are considered separately, consistently gives the most accurate predictions of these co-ordinates; and the predictions may be considered as highly accurate (within 0.6m).

Therefore, on the basis of the foregoing analysis, the networks created using the General Regression architecture were selected as the optimum to be used for further comparison. In particular, in respect of minimum and maximum times, those networks where the outputs were considered separately were selected as the optimum (the co-ordinate system is not relevant). In respect of the co-ordinates associated with the minimum times, the optimum networks is considered to be that created using Cartesian co-ordinates and where all outputs are considered together. On the other hand, in respect of the co-ordinates associated with maximum times, the optimum network is considered to be that created using Cartesian co-ordinates and where all outputs are considered separately.

This combination of networks has been used to predict the values of minimum and maximum times and the associated co-ordinates for four other positions of the moving facility, selected more or less at random: (10,30), (25,25), (30,20) and (40,40). Table 8.10 tabulates the values of minimum times and associated co-ordinates for these four additional positions of the moving facility and for the existing layouts, 1 – 10 (see Figure 7.1). Table 8.11 tabulates the corresponding values of maximum times and associated co-ordinates. In order to examine further the predictive capabilities of the selected neural network, ten further layouts have been designed, Layouts 11 – 20, with the same number of total movements (1000); these layouts, referred to as new layouts, are shown in Figure 8.4. Table 8.12 tabulates the values of minimum times and associated co-ordinates for the five sets of co-ordinates referred to previously (i.e. (10,30), (20,10), (25,25), (30,20) and (40,40)) for these new layouts. Table 8.13 tabulates the corresponding values of maximum times and associated co-ordinates.

A general examination of the data contained within Tables 8.10 to 8.13, together with the relevant portions of Tables 8.8 and 8.9 (the relevant portions associated with the neural networks that have been selected as the best, are highlighted), shows that generally, in respect of minimum and maximum times, the neural network performs relatively well. Table 8.14 tabulates:

- the correlation coefficient *r* between actual and predicted values;
- the test statistic *t* calculated for small matched samples:

$$t = (\overline{D} - \mu_D)/(s_D/\sqrt{n})$$

Null hypothesis H_0: $\mu_D = 0$

Alternative hypothesis H_1: $\mu_D \neq 0$

where $\overline{D}$ = mean of the differences

μ_D = mean of the sampling distribution $\overline{D}$

s_D = standard deviation o f the differences

n = sample size

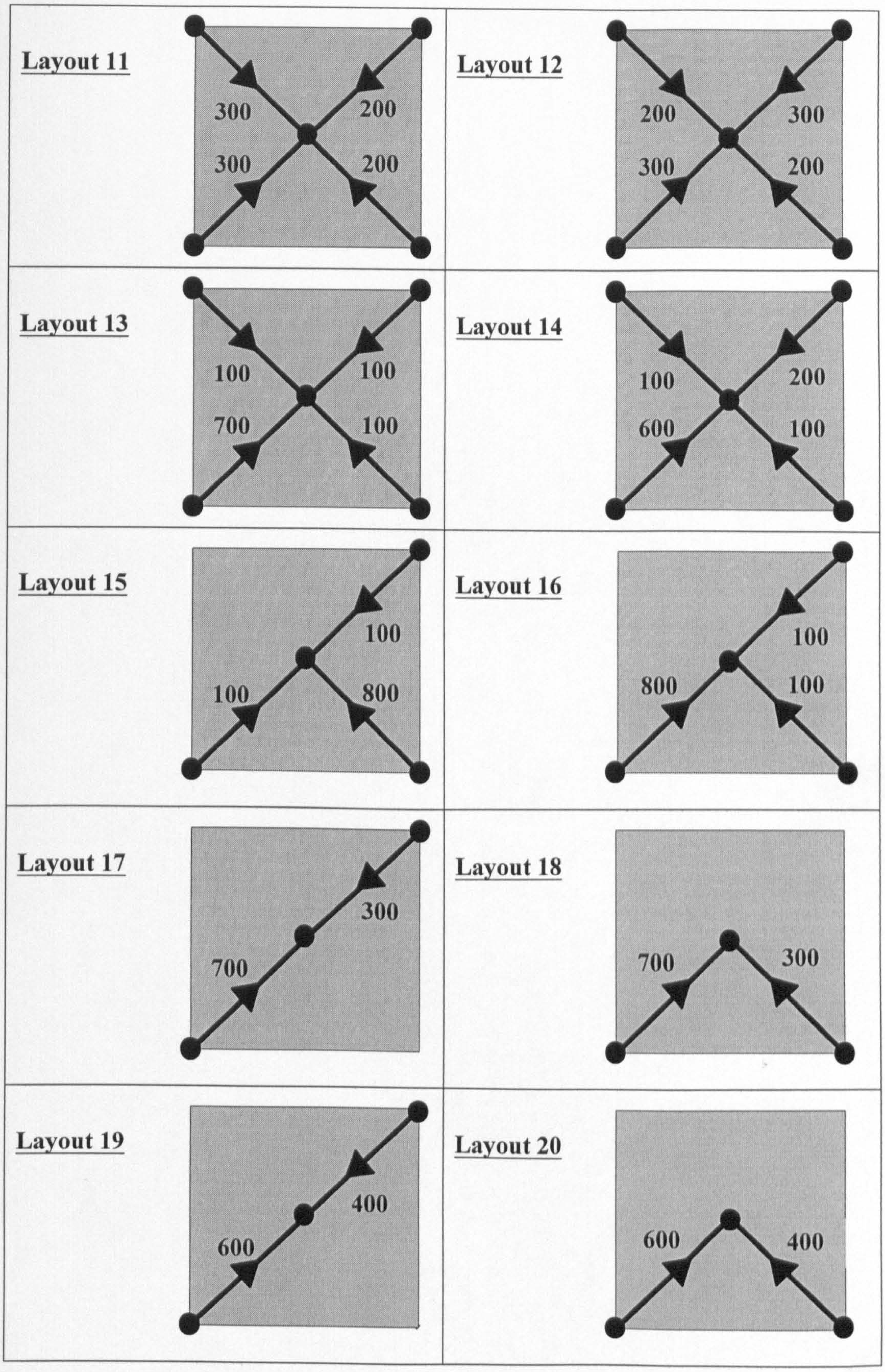


Figure 8.4 **Layouts showing different movement scenarios**

Table 8.10 **Existing layouts: actual and predicted output for minimum times for various sets of moving facility co-ordinates**

Layout	Moving facility Co-ord's (10,30)		Moving facility Co-ord's (25,25)		Moving facility Co-ord's (30,20)		Moving facility Co-ord's (40,40)	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's	Minimum Time (hours) Co-ord's
1	22.63	22.63	22.44	22.44	21.91	21.91	23.42	23.42
	(50.50)	(50.00,47.98)	(0,0) (0,50) (50,0) (50,50)	(25.17,25.17)	(0,50)	(0.69,49.63)	(0,50) (50,0)	(32.32,17.66)
2	22.39	22.39	22.31	22.31	22.77	23.00	21.88	21.88
	(50,50)	(49.96, 44.02)	(0,0) (50,50)	(17.98,17.95)	(0,0)	(47.35,47.35)	(0,0)	(1.04,0.00)
3	21.62	24.03	22.22	22.22	20.37	20.37	21.62	21.06
	(0,50)	(50.00,1.71)	(0,50) (50,0)	(17.75,3.25)	(0,50)	(0.01,49.99)	(0,50)	(0.00,49.73)
4	24.53	23.03	22.31	22.31	20.62	20.62	22.63	22.08
	(0,50) (50,0)	(49.08,49.08)	(0,0) (50,50)	(30.38,33.74)	(0,50)	(0.02,49.99)	(0,50)	(0.00,48.07)
5	23.74	23.75	22.31	22.31	20.62	20.62	21.12	21.12
	(50,50)	(49.95,49.93)	(0,0) (50,50)	(30.46, 31.78)	(0,50)	(0.02,48.65)	(0,20)	(0.00,19.53)
6	20.52	20.52	21.80	21.80	20.06	20.06	20.36	20.36
	(50,0)	(49.54.0.04)	(0,50) (50,0)	(25.16,24.84)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(24.83,25.17)
7	21.67	21.67	22.44	22.44	20.52	20.52	23.69	23.69
	(50,50)	(50.00,49.99)	(0,0) (0,50) (50,0) (50,50)	(25.00,25.83)	(0,50)	(0.37,49.78)	(0,50)	(0.00,49.79)
8	19.82	19.82	21.80	21.80	20.06	20.06	22.08	22.08
	(50,10)	(50.00,9.07)	(0,50) (50,0)	(25.00,25.00)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(17.51,32.48)
9	22.99	21.95	22.05	22.05	20.25	20.25	23.41	23.41
	(50,50)	(50.00,47.96)	(0,50) (50,0)	(32.05,17.97)	(0,50)	(0.02,49.98)	(0,50)	(2.30,47.69)
10	18.97	18.97	21.80	21.80	20.06	20.06	23.22	23.22
	(50,10)	(50.00,9.68)	(0,50) (50,0)	(25.59,24.95)	(0,50)	(0.02,49.79)	(0,50) (50,0)	(24.84,25.16)

Table 8.11 **Existing layouts: actual and predicted output for maximum times for various sets of moving facility co-ordinates**

Layout	Moving facility Co-ord's (10,30)		Moving facility Co-ord's (25,25)		Moving facility Co-ord's (30,20)		Moving facility Co-ord's (40,40)	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's	Maximum Time (hours) Co-ord's
1	32.64	32.64	31.62	36.61	30.69	30.69	33.22	33.22
	(20,30)	(19.95,29.88)	(20,20) (20,30) (30,20) (30,30)	(25.00,25.01)	(20,20) (30,30)	(25.03,25.01)	(30,40) (40,30)	(33.31,36.56)
2	32.87	32.87	34.49	34.48	32.90	32.19	33.26	33.25
	(10,40)	(10.09,39.92)	(20,30)	(19.92,30.14)	(30,30)	(20.03) (20.18)	(30,40)	(29.97) (40.00)
3	34.58	36.02	34.47	34.45	32.04	32.04	34.58	31.54
	(20,10)	(10.08,20.08)	(30,20)	(30.09,19.85)	(40,10)	(40.00,10.00)	(40,30)	(39.97,20.20)
4	41.51	37.91	39.08	39.06	36.93	36.92	38.44	35.59
	(20,30)	(20.06,20.00)	(30,20)	(30.17,19.71)	(40,10)	(40.00,10.00)	(40,30)	(40.00,22.61)
5	40.74	39.30	34.54	39.06	36.93	36.92	36.28	36.26
	(20,20)	(20.13,29.57)	(30,20)	(30.12,19.78)	(40,10)	(40.00,10.00)	(40,30)	(40.00,29.96)
6	35.50	35.49	34.54	34.54	33.55	33.56	34.36	34.36
	(10,20)	(10.07,20.18)	(10,10) (20,20) (30,30) (40,40)	(25.01,25.02)	(10,10)	(10.19,10.31)	(10,10)	(10.00,10.00)
7	38.80	38.79	37.35	37.34	35.09	35.08	42.40	42.39
	(10,20)	(10.03,20.00)	(20,20) (30,20)	(20.03, 24.75)	(40,10)	(39.95,10.00)	(40,30)	(39.97,29.97)
8	38.53	38.52	41.42	41.41	39.15	39.15	44.47	44.47
	(10,20)	(10.00,19.92)	(10,10) (20,20)	(14.94,14.90)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
9	38.63	39.84	42.54	42.52	38.74	38.74	45.46	45.46
	(10,20)	(10.00,19.96)	(20,20)	(19.83,19.71)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
10	40.55	40.54	46.01	45.99	39.96	36.99	51.21	51.21
	(10,20)	(9.99,19.94)	(10,10) (20,20)	(15.00,15.01)	(20,20)	(19.97,19.84)	(10,10)	(10.00,10.00)

Table 8.12 **New layouts: actual and predicted output for minimum times for various sets of moving facility co-ordinates**

Layout	Moving facility Co-ord's (10,30)		Moving facility Co-ord's (20,10)		Moving facility Co-ord's (25,25)		Moving facility Co-ord's (30,20)		Moving facility Co-ord's 40,40)	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's	Min. Time (hours) Co-ord's
11	22.19	22.63	22.50	22.63	22.44	22.44	22.19	21.91	23.47	23.42
	(0,50)	(50.00,47.98)	(50,50)	(1.99,50.00)	(0,0) (0,50) (50,0) (50,50)	(25.17,25.17)	(0,50)	(0.69,49.63)	(50,0)	(32.32,17.66)
12	22.49	22.63	22.00	22.63	22.31	22.44	21.54	21.91	22.81	23.42
	(0,50)	(50.00,47.98)	(0,50)	(1.99,50.00)	(0,50) (50,0)	(25.17,25.17)	(0,50)	(0.69,39.63)	(0,50) (50,0)	(32.32,17.76)
13	21.01	21.05	19.73	18.60	22.05	21.92	20.80	20.17	23.30	22.84
	(50,10)	(50.00,30.94)	(0,50)	(0.28,50.00)	(0,50) (50,0)	(28.09,21.82)	(0.50)	(0.02,49.98)	(0,50) (50,0)	(8.96,41.03)
14	21.21	19.81	20.07	18.47	22.05	21.79	20.80	20.05	22.73	22.06
	(50,0)	(50.00,9.07)	(0,50)	(0.34,50.00)	(0,50) (50,0)	(25.00,25.00)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(17.51,32.48)
15	22.12	22.03	20.59	21.08	22.05	22.31	20.80	20.62	21.71	22.08
	(50,50)	(49.98,49.98)	(40,50)	(1.33,50.00)	(0,0) (50,50)	(30.38,33.74)	(0,50)	(0.02,49.99)	(0,20)	(0.00,48.07)
16	20.92	21.04	18.57	18.59	21.93	21.90	20.16	20.16	22.74	22.84
	(50,10)	(50.00,30.94)	(0,50)	(0.28,50.00)	(0,50) (50,0)	(28.09,21.82)	(0,50)	(0.02,49.98)	(0,50)	(8.96,41.03)
17	20.22	19.82	18.82	18.48	21.80	21.80	20.06	20.06	21.50	22.08
	(50,0)	(50.00,9.07)	(0,50)	(0.34,50.00)	(0,50) (50,0)	(25.00,25.00)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(17.51,32.48)
18	21.55	21.95	19.10	18.66	22.18	22.05	20.34	20.25	23.50	23.41
	(50,50)	(50.00,47.96)	(0,50)	(0.24,50.00)	(0,50) (50,0)	(32.05,17.97)	(0,50)	(0.02,49.98)	(0,50)	(2.30,47.69)
19	20.37	20.52	19.16	19.50	21.80	21.80	20.06	20.06	20.93	20.36
	(50,0)	(49.54,0.04)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(25.16,24.84)	(0,50)	(0.02,49.98)	(0,50) (50,0)	(24.83,25.17)
20	21.76	21.67	19.49	19.41	22.31	22.44	20.43	20.52	23.59	23.69
	(50,50)	(50.00,49.99)	(40,50)	(39.91,50.00)	(0,50) (50,0)	(25.00,25.83)	(0,50)	(0.37,49.78)	(0,50)	(0.00,49.79)

Table 8.13 **New layouts: actual and predicted output for maximum times for various sets of moving facility co-ordinates**

Layout	Moving facility Co-ord's (10,30)		Moving facility Co-ord's (20,10)		Moving facility Co-ord's (25,25)		Moving facility Co-ord's (30,20)		Moving facility Co-ord's (40,40)	
	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted
	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's	Max. Time (hours) Co-ord's
11	31.88	32.64	32.54	32.64	32.76	31.61	31.88	30.69	35.05	33.22
	(20,20)	(19.95,29.98)	(20,20)	(20.08,19.88)	(20,20) (20,30)	(25.00,25.01)	(20,20)	(25.03,25.01)	(30,40)	(33.31,36.56)
12	32.86	32.64	32.43	32.64	32.20	31.61	30.87	30.69	32.52	33.22
	(20,30)	(19.95,29.98)	(20,20)	(20.08,19.98)	(20,20) (30,30)	(25.00,25.01)	(20,20) (30,30)	(25.03,25.01)	(30,40) (40,30)	(33.31,36.56)
13	37.20	39.27	33.36	33.34	40.25	41.89	37.22	38.95	42.09	45.09
	(10,20)	(10.00,19.94)	(10,10)	(10.00,9.91)	(20,20)	(17.04,16.97)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
14	36.19	38.52	33.14	34.47	37.96	41.41	35.35	39.15	38.72	44.47
	(10,20)	(10.00,19.92)	(10,10)	(10.00,9.92)	(20,20)	(14.94,14.90)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
15	42.22	37.91	38.21	35.86	42.54	39.06	40.60	36.92	41.34	35.59
	(40,10)	(20.06,20.00)	(30,10)	(30.03,10.00)	(30,20)	(30.17,19.71)	(40,10)	(40.00,10.00)	(40,30)	(40.00,22.61)
16	39.19	39.27	33.49	33.34	41.98	41.89	38.94	38.95	44.96	45.03
	(10,20)	(10.00,19.94)	(10,10)	(10.00,9.91)	(20,20)	(17.04,16.97)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
17	37.52	38.52	34.27	34.47	39.13	41.41	37.28	39.15	41.10	44.47
	(10,20)	(10.00,19.92)	(10,10)	(10.00,9.92)	(10,10) (20,20)	(14.94,14.90)	(10,10)	(10.03,10.00)	(10,10)	(10.00,10.00)
18	39.50	39.84	31.27	32.48	40.81	42.52	36.67	38.74	43.07	45.46
	(10,20)	(10.00,19.96)	(10,10)	(10.00.9.90)	(20,20)	(19.83,1971)	(10,10)	(10.03,10.00)	(30,30)	(10.00,10.00)
19	36.51	35.49	34.05	33.84	36.84	34.54	35.41	33.56	37.73	34.36
	(10,20)	(10.07,20.18)	(10,10)	(29.99,29.95)	(10,10) (20,20)	(25.01,25.02)	(10,10)	(10.19,10.31)	(10,10)	(10.00,10.00)
20	39.15	38.79	30.06	30.59	39.08	37.34	34.60	35.08	42.03	42.39
	(10,20)	(10.03,20.00)	(10,10)	(29.93,9.97)	(20,20)	(20.03,24.75)	(10,10)	(39.95,10.00)	(40,30)	(39.97,29.97)

Table 8.14 **Statistical data for comparison between actual and predicted minimum and maximum times for existing and new layouts**

Moving facility Co-ord's	Layouts	Minimum times		Maximum times	
		r	t	r	t
(10,30)	Existing	0.83	0.004	0.90	0.054
	New	0.87	0.041	0.80	0.011
(20,10)	Existing	1.00	0.150	1.00	0.225
	New	0.92	0.088	0.92	0.027
(25,25)	Existing	1.00	0.000	0.90	0.148
	New	0.86	0.006	0.86	0.004
(30,20)	Existing	1.00	0.100	0.96	0.124
	New	0.89	0.139	0.78	0.044
(40,40)	Existing	0.98	0.150	0.98	0.151
	New	0.89	0.006	0.78	0.043

Inspection of Table 8.14 shows that there is good correlation between actual and predicted minimum and maximum times for both existing and new layouts, and although the correlation coefficients are slightly better for the existing layouts, compared to the new layouts, there is no reason to assume that the chosen neural network is not a good predictor when faced with unseen layouts. In respect of the test statistic *t*, the largest value in 0.225 and, for 9 degrees of freedom, the critical value at a 5% level of significance is 2.262 (Fleming and Nellis, 1994). Therefore, the null hypothesis is accepted in all cases, i.e. there is no difference in the predictive capabilities of the neural network in respect of the existing and new layouts.

In respect of the co-ordinates associated with the minimum and maximum times predicted by the neural networks, the situation is not so simple, as there are two components of any co-ordinate. Also, as mentioned before, it is not possible to make comparison when the model developed here shows that there is more than one set of co-ordinates associated with either the minimum or maximum time. Table 8.15

Table 8.15 **Data concerning the accuracy of the co-ordinates associated with the minimum and maximum times for existing and new layouts**

		Moving facility co-ordinates					
		(10,30)	(20,10)	(25,25)	(30,20)	(40,40)	Total
Minimum times within 0.1m	Existing	2/9	4/10	0/0	5/10	0/6	11/35
	New	2/10	2/10	0/0	7/10	0/5	11/35
Maximum times within 0.1m	Existing	4/10	7/9	0/5	6/9	7/9	24/42
	New	7/10	7/10	0/6	6/9	6/9	26/44
Minimum times within 0.5m	Existing	4/9	7/10	0/0	7/10	2/6	20/35
	New	3/10	7/10	0/0	8/10	1/5	19/35
Maximum times within 0.5m	Existing	7/10	8/9	5/5	8/9	7/9	35/42
	New	8/10	8/10	2/6	7/9	6/9	31/44
Minimum times within 5.0m	Existing	7/9	9/10	0/0	8/10	6/6	30/35
	New	4/10	8/10	0/0	9/10	2/5	23/35
Maximum times within 5.0m	Existing	7/10	9/9	5/5	8/9	7/9	36/42
	New	8/10	8/10	5/6	7/9	7/9	35/44

shows a comparison in terms of accuracy of the predicted co-ordinates (compared to the actual co-ordinates) for each of the five moving facility co-ordinates used previously and for the existing and new layouts. Inspection of these data shows that whilst the neural network can be considered as a good predictor of the minimum and maximum times, it is not such a good predictor of the associated co-ordinates. However, a visual inspection of the data also shows that there is no notable difference in the performance of the neural network when the new layouts are compared with the existing layouts.

8.3.4 Discussion

The developed neural network has shown good predictive capabilities in terms of the minimum and maximum times to complete all movements, but has been less impressive in terms of predicting the associated co-ordinates.

The data presented to the network for training purposes were simulated data which therefore eliminated much of the noise which may be associated with 'real' data collected in the field. And, as 4840 data sets were presented to the network (although in reality this is 1210 sets as every data set was entered four times to allow for the fact that there are, on some occasions, four sets of optimum co-ordinates associated with the minimum and/or maximum times), which has 6 inputs and either 1 or 6 outputs, there are certainly adequate data for training purposes.

In terms of the preferred architecture, General Regression neural networks outperformed Back Progagation networks and those networks created using General Regression architecture the Cartesian co-ordinate system were chosen as the optimum network. With the exception of the co-ordinates associated with the minimum times, networks where all outputs were considered separately performed slightly better than those where the outputs were considered together; in respect of the co-ordinates associated with minimum times the opposite observation was made, although high values of *R squared* are obtained in both instances. The values of *R squared* for the selected networks ranges from 0.9309 to 0.9998 (See Table 8.7).

The problem in respect of predicting the co-ordinates is one which needs further investigation should the concept be further developed. Initially it was thought that using Cartesian co-ordinates might not be ideal as there would be a tendency for the network to average out the most common solutions (in the corners, in respect of the minimum times) giving a nonsensical result. However, experimentation with polar and perimeter co-ordinate systems offered no improvement in the accuracy of predicting the co-ordinates. In terms of the accuracy of the predictions, Table 8.15 demonstrates that those co-ordinates associated with the maximum times are more often accurately predicted than those associated with the minimum times, whilst when the accuracy is reduced this effect is less pronounced. This result was anticipated, as the co-ordinates associated with maximum times are centrally located and this presents less problems to the neural network compared with the perimeter and edge co-ordinates associated with the minimum times. In some cases a comparison between the actual and predicted values is not possible, as the actual values (those predicted by the model) are not unique, and there are as many as four sets of co-ordinates associated with the minimum and/or maximum times. In practice this is unlikely to be a problem, as this situation only occurs due the symmetry of the layout, but in reality such symmetry is unlikely to occur. However, unlike the errors which occur in respect of minimum and maximum times, which are uniformly of a small magnitude, there remains a possibility that the prediction of the co-ordinates may result in an error of large magnitude. For example, in respect of Layout 2 with the moving facility located at (30,20) the predicted co-ordinates associated with the minimum time are (47.35,47.35) compared to the actual co-ordinates of (0,0) (Table 8.10). In may be that the times associated with this predicted position are very close to the maximum but this does not deflect from the issue that the error is very large in this case.

An encouraging aspect of the results obtained was that there was no noticeable deterioration in the performance of the network when it was presented with unseen layouts (i.e. networks which had not been used for training purposes). This was verified by inspecting the values of correlation coefficient r and test statistic t for small matched samples. Although there was a slight reduction in these values when the new unseen layouts were compared with the existing layouts, in all cases the null hypothesis that there is no statistical difference in the actual and predicted values for the new layouts is accepted.

8.4 Model validation

A postal questionnaire survey was designed and distributed to 108 construction companies in the United Kingdom, whose names and addresses were obtained from the Contractors File (New Civil Engineer, 2001). Twenty-nine completed questionnaires were returned (response rate 27%). A copy of the questionnaire is given in Appendix G, along with a copy of the covering letter.

A questionnaire was chosen as the vehicle for ascertaining the views of practitioners in preference to interviews, as they enable a larger sample to be contacted more quickly and cheaply (Naoum, 1998). Views of colleagues were sought to ensure that any ambiguity in the way that questions were worded and structured was eliminated. The questionnaire was distributed as an A3 sheet folded in two, and was deliberately kept short to encourage a high response rate.

8.4.1 Questionnaire content and responses

The first six questions were factual questions designed to ascertain respondents' background, the size of the organization they work for and their experience of selecting and locating tower cranes. Subsequent questions were intended to ascertain the views of respondents about crane location strategy generally (Question 7), the importance of crane location (Question 8) and the reasons for this view (Question 9), factors which influence the use of cranes (Question 12) and the decision as where to locate a crane (Question 10) and whether respondents would consider locating the crane at the perimeter if this resulted in savings in the time to complete crane-related activities (the main result of this research) (Questions 13). In addition, Question 11 was concerned with the methods used to locate cranes. Respondents were also free to add their own comments (Question 14).

A summary of the responses received is provided in Appendix G. Having examined the responses it was decided to initially analyze all responses and then to compare the results obtained from those respondents who claimed to have experience in selecting and locating tower cranes (18) with those who did not claim to have such experience (11), in order to see if there was any statistically significant difference in their responses; because of the relatively small number of responses, it was thought that any other division of the respondents (based on company annual turnover, for example) was inappropriate.

8.4.2 Overall results and analyses

Respondents were asked to rank the following location strategies (with 1 representing the most favoured strategy and 4 representing the least favoured strategy):

- place inside the structure in a lift shaft, court yard or other opening;
- place inside the structure where 'making good' later is required;
- place outside the structure but sufficiently close so that it can be tied to the structure; and

- place away from the structure.

No consistent ordering of preferences was obtained and every strategy was ranked in every position, thus reinforcing the discussion in Section 1.1 where the conflicting opinions concerning preferred crane locations were highlighted.

Using the data presented in Appendix G, an analysis of variance was carried out.

Null hypothesis H_o: $\mu_A = \mu_B = \mu_C = \mu_D$

Alternative hypothesis H_1: $\mu_A \neq \mu_B \neq \mu_C \neq \mu_D$

Where: $\mu_A =$ mean of ranks associated with placing inside the structure in a lift shaft, court yard other opening

$\mu_B =$ mean of ranks associated with placing inside the structure where 'making good' later is required

$\mu_C =$ mean of ranks associated with placing outside the structure but sufficiently close so that it can be tied to the structure

$\mu_D =$ mean of ranks associated with placing away from the structure.

The analysis of variance table is given in Table 8.16.

Table 8.16 **Analysis of variance table for preferred crane location**

Source	Sum of squares	Degrees of freedom	Mean Square	F
Treatment	14.11	3	4.70	3.98
Error	89.69	76	1.18	
Total	103.80	79		

At the 5% level of significance the critical F value is 2.76 (Fleming and Nellis, 1994). Hence the null hypothesis is rejected and the alternative hypothesis is accepted and so there is a difference in the means of the populations from which the four samples have been taken, although it should be noted that the critical value at the 1% level of significance is 4.13, which means the null hypothesis would be accepted.

Examining the statistical analysis data shows that the sample data associated with 'Place inside the structure where 'making good' later is required' appears to have significantly higher values than the remaining three samples (that is, it is ranked lower). If a further analysis of variance is carried out with the three remaining options, an F value of 0.72 is obtained, compared to a critical value of 3.15 (at the 5% level of significance). Thus the null hypothesis can be accepted and there is no perceived difference by the respondents between the three remaining location options, but the least preferred option is that identified above.

The majority of respondents (28 out of 29) consider that tower crane location is 'of great importance', with only one respondent considering it to be of 'some importance'. This confirms the significance of the research carried out in this thesis. Reasons given for holding this view include:

- correct positioning reduces costs and saves time;
- a crane is an expensive item of plant and needs to be able to operate efficiently, effectively and safely;
- access for erection and dismantling, site coverage and ground conditions at the location are all important;
- once a crane has been selected it usually the only means of loading and placing materials and if crane strategy, including location, is not correct, project programme and costs will be impacted;
- crane location is critical to all operations;
- crane location can affect other site works and may have safety implications;
- it is essential that the tower crane can reach the area of the structure, plus adjacent areas for unloading;
- the crane driver must be allowed maximum visibility of the load handling area;
- a carefully considered position is critical to enable loads to be lifted at varying

radii;

- general site efficiency relies on the crane and its position;
- correctly sized and located plant is necessary to ensure efficient and economic working practice; and
- the siting of a tower crane or cranes is of paramount importance in order to avoid sterilised sections of the site which may not be reached by alternative craneage.

In terms of the factors that may be taken into account when deciding where to locate a tower crane, respondents were asked to rate the following six factors in terms of their importance:

- ease of erection;
- the need to provide a base;
- the need to ensure the crane can reach the whole site:
- the need to avoid over-swing onto adjacent property/roads:
- the need to avoid locating where 'making good' later in required; and
- ease of erection.

An analysis of variance identified the most critical factor as being the need to ensure the crane can reach the whole site, followed by the need to avoid over-swing onto adjacent property/roads and, thirdly, ease of dismantling. The three remaining factors were considered to be of lesser but equal importance by the respondents. The following seven factors were also suggested by some respondents as being important when deciding where to locate a tower crane:

- crane type;
- accessibility of pick-up points;
- ground conditions;
- obstructions;
- crane capacity;
- minimum radius for heavy loads; and
- operator visibility.

The popularity of various methods used to locate tower cranes is given in Table 8.17, which shows that past experience is the most common method and that common sense and graphical methods are also frequently used. Not surprisingly, computer methods are not widely used, but it may be surprising to note that in-house company systems are the least popular method. Only one other method was suggested by respondents, which was 'Discuss with tower crane hire companies'.

Table 8.17 **Frequency of use of methods used to locate tower cranes**

Method	Frequency of use
Common sense	18
Past experience	21
Company 'system'	2
Graphical methods	14
Computer methods (such as expert system)	5

Respondents were also asked to rate how important they considered the following considerations to be in respect of the use of tower cranes:

- the need to place the crane centrally and so use a crane with the shortest possible jib length;
- the need to ensure the crane is fully utilized; and
- the need to ensure the crane works efficiently (that is, does not experience any undue delays).

An analysis of variance carried out on the results obtained showed that the need to ensure the crane is fully utilized and works efficiently were both ranked equally by respondents but less importance was placed on the need to place the jib centrally.

The most important question (Question 13), in terms of validating the research, was as given in Figure 8.5 and the results obtained are tabulated in Table 8.18.

Some research has shown that placing the crane on the site perimeter could result in time savings in respect of the time to complete crane-related activities. Would you consider placing the crane at the perimeter, even though this would require a crane with a longer jib length than if the crane centrally located?
Please tick one box as appropriate

Would seriously consider ☐ **May consider** ☐

Unlikely to consider ☐ **Would not consider** ☐

Not sure/don't know ☐

Figure 8.5 **Questionnaire survey: Question 13**

Table 8.18 **Frequency of responses to Question 13 of the questionnaire survey**

Answer	Frequency
Would seriously consider	14
May consider	11
Unlikely to consider	3
Would not consider	0
Not sure/don't know	1

The results in Table 8.18 demonstrate that nearly half of the respondents (48%) would seriously consider complying with the main conclusion of this research and placing the crane at the perimeter whilst a further 38% may consider such action. Only 14% of respondents fall outside these two categories, thus the responding practitioners provide reasonable validation of the results obtained from the model.

Finally, respondents were invited to provide any further comments they felt appropriate. Such comments included the following.

- Commercially, we are looking for the most economical solution.
- Safety is an overriding consideration.
- Topography and availability are issues to be considered.
- Location of the tower crane is crucial to its efficient operation.
- Larger cranes may be significantly more expensive.
- There are many considerations when siting a crane. Centrally is usually the best but has certain difficult aspects during dismantling and during inspections.
- Tower cranes can be set up on short runs of rail track to increase coverage.
- Type and height of building and speed of construction required are all factors which are considered.
- On some projects the preferred position of the crane may obvious or there may be more than one possible location. More often there are conflicting factors which affect the choice of position and the final chosen position may be a balance or a compromise. Every project has to be looked at individually.

8.4.3 Comparison between experienced and inexperienced practitioners

As mentioned earlier, the results obtained can be divided into two main categories- those associated with respondents who claim to have experience in tower crane selection and location and those who claim no recent experience.

Where appropriate a *t* test between two small independent samples was carried out. As summary of the results are tabulated in Table 8.19.

Null hypothesis H_o: $\mu_A = \mu_B$

Alternative hypothesis H_1: $\mu_A \neq \mu_B$

Where: μ_A = mean of the results associated with respondents with experience

μ_B = mean of the results associated with respondents without experience

The critical *t* values used were for a 5% level of significance.

Table 8.19 **Comparison between experienced and inexperienced respondents**

Preferred location strategy	
Inside opening	Accept H_0
Inside with 'making good'	Accept H_0
Outside structure but tied to it	Reject H_0
Away from the structure	Reject H_0
Factors influencing location	
Ease of erection	Reject H_0
Need for a base	Accept H_0
Need to reach whole site	Accept H_0
Need to avoid over-swing	Accept H_0
Need to avoid 'making good'	Accept H_0
Ease of dismantling	Reject H_0
Considerations when using cranes	
Place centrally and utilize shortest jib	Accept H_0
Full utilization	Reject H_0
Efficient operation	Reject H_0

Mostly, there is no statistically significant difference between the results obtained for those respondents with experience and those respondents without experience. The exceptions are as follows.

- Preferred location strategy: experienced respondents rank placing the crane away from the structure higher than inexperienced respondents while the reverse is true in respect of placing the crane outside the structure but tied to it.
- Factors influencing location: ease of erection and dismantling are both considered more important by experienced respondents than those without experience.
- Considerations when using cranes: experienced respondents rate the efficient use of the crane higher than inexperienced respondents while the reverse is true

in respect of ensuring the crane is fully utilized.

In addition, a goodness of fit test was carried out to see if there was any statistically significant difference between the number of responses obtained in respect of methods used to locate cranes and respondents' willingness to locate the crane at the perimeter. In both cases there was found to be no difference between the number of responses in each category between those respondents who were experienced and those who were not experienced.

8.4.4 Model input

Three practitioners were contacted by telephone to ascertain the availability of the data required as input into the model. The data required may broadly be classified as:

- data associated with the characteristics of the crane, such as load-radius characteristics;
- data associated with the layout of the construction site, such as location of facilities that the crane is required to serve; and
- data associated with the numbers of movements which are anticipated to take place between different sets of facilities.

All agreed that the data associated with the crane and the construction site were readily available. However, there was less confidence about the data associated with the number of movements. It was generally agreed that some assessment of the number of anticipated movements must be made in order that a solution to the need for materials handling can be formulated. For example, more than one crane may be needed and it may be decided to supplement a single tower crane with other material handling devices, such as hoists and mobile cranes, rather than using a further tower crane. However, currently not all practitioners routinely have details of the numbers of anticipated movements between different set of facilities readily to hand, although, in all cases, some estimate of these numbers could be made relatively easily.

Trials were also carried out to test the ease of use of the four computer programs which have been developed (see Section 5.4 for a detailed description of these programs). To facilitate this, a pro-forma was developed listing the data to be entered, based on the real life example provided by Choi and Harris (1984) (see Section 6.3 for more details). Using the data provided, two data files were created in respect of the crane details and site layout details using the CRANE and LAYOUT programs respectively. A third data file was then created using the MOVEMENT program, which determined the balancing movement which must occur, and all three data files were then read by the POSIITON program which enabled the suitability of potential crane locations to be investigated. Generally, it was agreed that the programs were easy to use, they were robust (for example maximum crane radius must exceed minimum crane radius and all facilities must be located within the site boundary) and the output was easy to interpret. One suggestion for improvement was that if data were entered erroneously (although within the constraints which exist), the only way to correct that mistake, once the 'Enter' key had been pressed, was to use the 'Edit' option from the main menu, whereas it would have been preferable to have the option to return immediately to correct the information. This suggestion is accepted and is a matter of programming technique.

8.4.5 Summary

Then main result obtained from the questionnaire survey is that the majority of respondents (86%) would either seriously consider or may consider placing the crane at the perimeter, if it could be demonstrated that time savings is respect of crane-related activities would ensue, thus validating the main outcome of the research presented in this thesis.

The survey results also confirmed that, with the exception of locating the crane inside the structure and 'making good' later, there is no clear strategy which is preferred by the respondents. However, crane location is overwhelming considered to be of great importance with the most critical factor as being the need to ensure the crane can reach the whole site, followed by the need to avoid over-swing onto adjacent property/roads and, thirdly, ease of dismantling. Past experience, common sense and graphical methods are the most common means of locating a crane and the need to ensure that the crane is both fully utilized and works efficiently is of more importance than placing the crane centrally and hence using a crane with the shortest possible jib length. Finally, there is mostly agreement between those respondents who claim they are experienced in crane selection and location and those who claim to have no experience.

The data requirements of the model were found to match reasonably well with data that are easily available, although the need to have knowledge of the numbers of movements between different sets of facilities may not be so readily available, although this should not present an insurmountable difficulty. Finally, the four computer programs which embody the workings of the model were found to be easy to use.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

The main objective of this chapter is to draw conclusions from the work described in the previous chapters. To facilitate this, reference is made to the aim and objectives developed in the first chapter and, in particular, to accepting or rejecting the hypothesis which was postulated. Subsequently, recommendations about the location of tower cranes within construction sites are made and the thesis concludes with recommendations for further research.

9.2 Conclusions

In Chapter 1, the aim of this thesis was stated as the development of a model to optimize the location of a single tower crane within a site. In order to achieve this aim, eleven objectives were identified and the following hypothesis postulated:

"The efficiency of the construction process will be improved by the development and application of a model to consider the quantitative factors, namely travel time, associated with the location of a single tower crane within a construction site."

It is believed that the aim of the research has been achieved and that a model to optimize the location of a single tower crane within a construction site has been developed. In respect of the hypothesis, the evidence suggests that it can be accepted, although with some caveats.

The contribution to knowledge made by the work described in this thesis may be summarized as follows:

- A review of the literature and the results of a survey carried out demonstrate that there is no agreement on the best strategy regarding crane location and diametrically opposed views on this matter are postulated in the literature and held by construction site layout planning practitioners.
- Crane location significantly influences the time taken to complete crane-related activities. Reduced times are obtained for locations at the site perimeter. The configuration of the site layout has little impact in respect of the times taken to complete activities.
- The benefits of placing a crane at the site perimeter are countered by the additional costs which would be incurred through the need to use a crane with a longer jib. Not withstanding this, the benefits of placing the crane at the perimeter are considered significant enough by practitioners to warrant further investigation.

Therefore, the main conclusions of the thesis are that there are significant differences (on some occasions in excess of 200%) in the time to complete all movements (the minimum time) when the crane is located at its optimum position compared to the position associated with the maximum time. The optimum position is one located at the perimeter whilst the position associated with the maximum time is one located internally. This would seem to confirm that the efficiency of the construction process can be improved by the application of such a model as that developed here. However, when the cost implications of this finding were assessed by considering the additional costs associated with the need to locate the crane at the perimeter and hence have a crane with a longer jib length than were the crane located internally, it was shown that it is unlikely that the savings in time would offset the additional costs incurred. Notwithstanding this, practitioners expressed considerable interest in locating the crane at the perimeter of the site if it could be shown that this would result in time savings to complete crane-related activities. The general summary is that potential time savings may be achieved by placing the crane at the perimeter but by doing so there are potential cost implications.

In order to demonstrate that the aim has been achieved, conclusions will be drawn under the following headings, which summarize the objectives initially stated:

- Review of previous work;
- Development of the model objective function;
- Construction site features;
- Global crane movement;
- Tower crane features;
- Crane location model;
- Computer model software;
- Other models;
- Crane location model simulations;
- Crane jib length;
- Neural networks; and
- Validate model use and output.

In respect of the first seven and final objectives, detailed summaries have been provided earlier in the thesis at the point where the subject has been discussed in detail. Therefore, only brief overall conclusions will be provided here, but more detailed discussion will be given in respect of the final four objectives.

9.2.1 Review of previous work

Objective:
Review previous research in respect of the general problem of site layout and the more specific sub-problem of tower crane location.

The importance of tower cranes in respect of materials handling is widely accepted and their central role in determining the pace of construction acknowledged. However, prior to determining the number, type and position of any tower crane their suitability for the particular circumstances should be assessed, not in isolation, but in the wider context of overall site layout planning.

Models which have previously been developed to select and locate tower cranes may be broadly classified as expert systems, simulation models and mathematical models. With the exception of the simulation model developed by Zhang *et al.* (1995 and 1996), models classified in either of the first two categories are generally too broad in respect of providing specific advice about crane location. However, the quantitative nature of mathematical models is such that they are more likely to address this issue through the use of an objective function; two specific mathematical models, developed by Rodriguez-Ramos and Francis (1983) and Choi and Harris (1991), that do attempt to optimize crane location in this way, have been identified.

Apart from the three models referred to in the preceding paragraph, it is believed that a search of the literature shows that no other models have been developed to seek to optimize the location of a tower crane within a construction site.

9.2.2 Development of the model objective function

Objective:
Develop a means of assessing optimum crane location in relation to the facilities which that crane must serve, and hence define the objective function of the model, which is a quantifiable measure of the effect of altering any of the decision variables (such as crane location).

Any mathematical model must have a quantifiable objective function. The objective function used by the model is the minimization of total travel to execute all movements.

Where the crane is used to deliver materials, which is surely its prime purpose, the crane may be considered as the delivery component linking the despatch and reception systems and acting as the point of interaction between these two systems. Therefore, by seeking to minimize the total time to execute all movements, there can only be benefits in respect of the productivity of all activities in which the crane is involved.

9.2.3 Construction site features

Objective:
Examine the features of a construction site which impinge upon the location of a tower crane on such a construction site.

Considered in isolation from the position of the crane, there are very few construction site features, apart from global crane movement discussed in the following section, that impact on the model.

In order that the model can function, information concerning the site boundary, the location and height of facilities to be served by the crane, the amount and maximum weight of materials to be moved between each facility, and the location and type of any obstructions are also required as input into the model. However, the impact of these data can only be appreciated when they are considered in conjunction with the data concerning the crane characteristics and proposed location.

9.2.4 Global crane movement

Objective:
Assessment of the global crane movement from the time of installation of the crane until its dismantlement and removal.

The model must make an assessment of the total number of movements which are expected to occur between the time when the crane is erected and the time when it is later dismantled and removed, and any decision concerning the crane location must be made on this number of movements and not on those which may occur on a day to day basis and which may vary in their magnitude.

In order to assist in the assessment of this global crane movement, five categories of movement are identified and defined. The most significant category is that of explicit movement, which is that which must occur to facilitate movement of materials from one facility to another and which is computed by dividing the total amount (or weight) of materials to be moved from one facility to another by the average amount (or weight) of materials moved on any one occasion. On some occasions such explicit movement will necessarily be countered by implicit movement of an equal magnitude (the second category of movement). The further categories are defined as linking, wasting and balancing movement; although these are subtly different the model does not, indeed cannot, distinguish between them, but computes the balancing movement which must occur to ensure that the basic premise that the total number of movements towards any facility must be matched by an equal number of movements away from that facility is satisfied.

The linear programming technique known as the Simplex Method was adopted as the most appropriate technique to compute balancing movement. In this case, the objective function is one of minimizing the total number of movements which occur, which will be at least the value of explicit and implicit movements, but, in most instances, will incorporate a value of balancing movement. The fact that the number of movements towards any facility must be equal to the number of movements away from that facility and that the known values of number of movements between any pair of facilities may be considered to represent the minimum number of movements which occur are both considered to be constraints in the model.

This problem is therefore one of minimization (rather than maximization) and one which contains a mixture of equalities (associated with the first set of constraints) and inequalities (associated with the second set of constraints). A problem of this type may be solved by adopted the solving the dual (as opposed to the primal) problem, which will eliminate the mixture of equalities and inequalities such that all constraints are in the form of inequalities of the less than or equal to type. By representing the problem in this way, the Simplex Method can be executed via a set of tableaux, which seeks to determine the optimum solution to the problem – that is the minimum number of movements which satisfy all the constraints. A further modification, which replaces the two resulting sets of slack variables with one set was also adopted, as this has the advantage of reducing the size of the tableaux. Finally, as the problem is now expressed as the dual problem, the result of applying the Simplex Method must be interpreted in respect of the primal problem.

9.2.5 Tower crane features

Objective:

Examine the features of a tower crane which impinge upon the location of such a crane on a construction site.

As far as the model is concerned, the most pertinent features of tower cranes are the range of operating radii and the load lifting capacity. The two features are very much interrelated because, as a general rule, the load capacity of a crane depends on the radius, with load lifting capacity increasing as the radius decreases. Hence the maximum load capacity occurs at the minimum radius and least load capacity occurs at the maximum radius.

Although there are many types of tower crane, the only distinction made by the model is between two jib types, saddle jib and luffing jib. This distinction is significant because the formulae for calculating load at a given radius are different for each jib type. It was initially difficult to ascertain formulae which would accurately predict the load at a given radius, using only information which could be readily ascertained by users of the model. However, these formulae were eventually obtained from a manufacturer.

Both saddle jib and luffing jib cranes have a range of working radii, from the minimum radius at which it is physically possible to lift loads, to the maximum radius, determined by the length of jib. In selecting an appropriate crane, attention must be paid to the maximum radius, as it is vital that the crane can reach all facilities, from its chosen location. However, it is equally important that the crane has adequate load capacity to pick up all anticipated loads at each facility. The crane characteristics and location must be considered together; a certain crane may be suitable in one position but unsuitable in another position. It is vital that the crane can reach all facilities from its chosen location and that the load capacity of the crane, at the radius determined by the distance between the position of the crane and each facility, is known in order to ensure that the crane can pick up all anticipated loads at each facility. However, these aspects can only be considered when the interaction of the specific construction site and specific tower crane are considered together.

9.2.6 Crane location model

Objective:
Develop a model to consider the interaction of construction site and tower crane characteristics.

Before the modelling process can commence, data concerning both the characteristics of the crane and construction site must be available; different results will be obtained if the same site is considered with respect to different cranes, and vice versa. Four stages in the model development have been identified: computation of the balancing movement (this is not strictly part of the modelling process as it is independent of the crane, but it is included as extensive computations are required), an initial check on crane lifting capacity to ensure that the crane type and position are viable, consideration of the impact of any obstructions which may occur, and, finally, computation of the time to execute all movements. However, the model which has been developed is a descriptive one and so will only evaluate alternative scenarios determined by the user and will not itself directly determine the optimum position; although this may effectively be achieved by determining the times associated with a range of crane positions based on a fine grid.

9.2.7 Computer model software

Objective:
Develop user friendly computer software, to enable the model to be used by people with no knowledge of the model philosophy.

In theory, the process described above could be carried out manually, but if a realistic number of facilities is considered, the computation of the balancing movement via the execution of the Simplex Method would prove to be overwhelming. Therefore a suite of four computer programs has been developed to facilitate the modelling process. The programs are run as executable versions of compiled programs written in Turbo Basic, which allows the programs to be executed directly from the operating system without any recourse to the programming language. The use of the programs has the further advantages of allowing data for commonly available cranes to kept in files and also to allow virtually unlimited experimentation in respect of the combination of cranes and possible locations.

9.2.8 Other models

Objective:
Assess other models developed for the same purpose.

The model developed in this thesis has been compared with three other models proposed by other authors, Rodriguez-Ramos and Francis (1983), Choi and Harris (1991) and Zhang *et al.* (1995 and 1996). The purpose of this comparison was to emphasise the perceived deficiencies of these models and to highlight the ways in which the proposed model addresses the issues raised. Differences between the models were discussed and, where appropriate, exemplified by the comparing the results arising from re-working the numerical example provided by the other authors.

As mentioned, the model provided by Rodriguez-Ramos and Francis was the motivation for this work. However, as the this model attempts to determine the optimum position of the crane hook whilst waiting between movements, and not, as claimed, the optimum position of the crane itself, it has limited value in the context of the model proposed here. Not withstanding this, an examination of the shortcomings of this model highlighted some aspects which were addressed by the model proposed in this thesis. In addition to the fundamental problems just outlined, two major deficiencies were that the model disregarded vertical movement and no provision was allowed for movement between facilities to be incorporated. Other authors have highlighted the importance of hoisting movement in high rise construction and the simulations carried out in Chapter 7 have also demonstrated that vertical movement is an influential factor. In respect of movement between facilities, the model proposed by Rodriguez-Ramos and Francis only considered movement between the crane hook and facilities to be served by the crane (due to the model's objective function being to locate the crane hook in its optimum position). However, movement between facilities (usually from points where material is delivered to the point of construction) must also be considered in determining the optimum crane position. Other aspects where it was suggested improvements could be made were:

- by adopting a Cartesian co-ordinate system rather than a polar co-ordinate system, as it was felt this is more representative of the way data are usually formatted;

- by the inclusion of a site boundary, to ensure overswing of the crane beyond the boundary did not occur; and

- by considering that movement in all dimensions (two in respect of Rodriguez-Ramos and Francis's model, but three in the model proposed here) does not necessarily occur consecutively. This is the assumption made by Rodriguez-Ramos and Francis and results in the worst possible scenario, whilst the optimum scenario would assume simultaneous movement equivalent to the movement component of the longest duration. This is the assumption made by Choi and Harris. The model proposed here considered that a more realistic assessment of the time to move from one point to another is somewhere between these two extremes and an average value has been taken, with some allowance for lifting and lowering at the beginning and end of the movement cycle.

The model proposed by Choi and Harris overcame many of the deficiencies inherent in the model proposed by Rodriguez-Ramos and Francis, whilst the incorporation of vertical movement into the model is still acknowledged as an omission. However, it is clear that this model attempts to locate the optimum position of the crane, rather than that of the crane hook, and the objective function is defined as minimization of total transportation costs. However, one fundamental difference between this model and the model proposed in this thesis, is the way in which movement between facilities is handled. Choi and Harris have adopted a concept of inter-facility weightings, which may be defined as *"the percentage measurement of the expected movement frequency between two specific facilities"*. This is similar to the approach adopted here, except that movements are expressed in percentage terms, rather than absolute terms.

However, while Choi and Harris also further state *that "every lifting movement must undergo a return movement ..."*, which is similar to the concept of implicit adopted here, no allowance is made for balancing movement to ensure that the number of movements towards a facility are matched by an equal number of movements away from that facility. Whilst Choi and Harris acknowledge this deficiency, they believe it has little or no influence on the determination of the optimum crane position. However, using the model proposed here with the data from the example provided by Choi and Harris shows that this is not the case; Choi and Harris found the optimum location to be centrally positioned, whilst this model found the optimum position to be located at or near the site boundary. Of less concern is that Choi and Harris's model does not incorporate the constraints of a site boundary or any constraints that may arise due to an inappropriate crane specification, such as, for example, the crane's jib length prevents it from reaching any facility or its load capacity prevents it from lifting any load.

The model proposed by Zhang *et al.* differs from the other two models proposed by different authors in that it is a stochastic simulation model, based on re-constructing the supply and demand of materials, rather than a mathematical symbolic model. Comparing the results of the example given by Zhang *et al.* (which is the same as that used by Choi and Harris) shows that this model compares favourably with the results given by the model proposed here. Nevertheless there are some fundamental differences between the two models. Firstly, in Zhang *et al.*'s model, the ways in which movements are generated are based on a series of three matrices which represent the number of anticipated lifts, the average number of requests and the frequency of requests. Random numbers are then used to generate the occurrence of a request. This requires a considerable amount of data, very little of which may be known with certainty at the time the model is used. Zhang *et al.* acknowledge that the more random movement which is likely to occur in practice is difficult to predict and concede that the linear programming solution, which is the basis of the model proposed here, may be used to overcome this problem. However, they highlighted the need for the solution to be in integer form and the claim that the final solution represents a specific sequence of events as two perceived inadequacies of this approach. It was shown that both the input and output to the model, in respect of the number of movements, were constantly in integer form, and so this was not an issue and that the approach does not, contrary to their view, make any assumption about the order in which the movements occur, only about the total number of movements taking place. The second fundamental difference is that vertical movement is again disregarded and only slewing and radial movements are considered. Thirdly, Zhang *et al.*'s model attempts to solve the issue of whether these movements should be considered as occurring simultaneously or consecutively by introducing a parameter α; a value of $\alpha = 0$ represents simultaneous movement and a value of $\alpha = 1$ represents consecutive movement, with a default value of $\alpha = 0.25$. From a theoretical point of view this is a valid solution because, as Zhang *et al.* acknowledge, this factor will depend on factors such as the skill of the operator and the spaciousness of the site. This factor will vary between sites and there may even be variations on the same site over a period of time. However, it is virtually impossible to predict the value that this parameter will take, and, therefore, to include it as a variable in the model has little validity from a practical point of view, although from a theoretical point of view it may be interesting to see how this parameter influences the outcome

Therefore, it is believed that the model proposed her overcomes many of the deficiencies demonstrated by other models and achieves a balance between onerous data requirements, specifically when data may not be available at the time the model is intended for use, and consideration of the critical factors which influence optimum crane position.

9.2.9 Crane location model simulations

Objective:
Examine a wide range of construction site scenarios to see if any general truths about the optimum crane location can be evinced.

In order to achieve the above objective, three series of simulations were carried out. For the most part these were based on hypothetical layouts, but the most significant result was verified by an example provided in the previous chapter, where existing models were investigated, and where a real life example was re-worked.

The simulations which were carried out were based on a 50m by 50m grid with a maximum of five facilities served by the crane, four of which were located in the corners and one of which was considered to be moving, although is some instances the situation was only considered when that facility was centrally located. A series of ten different layouts was devised, two of which used all four corner facilities, three of which used three corner facilities, four used two and the final layout, one only. It was intended that these layouts reflect, as far as possible, the widest range of possible scenarios in respect of the distribution of movements which would occur in real life. It should be noted that when the moving facility was centrally located, this was considered to be more representative of real life, with movement of materials taking place from the perimeter of the site towards the centre, although investigations when the moving facility was located elsewhere was also included. Another variable which was modified in the simulations was the speeds of the crane in respect slewing, trolleying and hoisting, with four cranes being used which gave a range of relative speeds (considered to be more significant than actual speeds). The final variable which was considered was the relative height of the facilities; it was assumed that all corner facilities were located at ground level and the height of the moving (central) facility (assumed to represent the building) was varied. In all cases and for all layouts, the same total number of movements was considered to take place, enabling direct comparisons to be made.

When the situation in which the moving facility is centrally located is considered, and variation in the height of that facility is also taken into account (i.e. Series A and Series B simulations), the most significant results are:

- the layout (i.e. the ways in which the same number of movements are distributed) has very little influence in the minimum time taken to complete all movements;

- the range between the minimum and maximum time is of a high order of magnitude and can be excess of 200%; and

- the positions associated with the minimum time are always located at the perimeter of the site, often at the corners, while the positions associated with the maximum time are always located internally.

Obviously the choice of crane (where the only significant variable is speed) has a significant bearing upon the time to complete all movements, but, regardless of crane type, the conclusions stated above are still valid. However, as expected, hoisting speed was shown the be the most critical factor in determining times to complete movements.

Some of these conclusions were also validated by investigating a real life situation (described in the previous chapter, Chapter 6), where the optimum solution (i.e. the one associated with the minimum time) was again shown to occur when the crane was located at the perimeter of the site. Although a direct comparison between the minimum and maximum times was not made, it was demonstrated that time savings were made by comparing the time at the position claimed by other authors to be the optimum one with the optimum one determined by the model proposed here. Such savings were, on average, 18%, with a maximum value of 60%, and, if comparisons were made between the minimum (optimum) times and the maximum ones (which were not determined) the savings would be even greater.

Another feature of the results obtained from the simulations described was that layouts where movement may be described as compact or compressed result in lower minimum times to complete all movements when compared with those layouts where the movements are more widely distributed. However, those layouts where the movements are described as compact or compressed have larger maximum times (hence the overall range is bigger) than those where the movements are more widely distributed (and hence the overall range is smaller). It was also found that, as the height of the central facility reduced, this effect became more pronounced and that there was slightly more variation between layouts. Notwithstanding these observations, the first conclusion, that the layout has very little influence in the minimum time taken to complete all movements is still valid, especially in the more likely cases where tower cranes are used in high rise construction.

A crude method of predicting the position associated with the maximum times was evolved. This involves determining the centre of gravity of the movement matrix by, for each axis, summating the number of movements away from each facility multiplied by the co-ordinate associated with that facility, and dividing by the total number of movements. This was shown to be a sufficiently accurate means of determining the position associated with the maximum time. However, what would be of more use would be a method to determine the position associated with the minimum time, but it was not possible to make such a proposal, although it was demonstrated that this position can be accurately ascertained by using a coarse 10m by 10m grid and applying the model to all positions generated by such a grid.

As mentioned, the simulations also investigated the outcomes when the moving facility was not necessarily centrally located but moved on a 5m by 5m grid around the site. This gives rise to some situations which are plausible (when this facility is located in the central area but not at the exact centre) but some which are less so (when this facility is located towards the perimeter). The results of these simulations show, somewhat surprisingly, that the optimum configuration is not that when the moving facility is centrally located, even when the movement scenario is evenly distributed about the central position. The optimum configuration is dependent upon the way in which the movements are distributed, but, in any event, choosing the optimum configuration in preference to one where the moving facility is centrally located only results in very minimal savings. Some configurations do give rise to situations where the position associated with the minimum time is no longer located at the perimeter, but these can be said to be configurations unlikely to occur in real life where the general idea of moving material from the perimeter inwards does not hold. However, overall, the three conclusions highlighted earlier as being most significant hold true, especially when the most likely scenario of movement from the perimeter towards the centre applies.

9.2.10 Crane jib length

Objective:

Examine the issue of crane cost, related to the length of the jib, versus the benefits from using jibs of varying lengths.

The conclusion of the preceding section demonstrates that whatever combination of movements and cranes are considered, the time to complete all movements will be reduced if the crane is placed at the site perimeter. If the benefits of placing a crane at the perimeter of the site are to be taken advantage of then it is necessary to utilize a crane with a longer jib length than if the crane was placed centrally. The evidence available, albeit limited, clearly shows that there are substantial cost implications in terms of the (hire) costs as the length of the jib varies; neither is the cost/length relationship linear but one where the increase in costs is exponential as length increases. Therefore there is a considerable need to justify the use of a jib length longer than absolutely necessary, although it is appreciated that one reason may be to provide greater load capacity, as smaller jib length cranes inevitably have reduced load capacity when compared to cranes with longer jib lengths.

All attempts to carry out a break even analysis demonstrated that without doubt the costs of the increased jib length are not justified by the order of magnitude of savings in time which can be achieved by adopting a longer jib length. Data generated for all the layouts and types of crane identified in the previous section were examined in coming to this conclusion, although the results were restrictive in that it was assumed that movement of materials took place from the facilities located at the corner of the site to one located centrally (believed to be typical of that scenario which would occur in real life). Also more emphasis was placed on the situation where the centrally located facility is 30m high (with all corner facilities at ground level); however, changing the height of the central facility had no significant effect.

The method of carrying out the break even analysis was to reduce the costs associated with all jib lengths, other than the smallest, by a percentage to reflect the percentage savings in time to complete all movements which are achieved as the crane location moves towards the perimeter. Whilst this approach may be open to criticism, the alternative option of attempting to express the potential savings in monetary terms requires knowledge of many factors, such as the number of workers involved. It is believed that this method gives a general picture of the type of savings which are needed to counteract the additional cost which would be incurred, were a longer jib length selected purely for the purpose of attempting to reduce the time to complete all movements.

9.2.11 Neural networks

Objective:
Develop a prototype neural network to illustrate the potential of neural networks as a possible tool to address the issue of crane location.

The neural network, which has been developed for a limited number of scenarios only, has demonstrated that neural networks have potential as a possible tool to address the issue of crane location. The main advantage offered by the use of neural networks is that, in theory at least, they can be trained on a series of optimum scenarios so that the network is then behaving as a prescriptive model rather than the current descriptive model.

From the limited experimentation which was carried out in terms of network architecture it was found that General Regression neural networks outperformed Back Propagation networks and provided robust values of *R squared* in respect of the prediction of the minimum and maximum times. Cartesian co-ordinates were also found to be a satisfactory way of representing the co-ordinates.

The networks which were developed all had six inputs: the number of movements from each of the four corner facilities to the central facility and the X and Y co-ordinates of the moving facility. Six outputs were also defined: minimum time and associated X and Y co-ordinates and maximum time an associated X and Y co-ordinates. Somewhat surprisingly there was little difference in the performance of the model when the inputs were considered together as one network, or separately, as six networks, although the latter option was selected as the final model in respect of predicting all outputs except the X and Y co-ordinates associated with the minimum time. However, if a more generalised model was to be developed the inputs used here would not be adequate and they would have to be extended to more truly reflect other influencing variables, including factors such as crane speeds, although the output variables are probably adequate.

Although the networks were trained on simulated data associated with a range of ten different layouts, when presented with unseen layouts the neural network continued to perform well and there was no statistical difference in the actual and predicted values of minimum and maximum times for the new layouts. The consistency of prediction in terms of the associated co-ordinates was also maintained, although the model failed to perform as well in this respect.

9.2.12 Validate model use and output

Objective:

Validate the use of the model and its output by seeking the view of practitioners.

An attempt was made to validate the output from the model by seeking the views of practitioners through the use of a questionnaire survey, In addition to validating the model output, the questionnaire addressed other issues concerning crane location and methods used to locate cranes.

Twenty none-responses were received. Nearly half of the respondents (48%) would seriously consider complying with the main conclusion of this research and placing the crane at the perimeter whilst a further 38% may consider such action. Only 14% of respondents fall outside these two categories, thus the responding practitioners provide reasonable validation of the results obtained from the model. In addition it was confirmed that the programs developed as user-friendly and that the data required as input to the model is readily available.

9.3 Recommendations

In the light of the foregoing discussion, and assuming that the decision has been made to install a tower crane on a construction site, the following recommendations are made:

- that as much information concerning the characteristics of the site, such as location and height of facilities, amount of materials to be moved etc. are collected before the decision as to the type and location of the crane are made;

- that data concerning available cranes, such as jib lengths, hire costs, foundation requirements etc. are also collected before this decision is made;

- that a qualitative assessment of all potential crane positions is made, taking into account such factors as possible difficulties in respect of erection and dismantling, the need to provide a base etc.;

- that a quantitative assessment of the viable alternative crane positions (i.e. those which have satisfied the criteria determined in the qualitative screen referred to above) is made using a model such as the one described in this thesis;

- that, not withstanding whether or not a thorough assessment of the alternative crane positions has been carried out as recommended, a check be carried out to ensure that the selected crane, in its designated position, can reach all facilities which it is intended that crane services and that it has sufficient load capacity to ensure that the loads anticipated can be lifted by the chosen crane at the requisite radius; and

- that the cost implications of the crane selection and location decision are assessed to ensure that neither a jib of longer length but at increased cost, nor a jib of reduced length but at reduced cost, would be a better decision in terms of cost.

9.4 Recommendations for further research

It is appreciated that the model proposed here is theoretical in nature and there has been no opportunity to collect data concerning the positions of different cranes on construction sites in order to validate the model; the ideal method of validation would be to have two construction sites identical in all aspects apart from crane location and make comparisons, but this is obviously not viable.

In the light of this, and considering the wider aspects of materials handling on construction sites, the following recommendations are made for further research.

- The collection of data to validate the model developed in this thesis. However, the problem would be in deciding exactly how the model could be validated, as whatever criterion is chosen, there needs to be some way of collecting appropriate data. For example, the criterion used in the model developed here is the minimization of travel time to complete all, or a certain number of, crane movements. In practice, the difficulty would be in isolating those times from those not directly associated with crane related activities.

- The development of a neural network model to predict the optimum location of a crane (or cranes) in real life situations. Neural networks have demonstrated potential in being able to predict the minimum and maximum times associated with hypothetical layouts but have had less success in terms of predicting co-ordinates. However, this problem is likely to be less acute in real life situations. Therefore, data could be collected to enable a neural network model to be developed. This has the advantage, compared with the model described here, of proposing an optimum solution (i.e. it is equivalent to a prescriptive model) rather than the current descriptive model where an optimum solution can only be found by trial and error. However, the problems of the criterion by which the model could be validated, referred to in the previous paragraph, still remain.

- Development of a model to ensure efficient use of a tower crane on a daily basis. A fixed tower crane must be located in a position which optimizes the overall crane related activity. However, there is still a need to plan that crane's use on a daily basis, particularly as the crane is likely to be critical to many activities. Decisions made about the use of the crane not only affect the crane but influence all other crane related activities.

- Investigation of the use of multiple cranes on construction sites. Observations indicate that many construction sites which utilize a tower crane often utilize more than one tower crane. Such a decision has particular impact in terms of the coverage provided by multiple cranes and the day to day planning of activities to ensure no overlap of jibs occur, which could be potentially dangerous.. Investigation of the use of multiple cranes would involve both the initial location of such cranes and the development of a model to optimize their daily use.

- The development of a model to optimize the location of mobile cranes. The culture of using mobile cranes, particularly for heavy one off lifts, is growing. Development of a model to ensure that the optimum location is selected and that the crane chosen is of adequate capacity would be a useful tool in respect of site planning.

- The development of a model to investigate the wider issue of materials handling. Tower cranes are only one solution to the problem of materials handling on a construction site. The development of a system which could model the performance of alternative systems, in quantitative terms, would be a useful tool to enable planners to determine the most timely yet economic solution to the materials handling problem.

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APPENDIX A

THE SIMPLEX METHOD

The Simplex Method is used to solve the following linear programming problem:

Find values of m_{12}, m_{13}, m_{21}, m_{23}, m_{31}, m_{32}
which will

minimize $z = m_{12} + m_{13} + m_{21} + m_{23} + m_{31} + m_{32}$

subject to the constraints

$$
\begin{array}{rcrcrcrcrcrl}
m_{12} & & & & & & & & & & & \geq 2 \\
 & & m_{13} & & & & & & & & & \geq 4 \\
 & & & & m_{21} & & & & & & & \geq 8 \\
 & & & & & & m_{23} & & & & & \geq 3 \\
 & & & & & & & & m_{31} & & & \geq 5 \\
 & & & & & & & & & & m_{32} & \geq 1 \\
m_{12} & + & m_{13} & - & m_{21} & & & - & m_{31} & & & \geq 0 \\
-m_{12} & + & & + & m_{21} & + & m_{23} & & & - & m_{32} & \geq 0 \\
 & - & m_{13} & & & - & m_{23} & + & m_{31} & - & m_{32} & \geq 0
\end{array}
$$

The dual maximisation problem may be stated as:

Find values of $w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8, w_9$
which will

maximize $z' = 2w_1 + 4w_2 + 8w_3 + 3w_4 + 5w_4 + w_6$

subject to the constraints

$$
\begin{array}{llllllllllllllll}
w_1 & & & & & & + & w_7 & - & w_8 & & & \leq 1 \\
& w_2 & & & & & + & w_7 & & & - & w_9 & \leq 1 \\
& & w_3 & & & & - & w_7 & + & w_8 & & & \leq 1 \\
& & & w_4 & & & & & + & w_8 & - & w_9 & \leq 1 \\
& & & & w_5 & & - & w_7 & & & + & w_9 & \leq 1 \\
& & & & & w_6 & & & - & w_8 & + & w_9 & \leq 1
\end{array}
$$

A.1 Method 1 - Introducing additional slack variables

Introducing the slack variables $u_1, u_2, \ldots, u_6$ the constraints may be re-written as:

$$
\begin{array}{llllllllllllllll}
w_1 & & & & & & + & w_7 & - & w_8 & & & + & u_1 & = 1 \\
& w_2 & & & & & + & w_7 & & & - & w_9 & + & u_2 & = 1 \\
& & w_3 & & & & - & w_7 & + & w_8 & & & + & u_3 & = 1 \\
& & & w_4 & & & & & + & w_8 & - & w_9 & + & u_4 & = 1 \\
& & & & w_5 & & - & w_7 & & & + & w_9 & + & u_5 & = 1 \\
& & & & & w_6 & & & - & w_8 & + & w_9 & + & u_6 & = 1
\end{array}
$$

The above is presented in Tableau 1.1.

Tableau 1.1

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
u_1	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
u_3	0	0	1	0	0	0	-1	1	0	0	0	1	0	0	0	1
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	0	0	0	0	1	0	-1	0	1	0	0	0	0	1	0	1
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	-2	-4	-8	-3	-5	-1	0	0	0	0	0	0	0	0	0	0

Using the method described in Chapter 3 (section 3.4.2) the pivot element is identified as occurring in the w_3 column and in the u_3 row and the new tableau is given in Tableau 1.2.

Tableau 1.2

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
u_1	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
w_3	0	0	1	0	0	0	-1	1	0	0	0	1	0	0	0	1
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	0	0	0	0	1	0	-1	0	1	0	0	0	0	1	0	1
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	-2	-4	0	-3	-5	-1	-8	8	0	0	0	8	0	0	0	8

In the above tableau the pivot element is identified as occurring in the w_7 column and in the u_1 row and the new tableau is given in Tableau 1.3.

Tableau 1.3

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
u_5	1	0	0	0	1	0	0	-1	1	1	0	0	0	1	0	2
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	6	-4	0	-3	-5	-1	0	0	0	8	0	8	0	0	0	16

In the above tableau the pivot element is identified as occurring in the w_5 column and in the u_5 row and the new tableau is given in Tableau 1.4.

Tableau 1.4

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
u_2	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
u_4	0	0	0	1	0	0	0	1	-1	0	0	0	1	0	0	1
w_5	1	0	0	0	1	0	0	-1	1	1	0	0	0	1	0	2
u_6	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	11	-4	0	-3	0	-1	0	-5	5	13	0	8	0	5	0	26

In the above tableau the pivot element is identified as occurring in the w_8 column and in the u_2 row and the new tableau is given in Tableau 1.5.

Tableau 1.5

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
w_8	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
u_4	1	-1	0	1	0	0	0	0	0	1	-1	0	1	0	0	1
w_5	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	2
u_6	-1	1	0	0	0	1	0	0	0	-1	1	0	0	0	1	1
	6	1	0	-3	0	-1	0	0	0	8	5	8	0	5	0	26

In the above tableau the pivot element is identified as occurring in the w_4 column and in the u_4 row and the new tableau is given in Tableau 1.6.

Tableau 1.6

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	0	1	0	0	0	0	1	0	-1	0	1	0	0	0	0	1
w_8	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
w_4	1	-1	0	1	0	0	0	0	0	1	-1	0	1	0	0	1
w_5	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	2
u_6	-1	1	0	0	0	1	0	0	0	-1	1	0	0	0	1	1
	9	-2	0	0	0	-1	0	0	0	11	2	8	3	5	0	29

In the above tableau the pivot element is identified as occurring in the w_2 column and in the w_8 row and the new tableau is given in Tableau 1.7.

Tableau 1.7

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	0	1	0	0	0	0	1
w_2	-1	1	0	0	0	0	0	1	-1	-1	1	0	0	0	0	0
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
w_4	0	0	0	1	0	0	0	1	-1	1	-1	0	1	0	0	1
w_5	1	0	0	0	1	0	0	-1	1	0	1	0	0	1	0	2
u_6	0	0	0	0	0	1	0	-1	1	-1	1	0	0	0	1	1
	7	0	0	0	0	-1	0	2	-2	9	4	8	3	5	0	29

In the above tableau the pivot element is identified as occurring in the w_9 column and in the u_6 row and the new tableau is given in Tableau 1.8.

Tableau 1.8

	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	u_1	u_2	u_3	u_4	u_5	u_6	
w_7	1	0	0	0	0	0	1	-1	0	1	0	0	0	0	0	1
w_2	-1	1	0	0	0	1	0	0	0	-1	1	0	0	0	0	1
w_3	1	0	1	0	0	0	0	0	0	1	0	1	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	2
w_5	1	0	0	0	1	-1	0	0	0	1	0	0	0	1	0	1
w_9	0	0	0	0	0	1	0	-1	1	0	0	0	0	0	1	1
	7	0	0	0	0	1	0	0	0	9	4	8	3	5	2	31

As there are no longer any zeros in the objective row the solution given in the above tableau is optimal. The solution occurs in the objective row and in the u_1, u_2, ..., u_6 columns. The solution is:

u_1 represents $m_{12} = 9$

u_2 represents $m_{13} = 4$

u_3 represents $m_{21} = 8$

u_4 represents $m_{23} = 3$

u_5 represents $m_{31} = 5$

u_6 represents $m_{32} = 2$

A.2 Method 2 - Without the introduction of additional slack variables

Let
$$v_1 = w_1 + u_1$$
$$v_2 = w_2 + u_2$$
$$v_3 = w_3 + u_3$$
$$v_4 = w_4 + u_4$$
$$v_5 = w_5 + u_5$$
$$v_6 = w_6 + u_6$$

and, substituting into the previous constraints, the constraints may be re-written as:

$$
\begin{array}{llllllllllllll}
v_1 & & & & & & + & w_7 & - & w_8 & & & = 1 \\
 & v_2 & & & & & + & w_7 & & & - & w_9 & = 1 \\
 & & v_3 & & & & - & w_7 & + & w_8 & & & = 1 \\
 & & & v_4 & & & & & + & w_8 & - & w_9 & = 1 \\
 & & & & v_5 & & - & w_7 & & & + & w_9 & = 1 \\
 & & & & & v_6 & & & - & w_8 & + & w_9 & = 1
\end{array}
$$

Tableau 2.1

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
v_1	1	0	0	0	0	0	1	-1	0	1
v_2	0	1	0	0	0	0	1	0	-1	1
v_3	0	0	1	0	0	0	-1	1	0	1
v_4	0	0	0	1	0	0	0	1	-1	1
v_5	0	0	0	0	1	0	-1	0	1	1
v_6	0	0	0	0	0	1	0	-1	1	1
	-2	-4	-8	-3	-5	-1	0	0	0	0

Using the method described in Chapter 3 (section 3.4.6) the pivot element is identified as occurring in the w_3 column and in the v_3 row and the new tableau is given in Tableau 2.1.

Tableau 2.2

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
v_1	1	0	0	0	0	0	1	-1	0	1
v_2	0	1	0	0	0	0	1	0	-1	1
w_3	0	0	1	0	0	0	-1	1	0	1
v_4	0	0	0	1	0	0	0	1	-1	1
v_5	0	0	0	0	1	0	-1	0	1	1
v_6	0	0	0	0	0	1	0	-1	1	1
	-2	-4	0	-3	-5	-1	-8	8	0	8

In the above tableau the pivot element is identified as occurring in the w_7 column and in the v_1 row and the new tableau is given in Tableau 2.3.

Tableau 2.3

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
v_2	-1	1	0	0	0	0	0	1	-1	0
w_3	1	0	1	0	0	0	0	0	0	2
v_4	0	0	0	1	0	0	0	1	-1	1
v_5	1	0	0	0	1	0	0	-1	1	2
v_6	0	0	0	0	0	1	0	-1	1	1
	6	-4	0	-3	-5	-1	0	0	0	16

In the above tableau the pivot element is identified as occurring in the w_5 column and in the v_5 row and the new tableau is given in Tableau 2.4.

Tableau 2.4

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
v_2	-1	1	0	0	0	0	0	1	-1	0
w_3	1	0	1	0	0	0	0	0	0	2
v_4	0	0	0	1	0	0	0	1	-1	1
w_5	1	0	0	0	1	0	0	-1	1	2
v_6	0	0	0	0	0	1	0	-1	1	1
	11	-4	0	-3	0	-1	0	-5	5	26

In the above tableau the pivot element is identified as occurring in the w_8 column and in the v_2 row and the new tableau is given in Tableau 2.5.

Tableau 2.5

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	0	1	0	0	0	0	1	0	-1	1
w_8	-1	1	0	0	0	0	0	1	-1	0
w_3	1	0	1	0	0	0	0	0	0	2
v_4	1	-1	0	1	0	0	0	0	0	1
w_5	0	1	0	0	1	0	0	0	0	2
v_6	-1	1	0	0	0	1	0	0	0	1
	6	1	0	-3	0	-1	0	0	0	26

In the above tableau the pivot element is identified as occurring in the w_4 column and in the v_4 row and the new tableau is given in Tableau 2.6.

Tableau 2.6

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	0	1	0	0	0	0	1	0	-1	1
w_8	-1	1	0	0	0	0	0	1	-1	0
w_3	1	0	1	0	0	0	0	0	0	2
w_4	1	-1	0	1	0	0	0	0	0	1
w_5	0	1	0	0	1	0	0	0	0	2
v_6	-1	1	0	0	0	1	0	0	0	1
	9	-2	0	0	0	-1	0	0	0	29

In the above tableau the pivot element is identified as occurring in the w_2 column and in the w_8 row and the new tableau is given in Tableau 2.7.

Tableau 2.7

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
w_2	-1	1	0	0	0	0	0	1	-1	0
w_3	1	0	1	0	0	0	0	0	0	2
w_4	0	0	0	1	0	0	0	1	-1	1
w_5	1	0	0	0	1	0	0	-1	1	2
v_6	0	0	0	0	0	1	0	-1	1	1
	7	0	0	0	0	-1	0	2	-2	29

In the above tableau the pivot element is identified as occurring in the w_9 column and in the v_6 row and the new tableau is given in Tableau 2.8.

Tableau 2.8

	v_1	v_2	v_3	v_4	v_5	v_6				
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	
w_7	1	0	0	0	0	0	1	-1	0	1
w_2	-1	1	0	0	0	1	0	0	0	1
w_3	1	0	1	0	0	0	0	0	0	2
w_4	0	0	0	1	0	1	0	0	0	2
w_5	1	0	0	0	1	-1	0	0	0	1
w_9	0	0	0	0	0	1	0	-1	1	1
	7	0	0	0	0	1	0	0	0	31

As there are no longer any zeros in the objective row the solution in the above tableau is optimal. The solution occurs in the objective row and is obtained by the addition of the values in the w_1, w_2, ..., w_6 columns to the original values. The solution is:

$$m_{12} = 2 + 7 = 9$$

$$m_{13} = 4 + 0 = 4$$

$$m_{21} = 8 + 0 = 8$$

$$m_{23} = 3 + 0 = 3$$

$$m_{31} = 5 + 0 = 5$$

$$m_{32} = 1 + 1 = 2$$

APPENDIX B

REGULATIONS CONCERNING TOWER CRANES

B.1 Clauses from The Construction (Lifting Operations) Regulations 1961 relevant to the use of tower cranes

Clause 19(4)

"After the erection of a crane on site ...., the security of anchorage or the adequacy of the ballasting, as the case may be, shall, before the crane is taken into use, be tested by a competent person, by the imposition either

a) of a load of 25% above the maximum load to be lifted by the crane as erected at the positions where there is maximum pull on each anchorage, or

b) of a less load arranged to provide an equivalent test of the anchorage or ballasting arrangements."

Clause 19(7)

"No crane shall be used or erected under weather conditions likely to endanger its stability. After exposure to weather conditions likely to have effected the stability of a crane, the anchorage arrangements and ballast shall be examined by a competent person as soon as practicable and before the crane is used, and any steps taken to ensure the stability of the crane."

Clause 29(1)

"The safe working load or safe working loads and a means of identification shall be plainly marked -

(a) upon each crane, crab or winch;

(b) upon every pulley block, gin wheel, shear legs, derrick pole, derrick mast or aerial cableway used in the raising or lowering of any load weighing one tonne or more."

Clause 29(2)

"Every crane of variable operating radius (including a crane with a derricking jib) shall:-

(a) have plainly marked upon it the safe working load at various radii of the jib, trolley or crab, and, in the case of crane with a derricking jib, the maximum radius at which the jib may be worked; and

(b) be fitted with an accurate indicator, clearly visible to the driver, showing the radius of the jib, trolley or crab at any time and the safe working load corresponding to that radius."

Clause 30(1)

"No jib crane having either a fixed or derricking jib (other than a mobile crane) shall be used unless it is fitted with an approved type of automatic safe load indicator which shall be properly maintained ...."

Clause 31

"None of the following appliances, nor any part of any such appliance, shall be loaded beyond the safe working load, that is to say cranes, crabs, winches, pulley blocks, gin wheels, shear legs, derrick poles and derrick masts; so however, that for the purpose of making tests of any such appliance the safe working loads may be exceeded by such an amount as a competent person appointed to carry out the tests may authorize."

Clause 32(1)

"Where there is lifted on a crane, crab, winch (other than a piling winch), shear legs or aerial cableway a load which is equal to or slightly less than the relevant safe working load and which is not already wholly sustained by the appliance, the lifting shall be halted after the load has been raised a short distance and before the operation is proceeded with."

Clause 34(4)

"No chain, rope or lifting gear shall be loaded beyond its safe working load except for the purpose of making tests and then only to such an extent as a competent person appointed to carry out the tests may authorize."

APPENDIX C

PREDICTED LOADS FOR SADDLE JIB TOWER CRANES

Data given in the following tables are based on Equations 4.2, 4.3 and 4.1 given in Chapter 4.

$$P_n = \frac{M_o}{R_n - D} - Q \quad .... \quad \textit{Equation 4.2}$$

where P_n = load capacity at corresponding radius R_n

M_o = constant moment about the point of jib articulation

D = distance from the point of jib articulation to the centre line of the tower

Q = weight of trolley, hooks and ropes

$$Q = \frac{P_1(R_1 - D) - P_2(R_2 - D)}{(R_2 - R_1)} \quad .... \quad \textit{Equation 4.3}$$

where P_1 = load capacity at corresponding radius R_1

P_2 = load capacity at corresponding radius R_2

$$M_o = (P + Q) \times (R - D) \quad .... \quad \textit{Equation 4.1}$$

where P = load capacity at corresponding radius R

Table C.1 **Predicted loads**
Liebherr 132HC saddle jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		D = 0.90m Q = 492.3kg M_o = 144369.2kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
17.9	8000.0	8000.0	0.0	0.00
20.0	7090.0	7066.3	23.7	0.33
22.5	6220.0	6191.5	28.5	0.46
25.0	5530.0	5498.1	31.9	0.58
27.5	4960.0	4935.1	24.9	0.50
29.0	4670.0	4645.4	24.6	0.53
30.0	4490.0	4468.8	21.2	0.47
32.5	4090.0	4076.3	13.7	0.33
34.0	3880.0	3869.3	10.7	0.28
35.0	3750.0	3741.4	8.6	0.23
37.5	3460.0	3452.2	7.8	0.23
39.0	3300.0	3296.9	3.1	0.09
40.0	3200.0	3200.0	0.0	0.00

Table C.2 **Predicted loads**
Peiner SK76 saddle jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		D = 0.60m Q = 333.8kg M_o = 72539.2kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
14.2	5000.0	5000.0	0.0	0.00
15.0	4690.0	4703.7	-13.7	-0.29
16.0	4360.0	4376.6	-16.6	-0.38
18.0	3810.0	3835.2	-25.2	-0.66
20.0	3370.0	3405.4	-35.4	-1.05
22.0	3020.0	3055.9	-35.9	-1.19
24.0	2730.0	2766.2	-36.2	-1.33
26.0	2490.0	2522.1	-32.1	-1.29
28.0	2290.0	2313.7	-23.7	-1.03
30.0	2110.0	2133.6	-23.6	-1.12
33.0	1890.0	1905.1	-15.1	-0.80
35.0	1760.0	1774.9	-14.9	-0.85
38.0	1600.0	1605.8	-5.8	-0.36
40.0	1500.0	1507.3	-7.3	-0.49
41.0	1460.0	1461.8	-1.8	-0.12
42.0	1410.0	1418.4	-8.4	-0.59
43.0	1370.0	1377.1	-7.1	-0.52
44.0	1340.0	1337.6	2.4	0.18
45.0	1300.0	1300.0	0.0	0.00

Table C.3 **Predicted loads**
Potain E2/23B saddle jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		D = 0.52m Q = 459.8kg M_o = 136099.3kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
31.04	4000.0	4000.0	0.0	0.00
32.0	3863.0	3863.6	-0.6	-0.01
33.0	3730.0	3730.5	-0.5	-0.01
34.0	3605.0	3605.5	-0.3	-0.01
35.0	3487.0	3487.4	-0.4	-0.01
36.0	3376.0	3376.2	-0.2	0.00
37.0	3271.0	3271.0	0.0	0.00
38.0	3171.0	3171.5	-0.5	-0.01
39.0	3077.0	3077.1	-0.1	0.00
40.0	2987.0	2987.5	-0.5	-0.02
41.0	2902.0	2902.3	-0.3	-0.01
42.0	2821.0	2821.3	-0.3	-0.01
43.0	2744.0	2744.1	-0.1	0.00
44.0	2670.0	2670.0	-0.4	-0.01
45.0	2600.0	2600.0	0.0	0.00

Table C.4 **Predicted loads**
Wolffkran WK280EC saddle jib tower crane

MANUFACTURER'S DATA		PREDICTED DATA		
		D = 1.0m Q = 910.6kg M_o = 269831.6kgm		
Radius (m)	Load (kg)	Load (kg)	Error (kg)	%Error
21.9	12000.0	12000.0	0.0	0.00
25.0	10380.0	10332.4	47.6	0.46
30.0	8550.0	8393.9	156.1	1.83
35.0	7150.0	7025.6	124.4	1.74
40.0	6110.0	6008.2	101.8	1.67
45.0	5290.0	5221.9	68.1	1.29
50.0	4640.0	4596.2	43.8	0.94
55.0	4110.0	4086.3	23.7	0.58
60.0	3660.0	3662.5	-2.8	-0.08
65.0	3290.0	3305.5	-15.5	-0.47
70.0	3000.0	3000.0	0.0	0.00

APPENDIX D

SERIES A SIMULATIONS

The results of the Series A simulations are presented for each layout as follows:

- a diagrammatic representation of the layout

and for each crane type (Crane 1, Crane 2A, Crane 2B and Crane 3)

- a grid giving times (hours) to complete all the movements for 36 possible crane positions based on 10m intervals within a 50m by 50m grid. The horizontal axis represents the x axis and the vertical axis represents the y axis. The co-ordinates associated with minimum and maximum times to complete all movements are annotated as follows:

  ☐ co-ordinates associated with minimum time

  ☐ co-ordinates associated with the maximum time

- a surface contour plot, based on the grid referred to above. Again, the horizontal axis represents the x axis and the vertical axis represents the y axis and the grid is 50m by 50m. The key is:

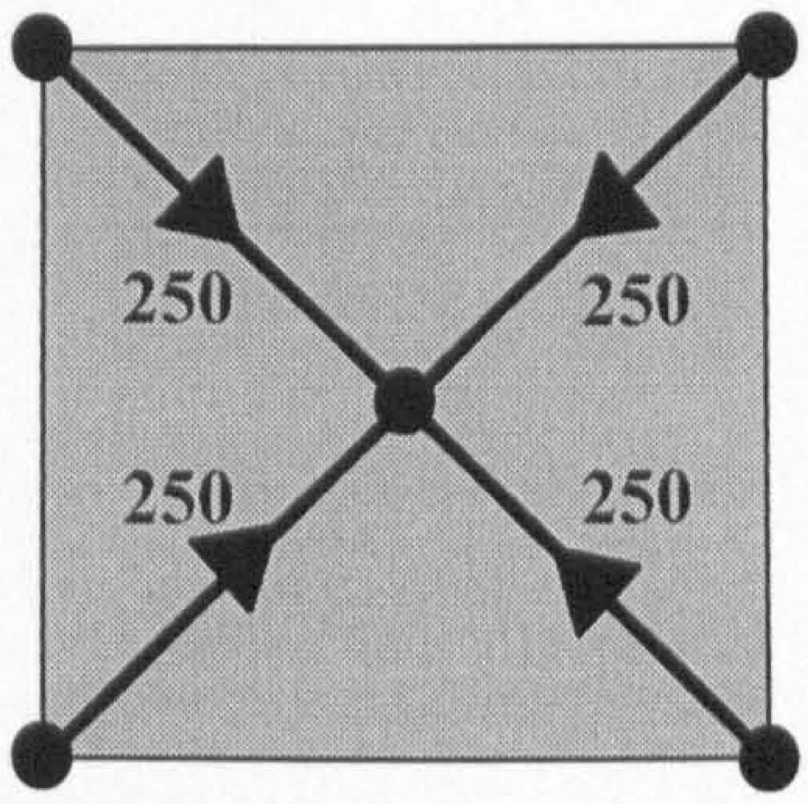
  ☐ 0% - 25% of the range from minimum value to maximum value

  ■ 25% - 50% of the range from minimum value to maximum value

  ☐ 50% - 75% of the range from minimum value to maximum value

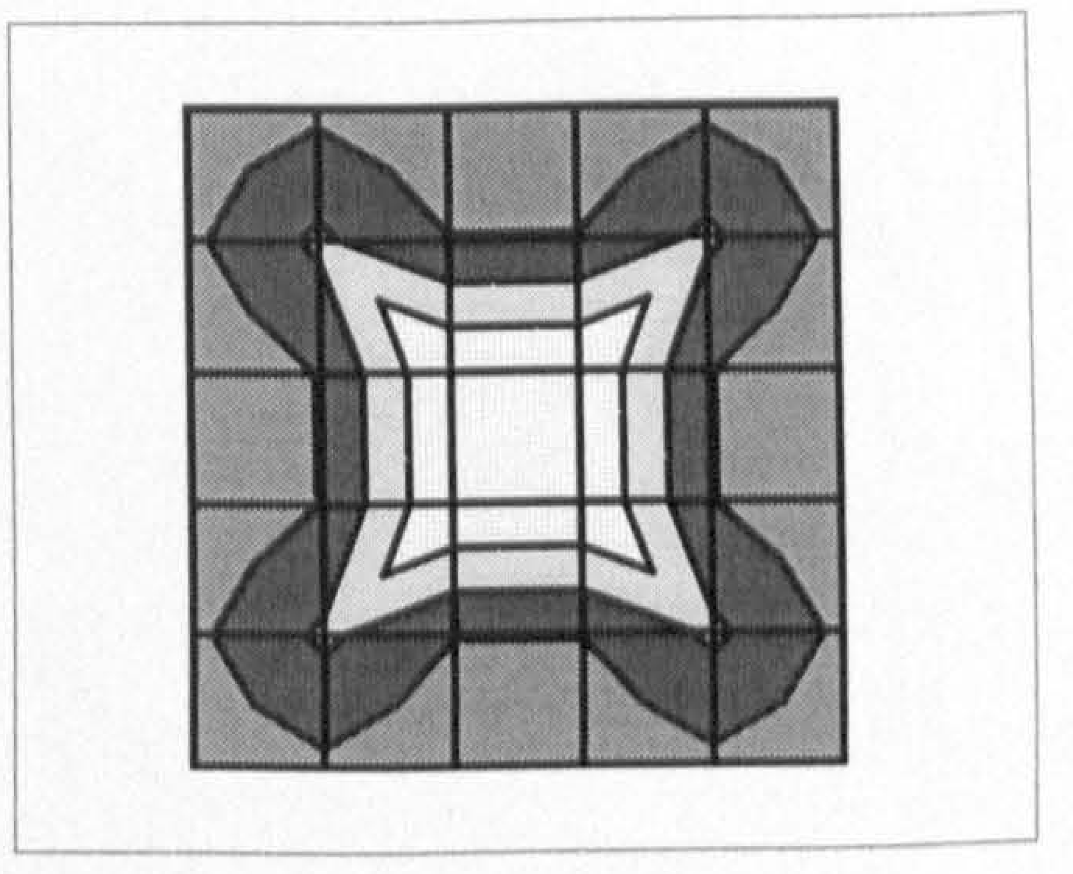
  ☐ 75% - 100% of the range from minimum value to maximum value

D.1 Layout 1



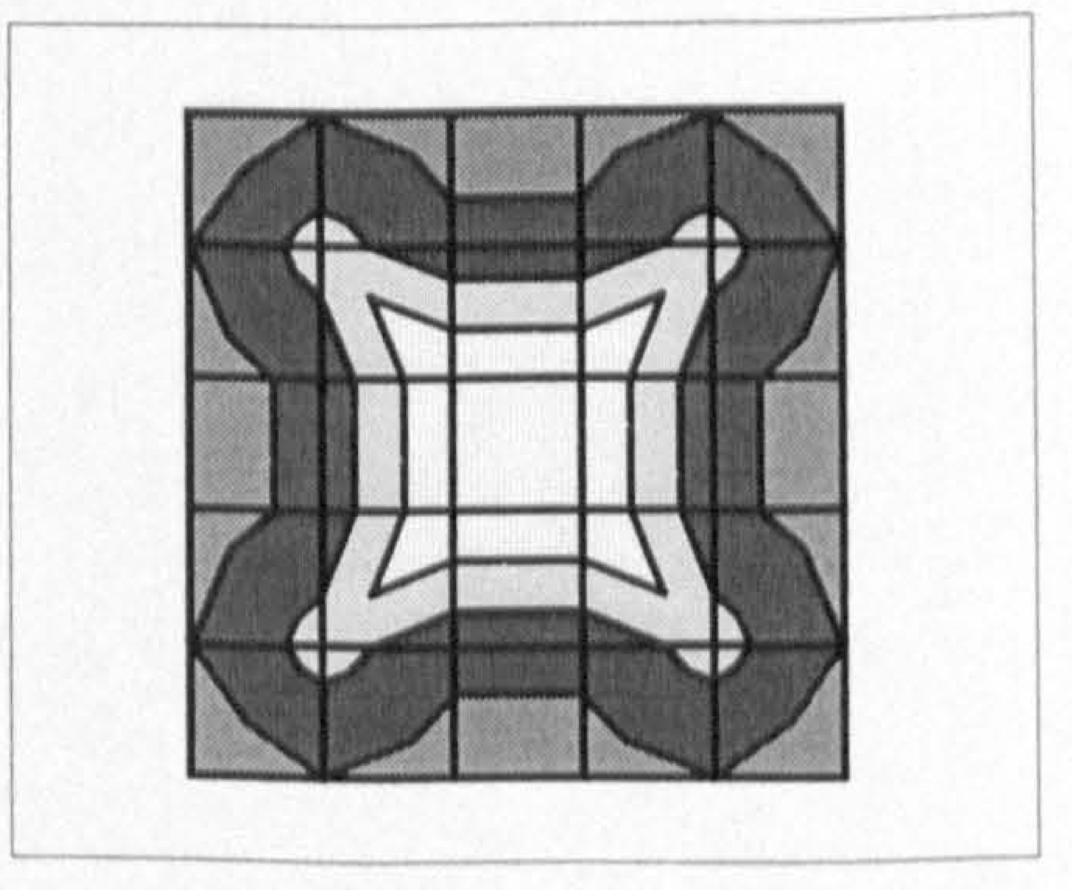
CRANE 1

	0	10	20	30	40	50
50	26.20	27.00	26.29	26.29	27.00	26.20
40	27.00	28.22	27.22	27.22	28.22	27.00
30	26.29	27.22	29.86	29.86	27.22	26.29
20	26.29	27.22	29.86	29.86	27.22	26.29
10	27.00	28.22	27.22	27.22	28.22	27.00
0	26.20	27.00	26.29	26.29	27.00	26.20



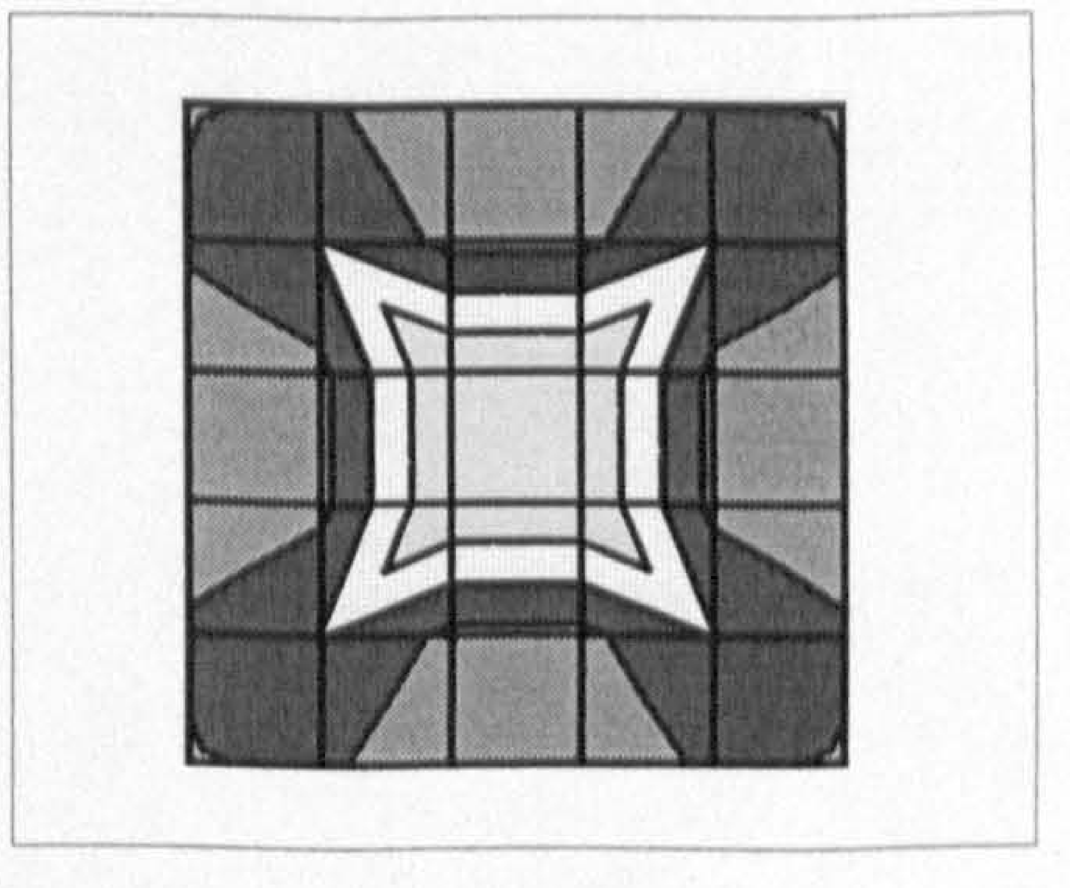
CRANE 2A

	0	10	20	30	40	50
50	89.76	90.83	90.19	90.19	90.83	89.76
40	90.83	92.39	91.23	91.23	92.39	90.83
30	90.19	91.23	94.15	94.15	91.23	90.19
20	90.19	91.23	94.15	94.15	91.23	90.19
10	90.83	92.39	91.23	91.23	92.39	90.83
0	89.76	90.83	90.19	90.19	90.83	89.76



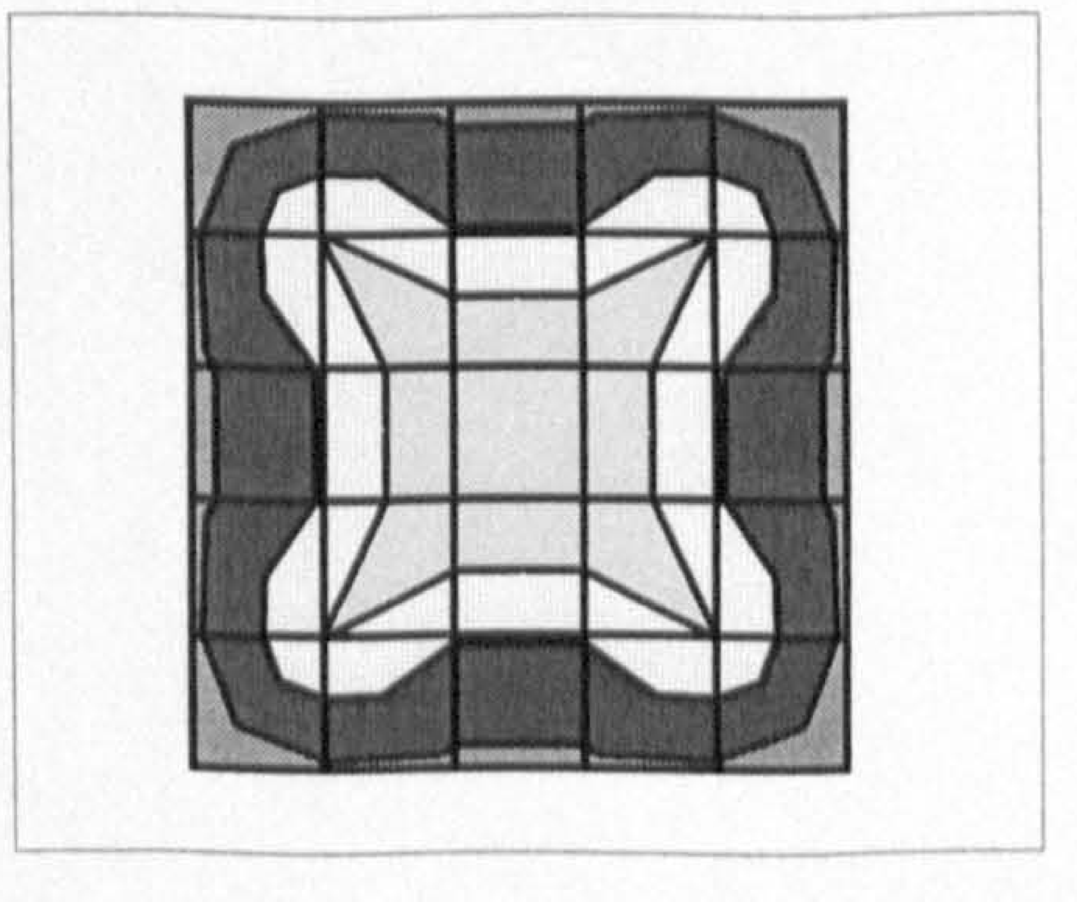
CRANE 2B

	0	10	20	30	40	50
50	94.84	95.35	93.62	93.62	95.35	94.84
40	95.35	96.47	94.66	94.66	96.47	95.35
30	93.62	94.66	99.20	99.20	94.66	93.62
20	93.62	94.66	99.20	99.20	94.66	93.62
10	95.35	96.47	94.66	94.66	96.47	95.35
0	94.84	95.35	93.62	93.62	95.35	94.84

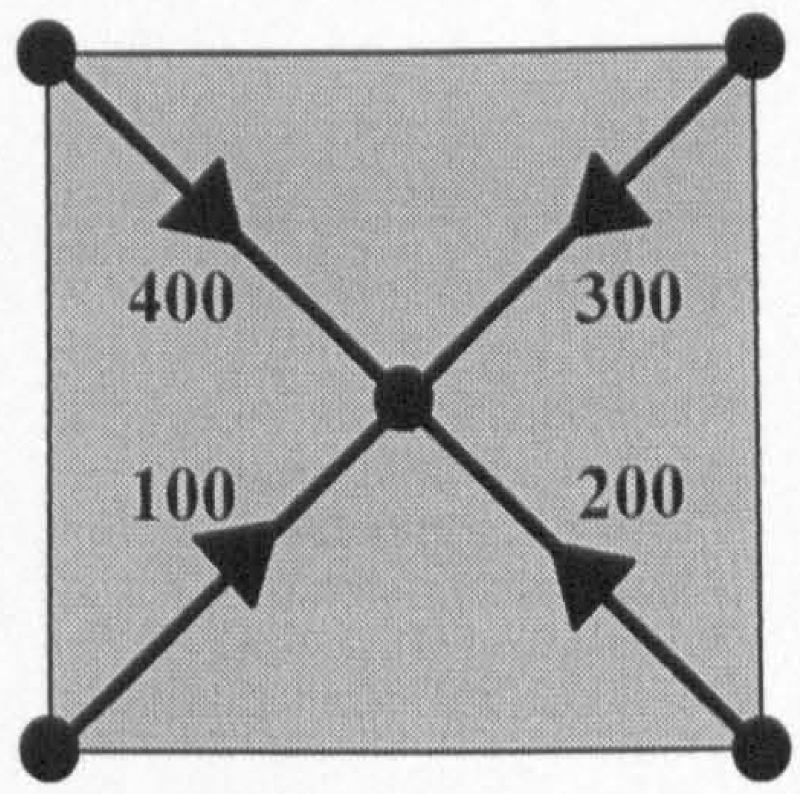


CRANE 3

	0	10	20	30	40	50
50	22.44	24.35	24.17	24.17	24.35	22.44
40	24.35	29.36	27.22	27.22	29.36	24.35
30	24.17	27.22	31.62	31.62	27.22	24.17
20	24.17	27.22	31.62	31.62	27.22	24.17
10	24.35	29.36	27.22	27.22	29.36	24.35
0	22.44	24.35	24.17	24.17	24.35	22.44

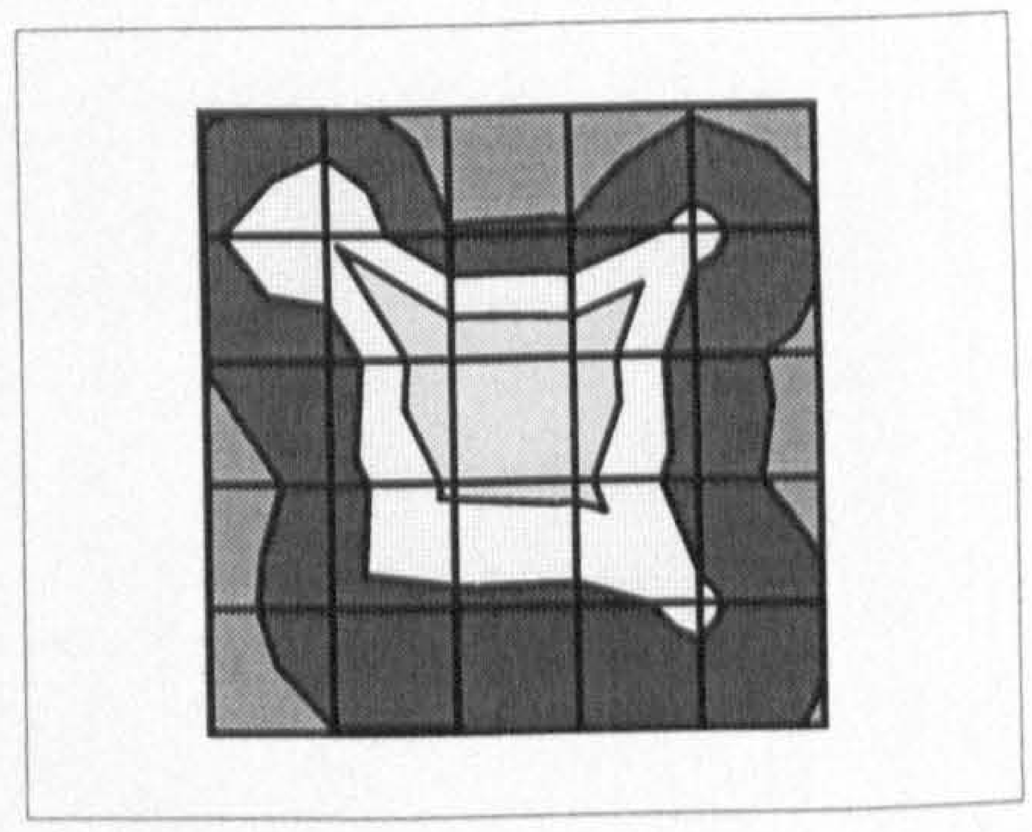


D.2 Layout 2



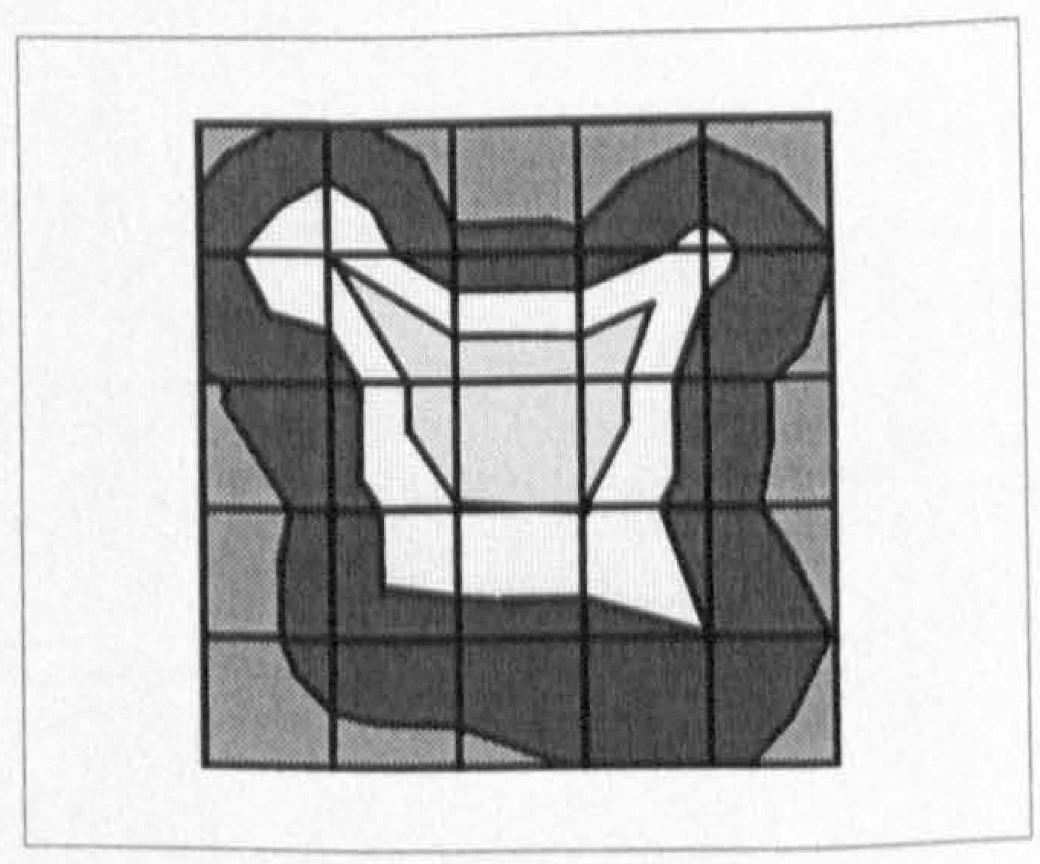
CRANE 1

	0	10	20	30	40	50
50	26.53	27.32	25.90	25.50	26.57	25.87
40	27.74	29.03	26.79	26.83	28.30	27.00
30	26.77	27.11	30.34	30.25	27.15	26.37
20	25.81	27.31	29.37	29.46	27.28	26.20
10	26.26	27.42	27.64	27.60	28.15	27.00
0	25.87	26.68	26.68	27.07	27.42	26.53



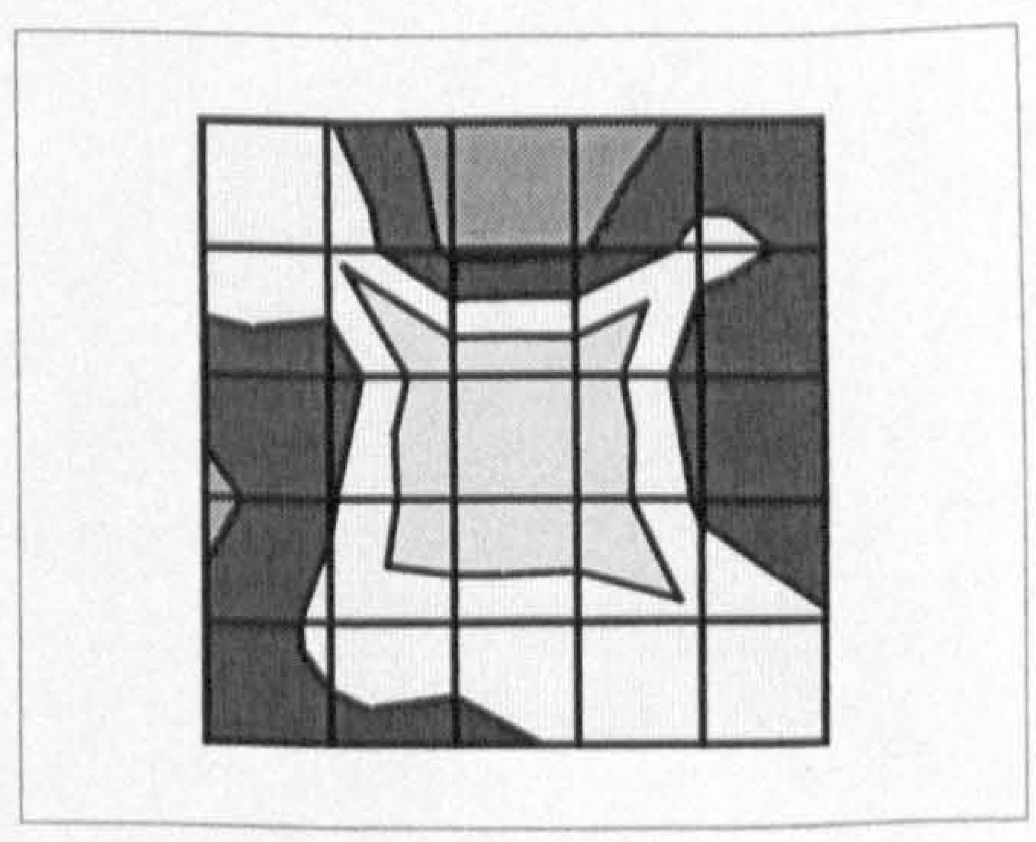
CRANE 2A

	0	10	20	30	40	50
50	90.04	91.24	89.93	89.53	90.50	89.47
40	91.63	93.44	91.08	91.10	92.62	90.89
30	90.71	91.31	94.85	94.74	91.33	90.31
20	89.68	91.34	93.44	93.56	91.33	90.08
10	90.02	91.33	91.57	91.55	92.15	90.76
0	89.47	90.42	90.46	90.86	91.15	90.04



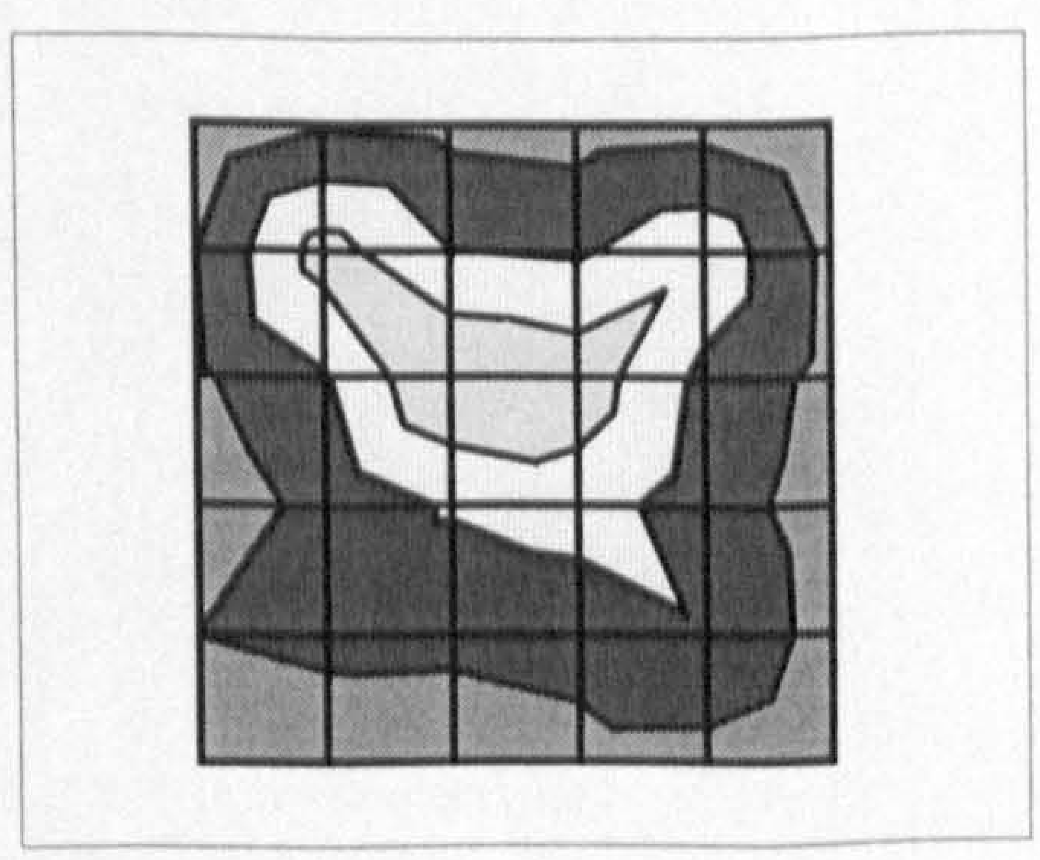
CRANE 2B

	0	10	20	30	40	50
50	95.68	95.62	92.36	91.58	94.11	94.00
40	96.59	97.08	93.06	93.23	95.95	95.08
30	94.45	94.07	99.27	99.23	94.25	93.67
20	92.79	95.24	99.14	99.17	95.06	93.57
10	94.11	95.86	96.25	96.08	96.98	95.62
0	94.00	95.08	94.88	95.66	96.59	95.68

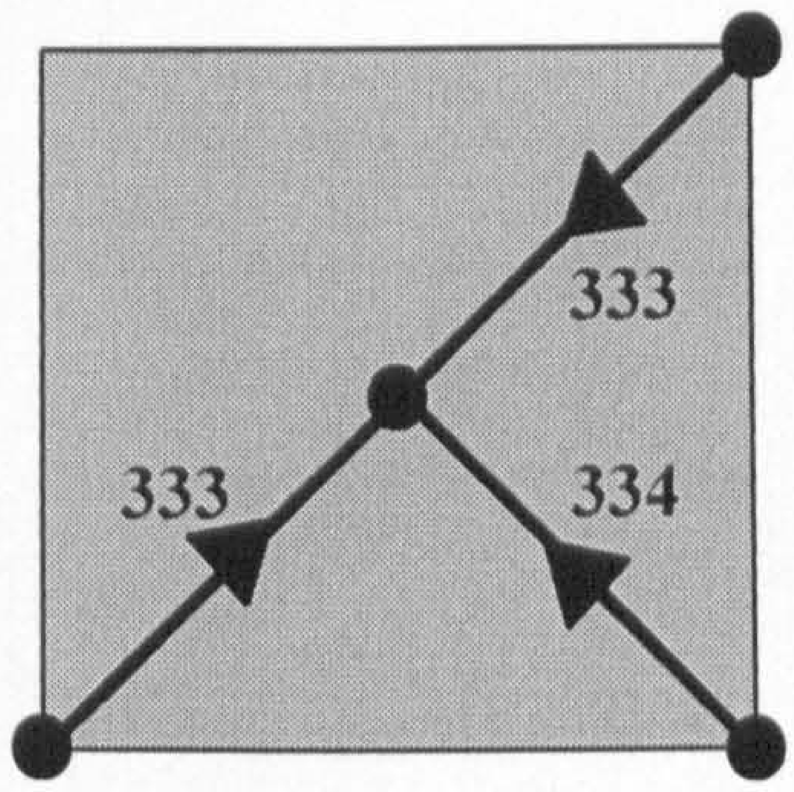


CRANE 3

	0	10	20	30	40	50
50	22.57	25.10	24.53	24.05	24.40	22.31
40	25.34	32.69	28.50	28.02	30.61	24.64
30	24.91	28.13	34.49	33.32	27.65	24.43
20	23.43	26.30	28.74	29.91	26.78	23.90
10	25.37	26.03	25.93	26.41	28.10	24.07
0	22.31	23.60	23.80	24.38	24.30	22.57

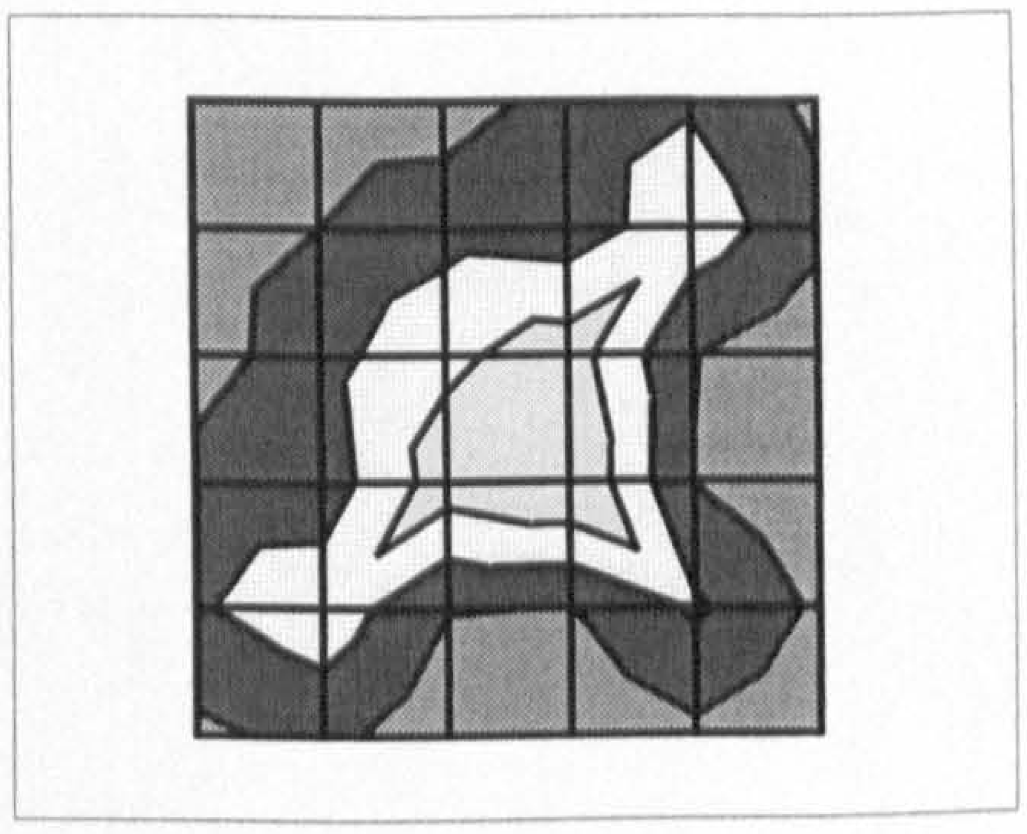


D.3 Layout 3



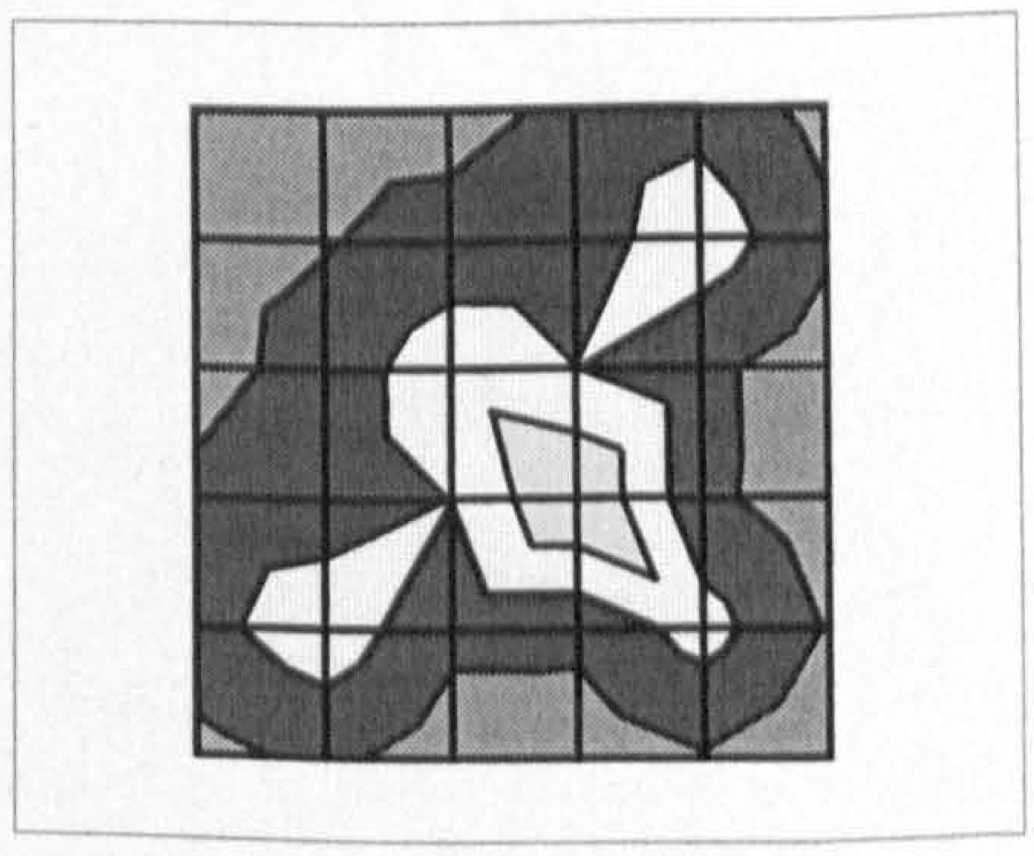
CRANE 1

	0	10	20	30	40	50
50	25.65	26.12	26.21	27.35	27.97	26.57
40	26.12	26.88	27.66	27.44	28.83	27.26
30	26.21	27.66	29.05	29.92	26.92	25.89
20	27.35	27.44	29.92	30.52	26.84	25.71
10	27.97	28.83	26.92	26.84	28.25	26.65
0	26.57	27.26	25.89	25.71	26.65	25.65



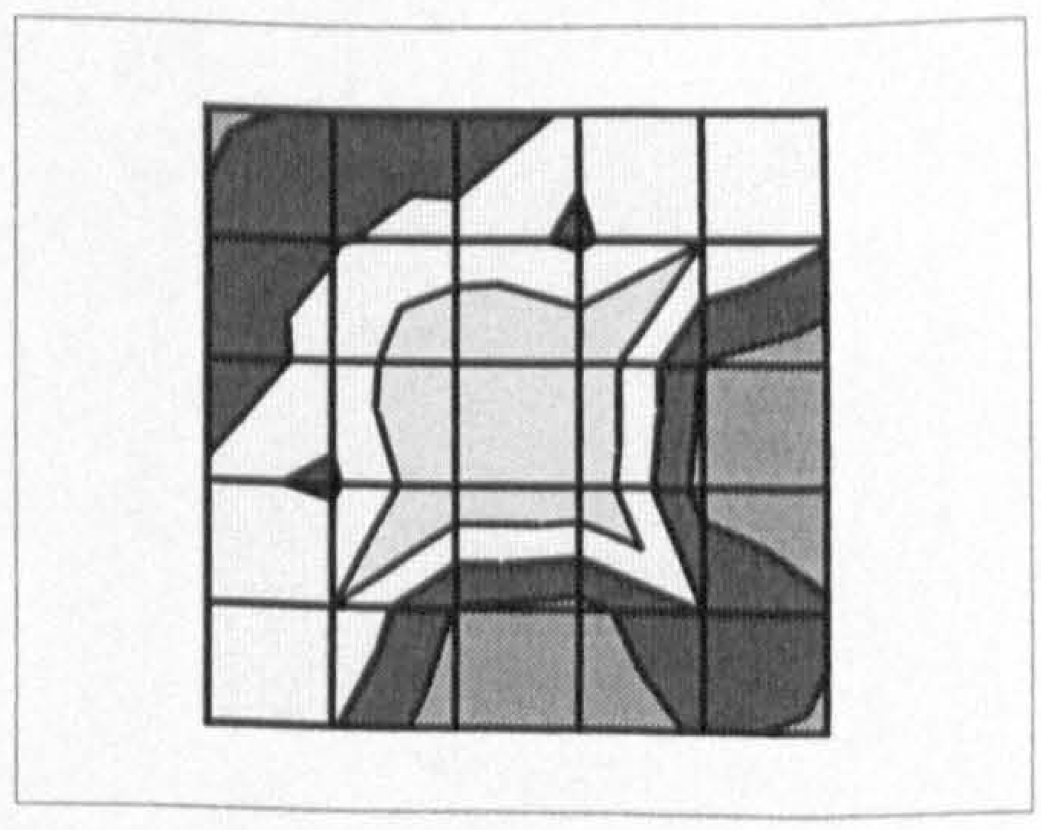
CRANE 2A

	0	10	20	30	40	50
50	89.28	89.82	89.99	91.18	91.77	90.23
40	89.82	90.62	91.54	91.49	93.07	91.11
30	89.99	91.54	92.97	92.24	91.12	89.87
20	91.18	91.49	92.24	95.14	91.14	89.73
10	91.77	93.07	91.12	91.14	92.79	90.61
0	90.23	91.11	89.87	89.73	90.61	89.28



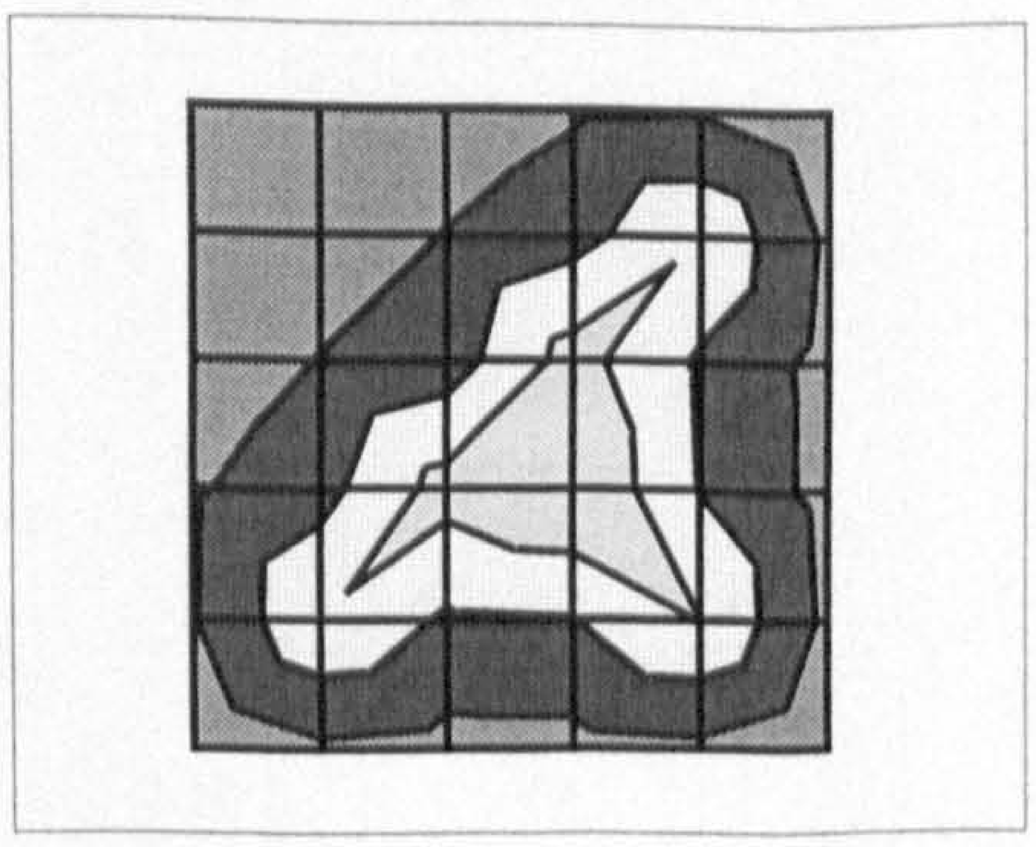
CRANE 2B

	0	10	20	30	40	50
50	93.44	94.10	93.98	96.01	97.42	96.24
40	94.10	95.45	96.47	95.36	97.40	95.79
30	93.98	96.47	99.10	99.23	93.66	92.52
20	96.01	95.36	99.23	99.35	93.13	91.97
10	97.42	97.40	93.66	93.13	95.61	94.09
0	96.24	95.79	92.52	91.97	94.09	93.44

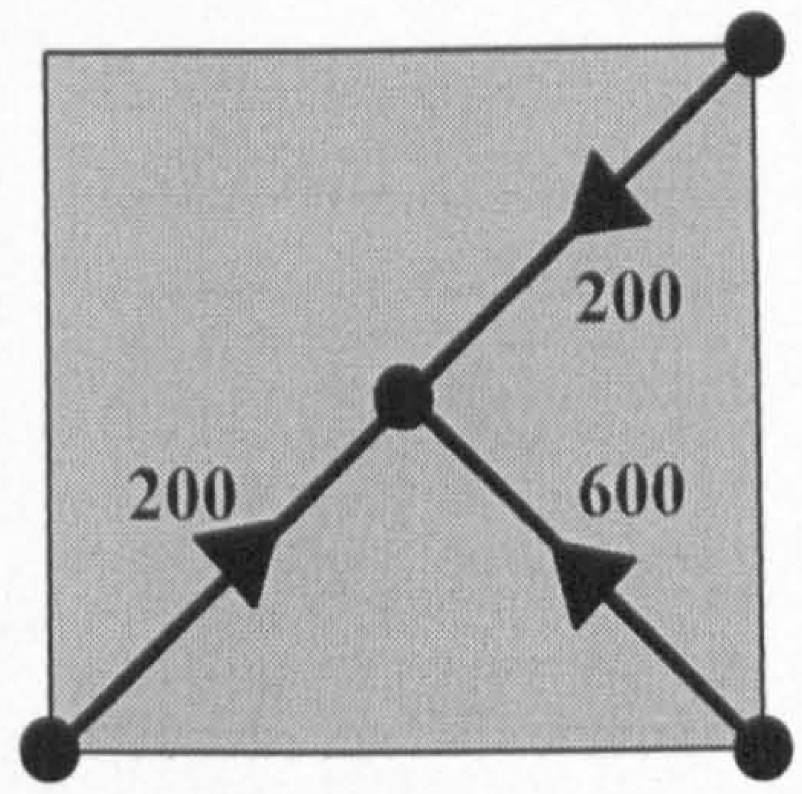


CRANE 3

	0	10	20	30	40	50
50	22.22	22.91	23.25	24.88	25.13	22.65
40	22.91	23.81	25.38	27.31	31.08	24.74
30	23.25	25.38	26.82	32.59	27.92	24.25
20	24.88	27.31	32.59	34.47	28.25	24.29
10	25.13	31.08	27.92	28.25	31.47	24.64
0	22.65	24.74	24.25	24.29	24.64	22.22

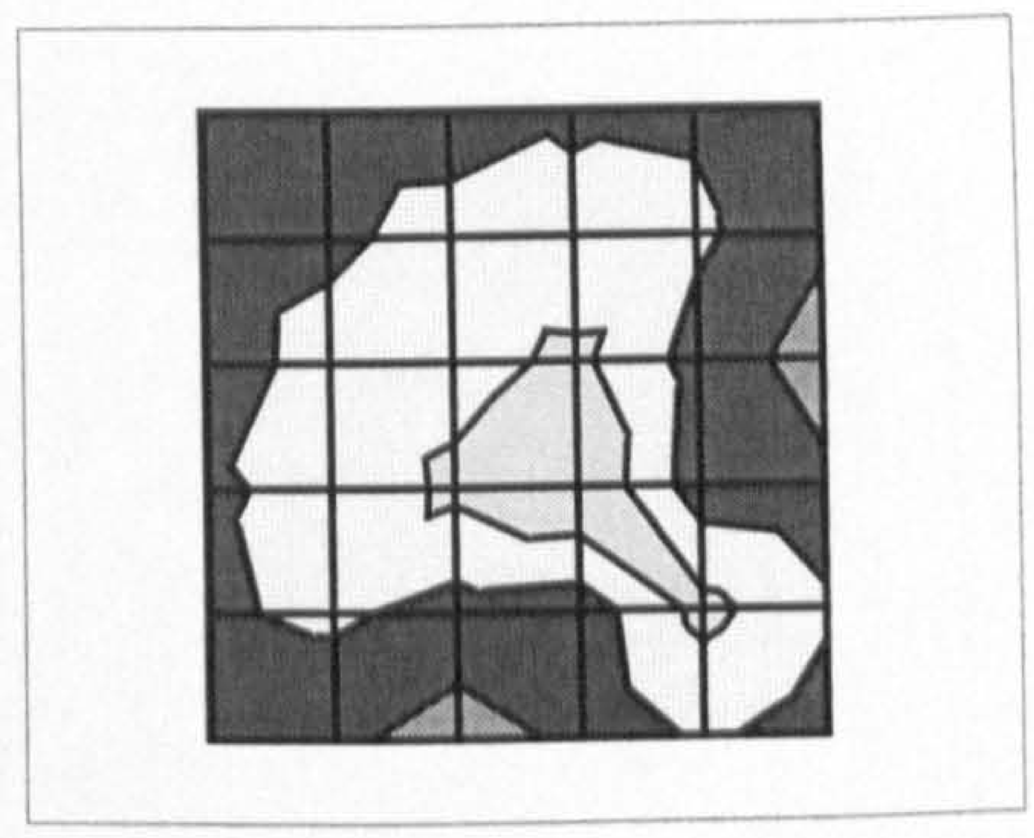


D.4 Layout 4



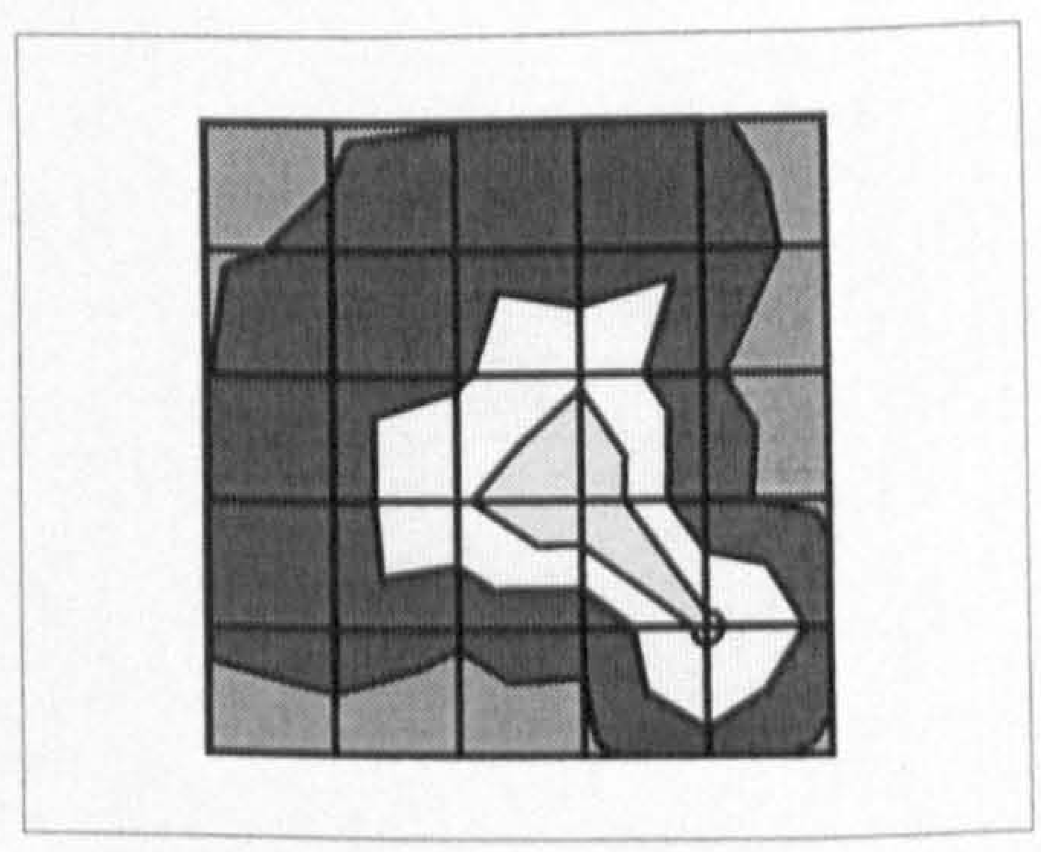
CRANE 1

	0	10	20	30	40	50
50	26.53	26.89	26.94	27.40	27.26	25.87
40	26.89	27.27	27.94	27.71	27.86	25.99
30	26.94	27.94	28.57	29.81	26.76	24.78
20	27.40	27.71	29.81	31.22	26.45	26.03
10	27.26	27.86	26.76	26.45	29.91	27.85
0	25.87	25.99	24.78	26.03	27.85	26.53



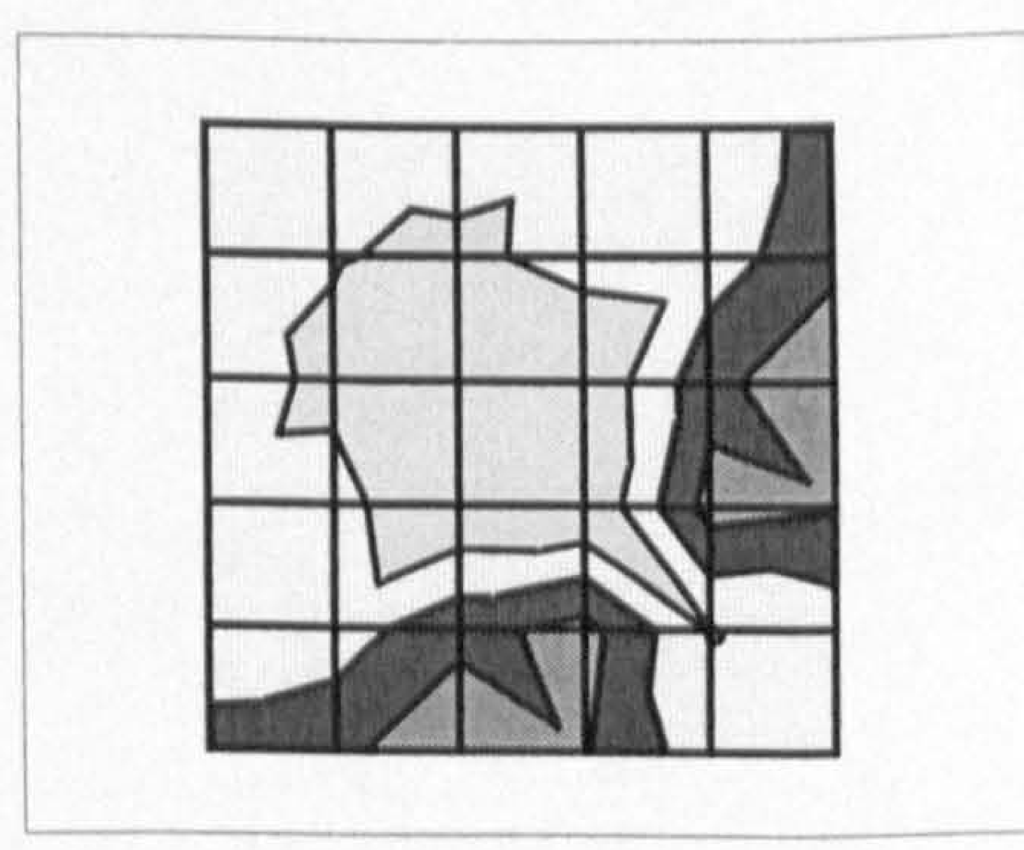
CRANE 2A

	0	10	20	30	40	50
50	90.04	90.48	90.62	91.17	91.05	89.47
40	90.48	90.85	91.68	91.16	91.98	89.87
30	90.62	91.68	92.26	94.09	91.00	88.82
20	91.17	91.67	94.09	96.15	90.95	90.17
10	91.05	91.48	91.00	90.95	94.74	91.91
0	89.47	89.87	88.82	90.17	91.91	90.04



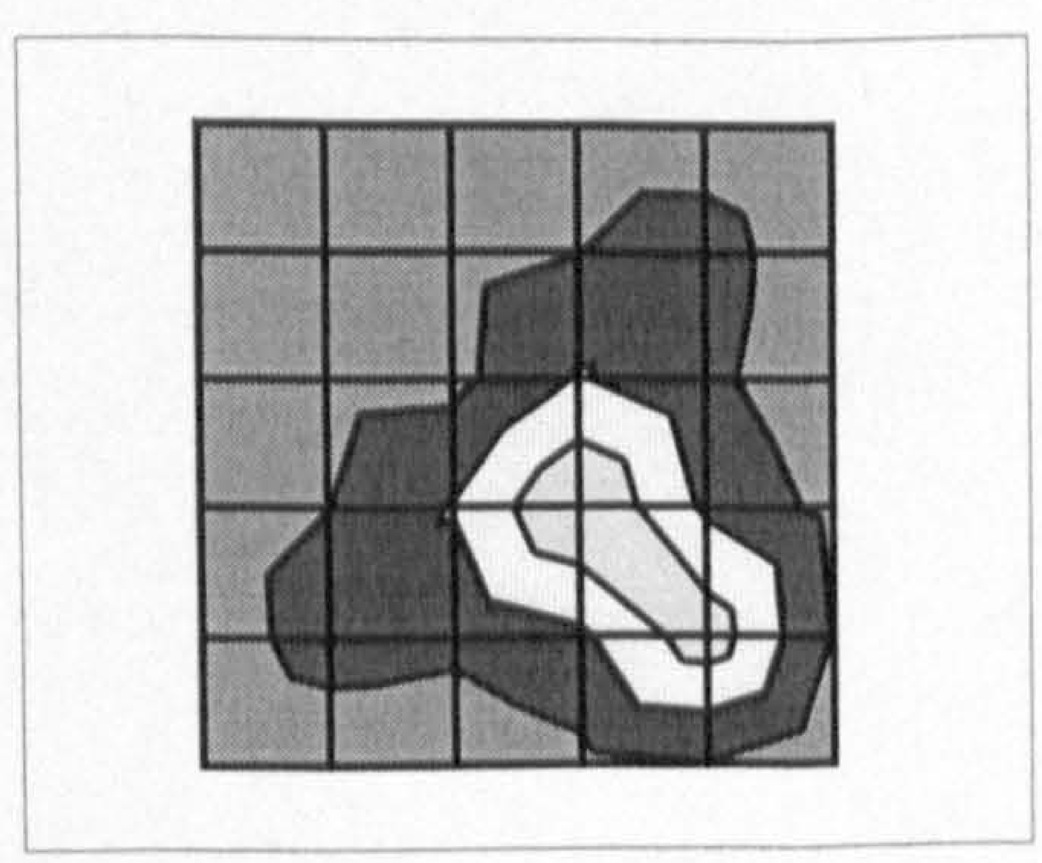
CRANE 2B

	0	10	20	30	40	50
50	95.68	96.11	95.82	96.37	96.06	94.00
40	96.11	96.89	97.58	96.27	95.90	93.13
30	95.82	97.58	99.08	99.19	93.22	90.10
20	96.37	96.27	99.19	99.36	91.56	92.20
10	96.06	95.90	93.22	91.56	97.17	96.10
0	94.00	93.13	90.10	92.20	96.10	95.68

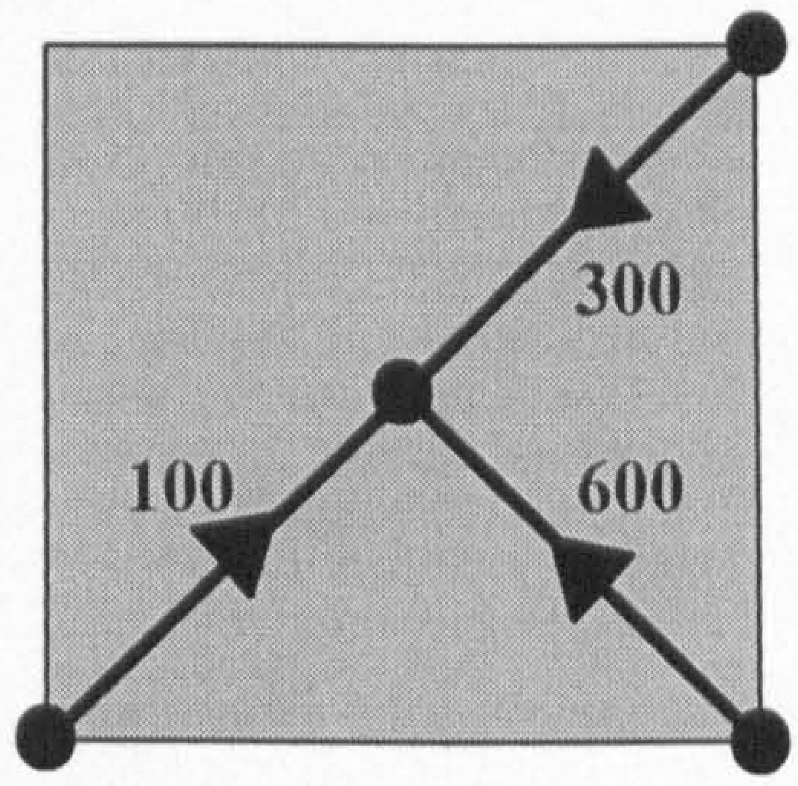


CRANE 3

	0	10	20	30	40	50
50	22.57	23.15	23.47	24.50	24.35	22.31
40	23.15	23.52	24.88	26.43	28.32	23.65
30	23.47	24.88	25.32	31.03	27.52	23.36
20	24.50	26.43	31.03	39.08	30.03	25.35
10	24.35	28.32	27.52	30.03	37.27	26.26
0	22.31	23.65	23.36	25.35	26.26	22.57

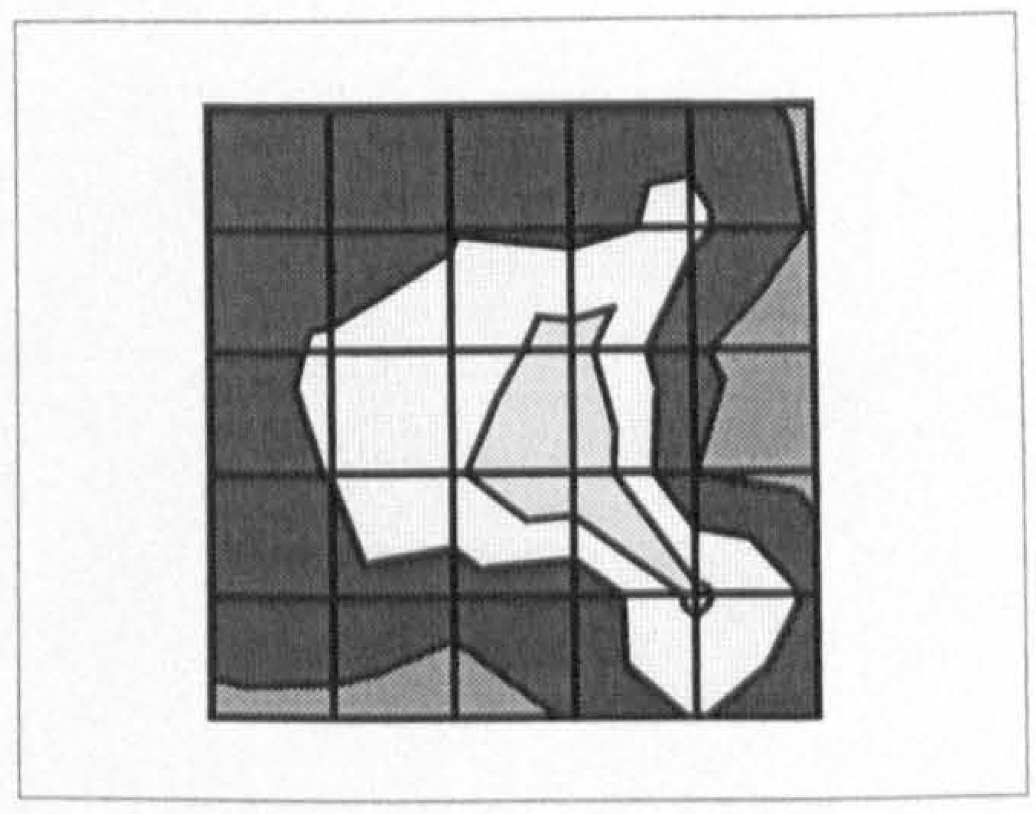


D.5 Layout 5



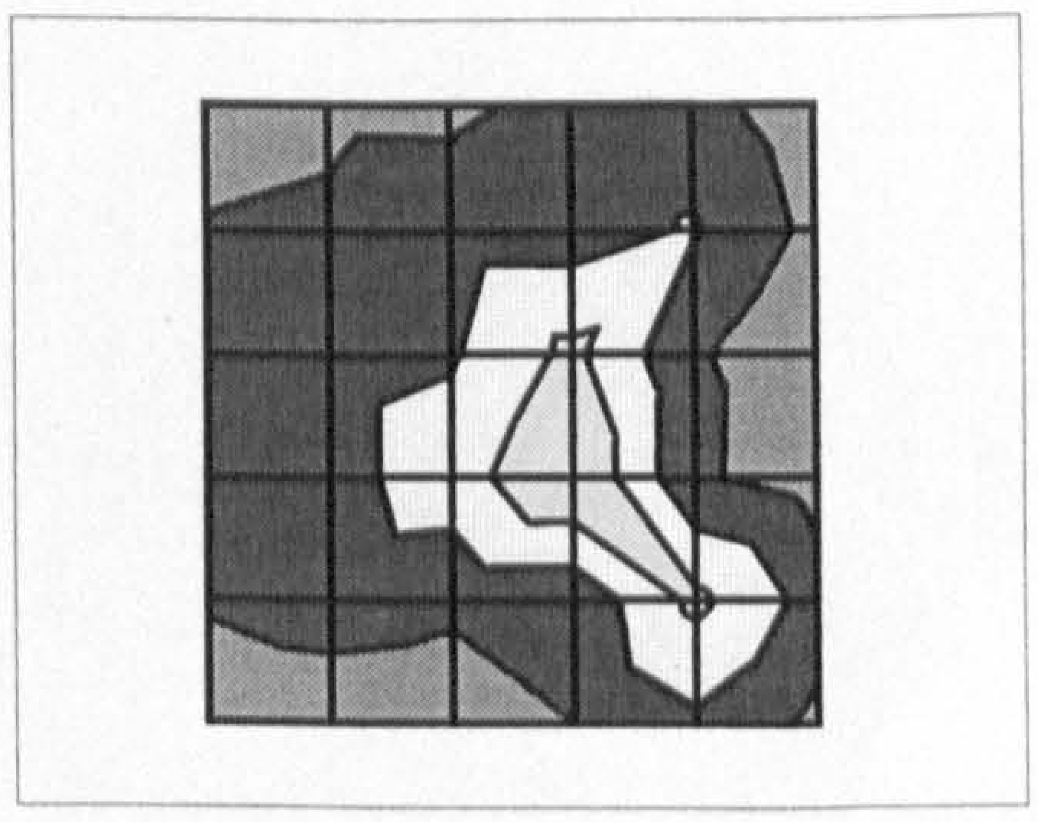
CRANE 1

	0	10	20	30	40	50
50	26.53	26.68	26.51	27.25	27.42	25.87
40	27.10	27.27	27.78	27.47	28.30	26.15
30	27.38	28.09	28.57	30.25	26.51	24.63
20	27.55	27.96	29.37	31.22	26.29	25.60
10	27.11	27.42	27.01	26.61	29.91	27.64
0	25.87	25.83	24.94	26.47	28.06	26.53



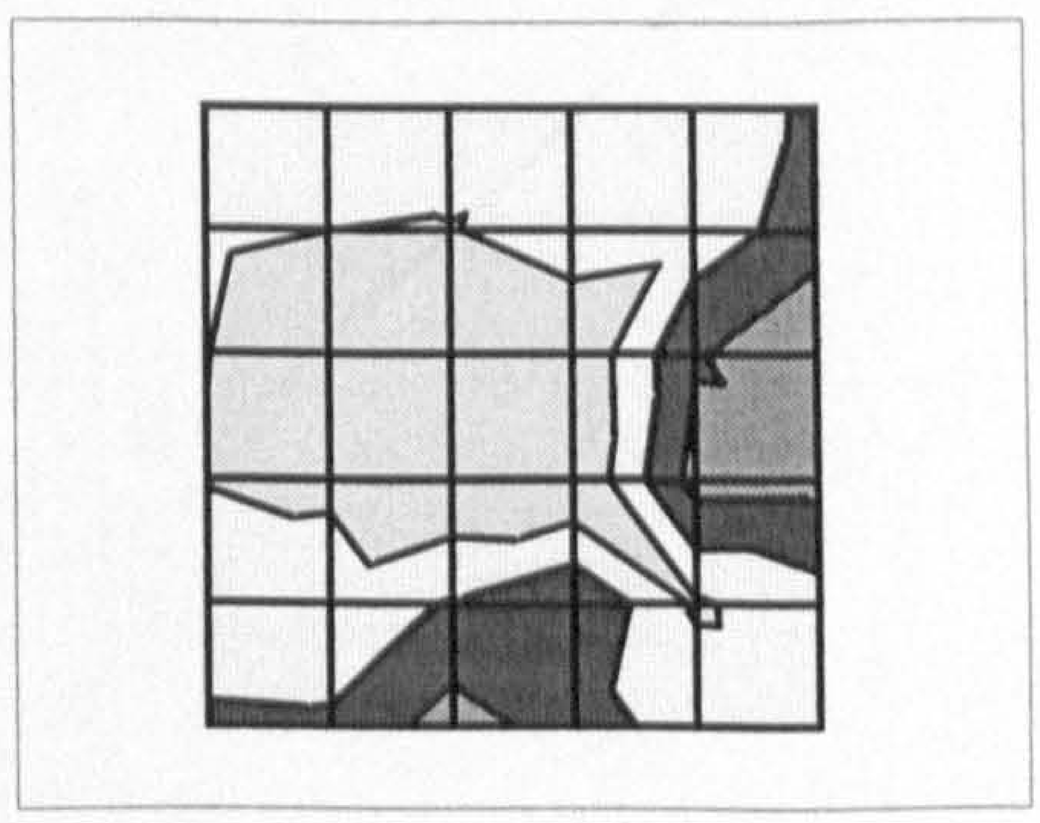
CRANE 2A

	0	10	20	30	40	50
50	90.04	90.28	90.23	91.09	91.29	89.47
40	90.67	90.85	91.57	91.55	92.62	90.11
30	91.01	91.79	92.26	94.74	90.88	88.74
20	91.25	91.79	93.44	96.15	90.84	89.78
10	90.81	91.33	91.12	91.07	94.74	91.72
0	89.47	89.63	88.89	90.56	92.11	90.05



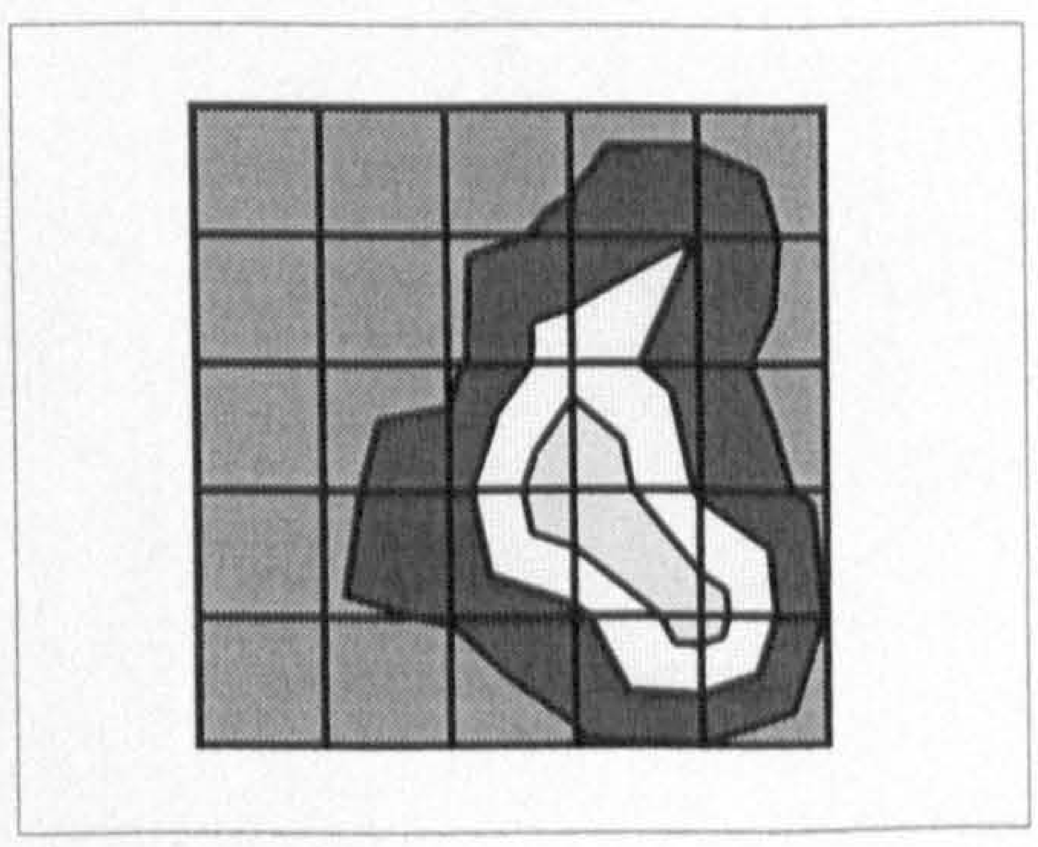
CRANE 2B

	0	10	20	30	40	50
50	95.68	95.62	94.78	95.76	96.06	94.00
40	96.60	96.89	97.07	95.27	95.95	93.13
30	96.87	98.09	99.08	99.23	92.22	89.50
20	96.97	97.27	99.14	99.36	91.05	91.16
10	96.06	95.86	94.22	92.07	97.17	95.61
0	94.00	94.13	90.70	93.24	95.59	95.68

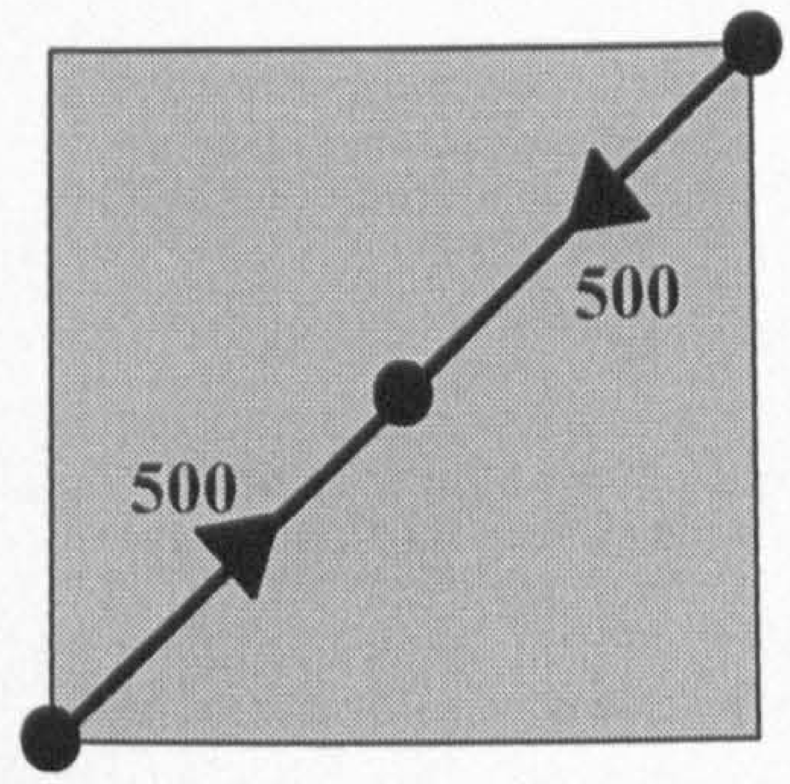


CRANE 3

	0	10	20	30	40	50
50	22.57	23.03	23.28	24.81	24.87	22.31
40	23.26	23.52	25.07	27.28	30.61	24.17
30	23.66	24.70	25.32	33.32	28.38	23.67
20	24.18	25.57	28.74	39.08	30.21	25.16
10	23.84	26.03	26.67	29.84	37.27	26.14
0	22.31	23.13	23.05	25.84	26.37	22.57

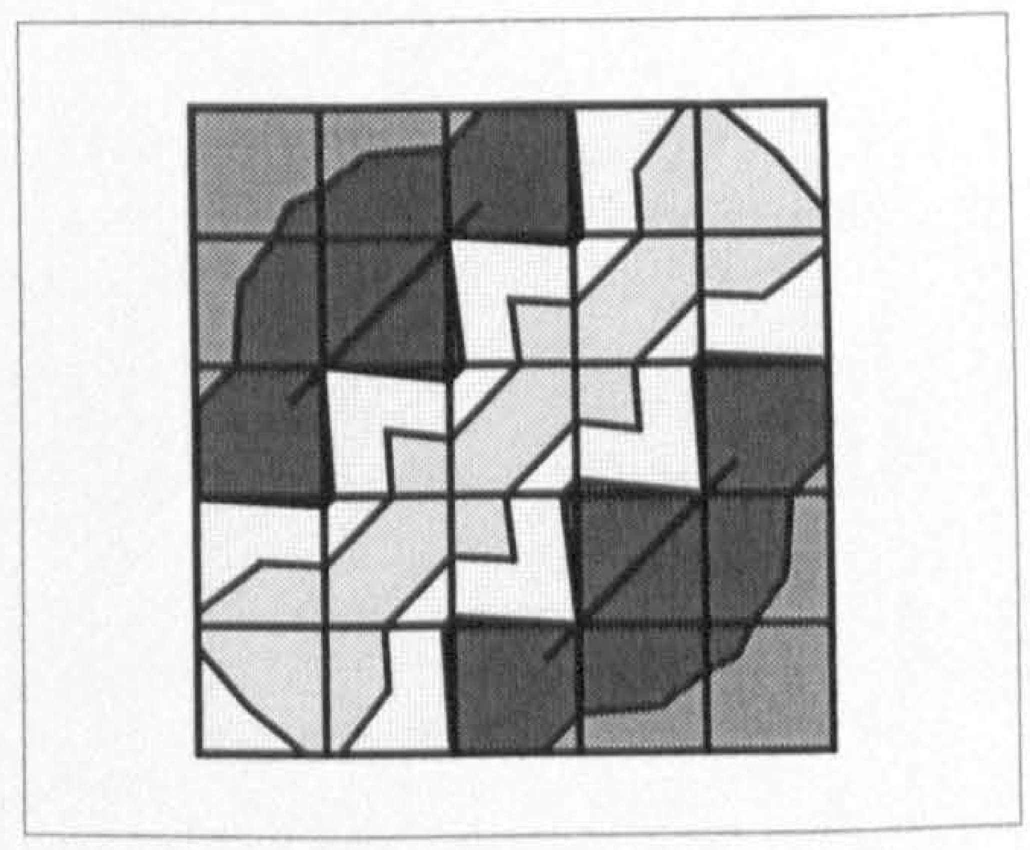


D.6 Layout 6



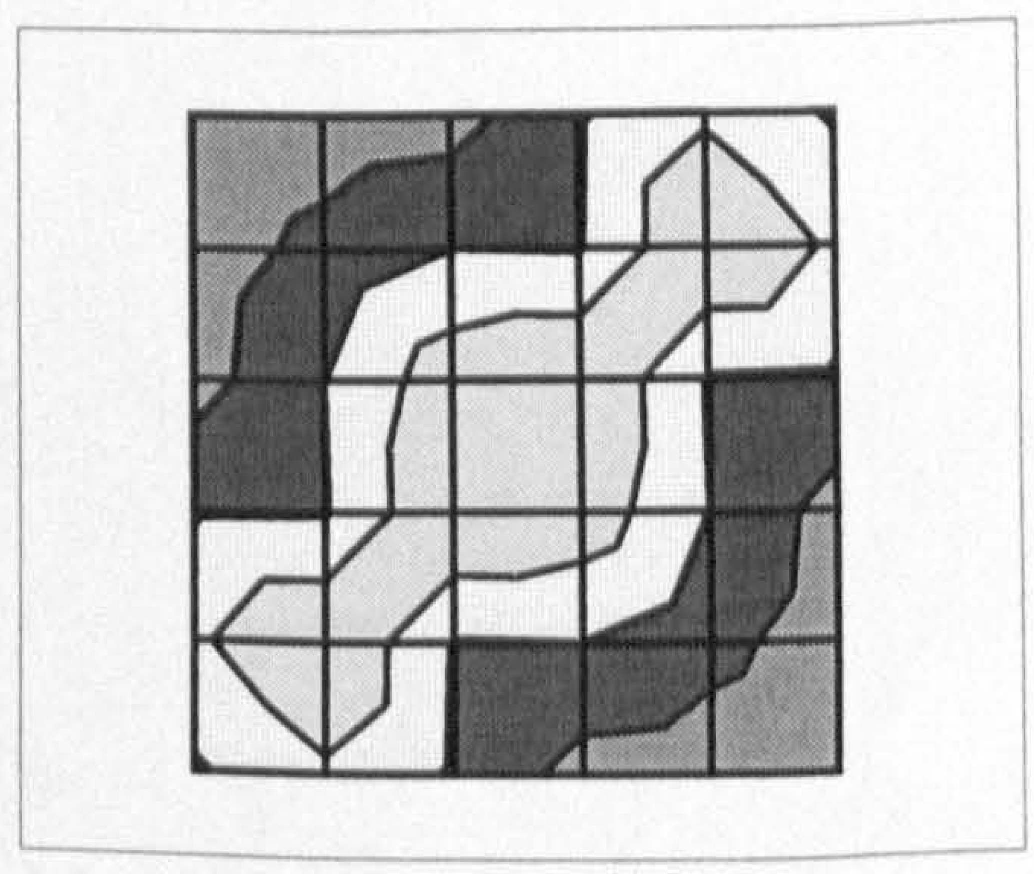
CRANE 1

	0	10	20	30	40	50
50	24.55	25.14	25.30	27.28	28.85	27.86
40	25.14	26.39	27.32	27.11	30.06	28.86
30	25.30	27.32	26.95	30.06	27.11	27.28
20	27.28	27.11	30.06	26.95	27.32	25.30
10	28.85	30.06	27.11	27.32	26.39	25.14
0	27.86	28.85	27.28	25.30	25.14	24.55



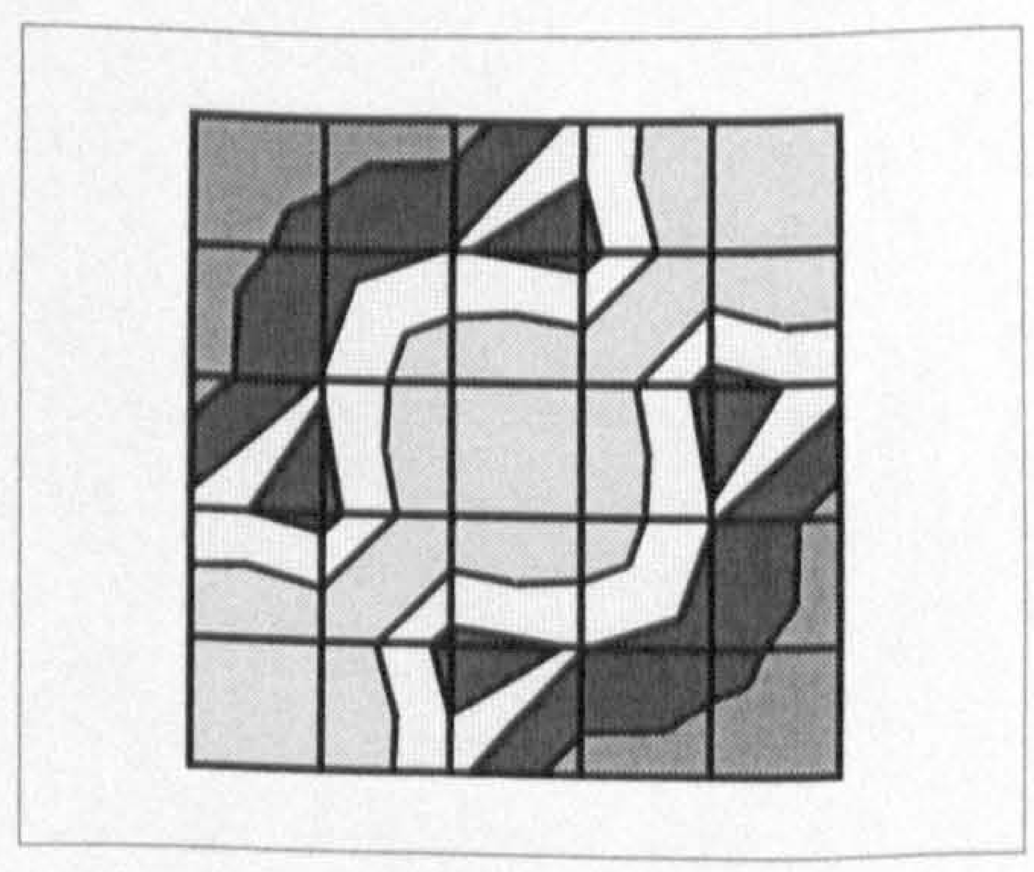
CRANE 2A

	0	10	20	30	40	50
50	88.33	88.99	89.19	91.20	92.67	91.19
40	88.99	90.34	91.37	91.28	94.43	92.67
30	89.19	91.37	93.86	94.43	91.28	91.20
20	91.20	91.28	94.43	93.86	91.37	89.19
10	92.67	94.43	91.28	91.37	90.34	88.99
0	91.19	92.67	91.20	89.19	88.99	88.33



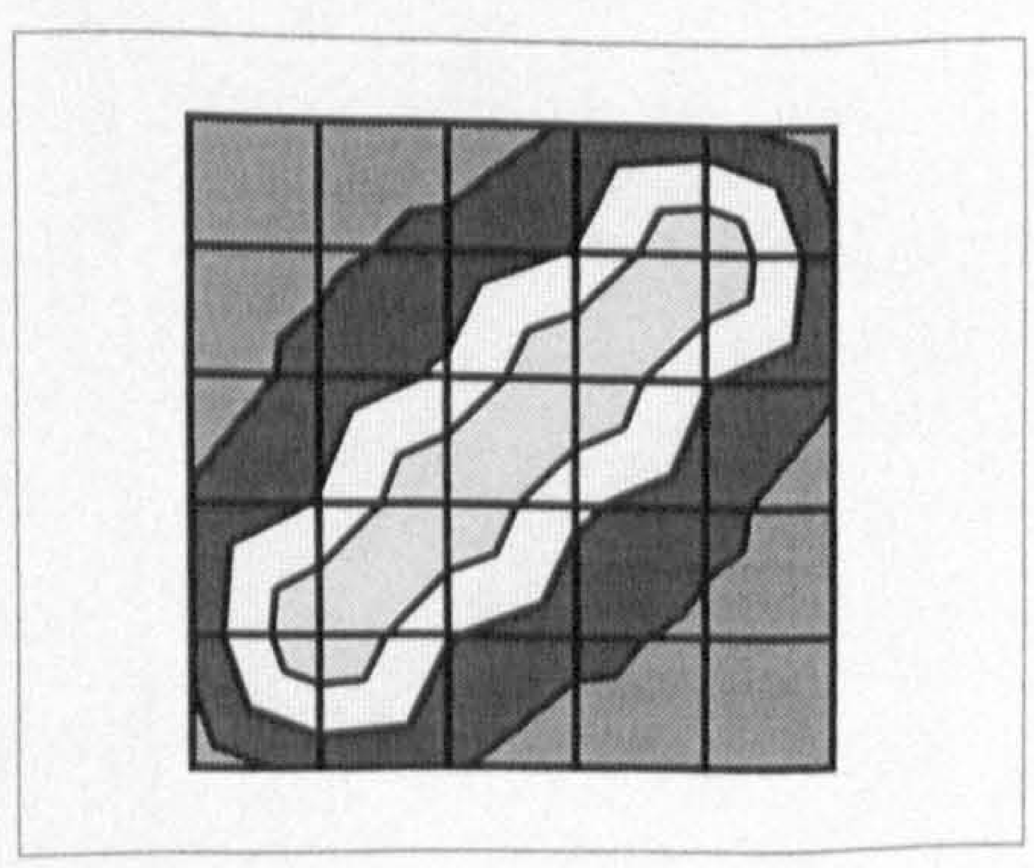
CRANE 2B

	0	10	20	30	40	50
50	90.64	91.58	91.68	95.57	99.12	99.05
40	91.58	93.65	95.09	94.22	99.29	99.12
30	91.68	95.09	99.12	99.29	94.22	95.57
20	95.57	94.22	99.29	99.12	95.09	91.68
10	99.12	99.29	94.22	95.09	93.65	91.58
0	99.05	99.12	95.57	91.68	91.58	90.64

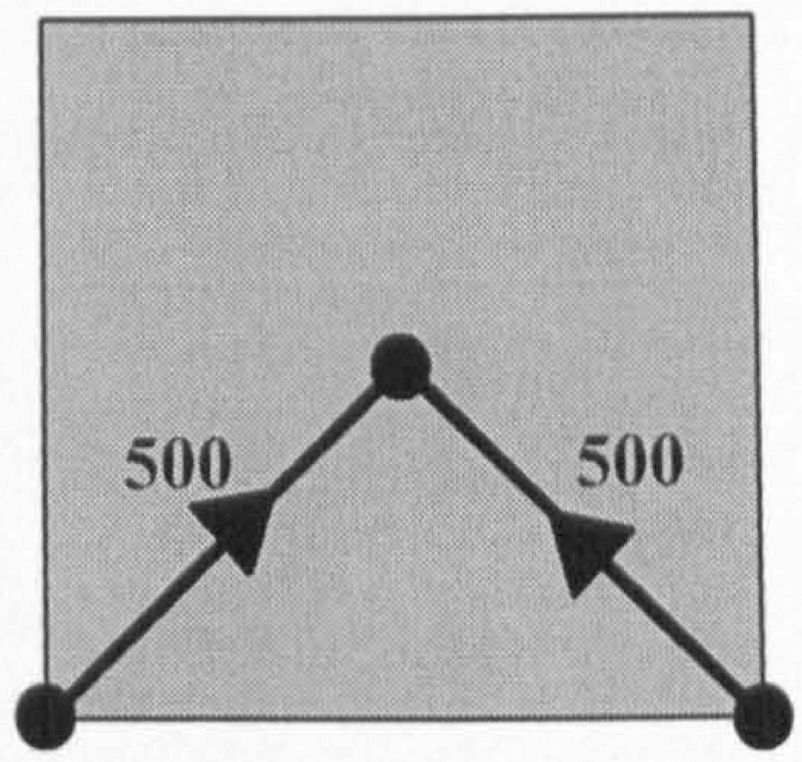


CRANE 3

	0	10	20	30	40	50
50	21.80	22.61	22.97	25.36	26.10	23.08
40	22.61	24.17	26.01	28.42	34.54	26.10
30	22.97	26.01	28.69	34.54	28.42	25.36
20	25.36	28.42	34.54	28.69	26.01	22.97
10	26.10	34.54	28.42	26.01	24.17	22.61
0	23.08	26.10	25.36	22.97	22.61	21.80

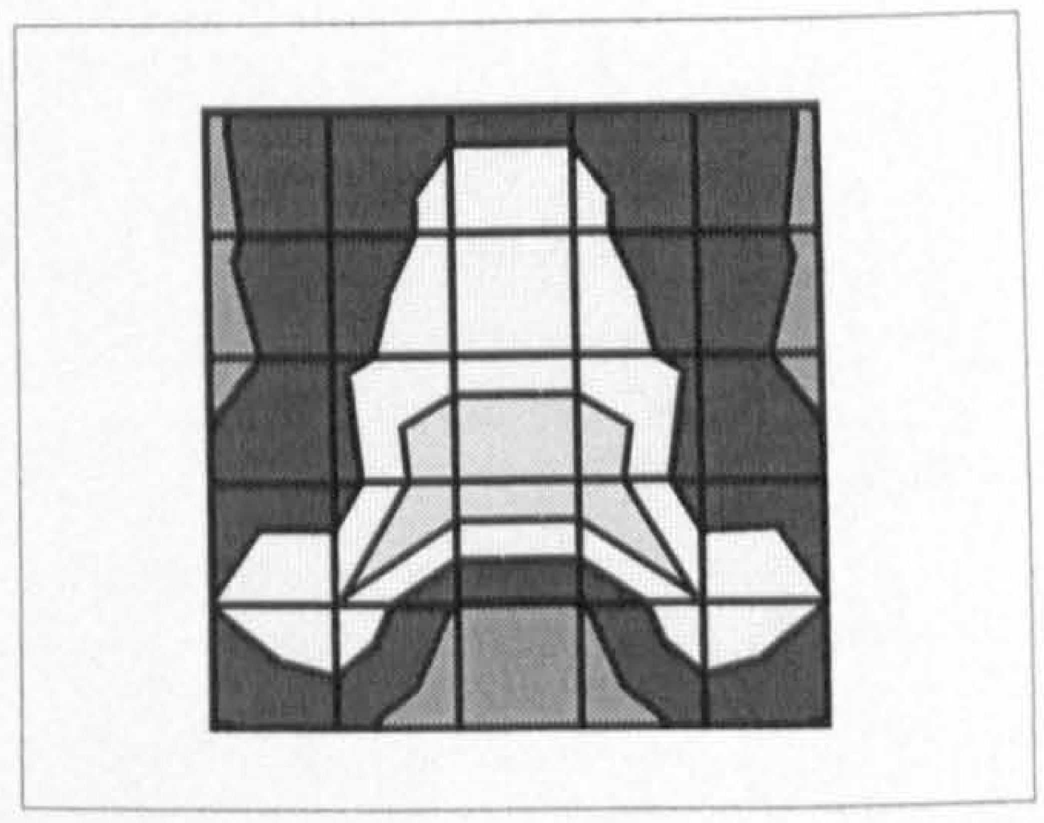


D.7 Layout 7



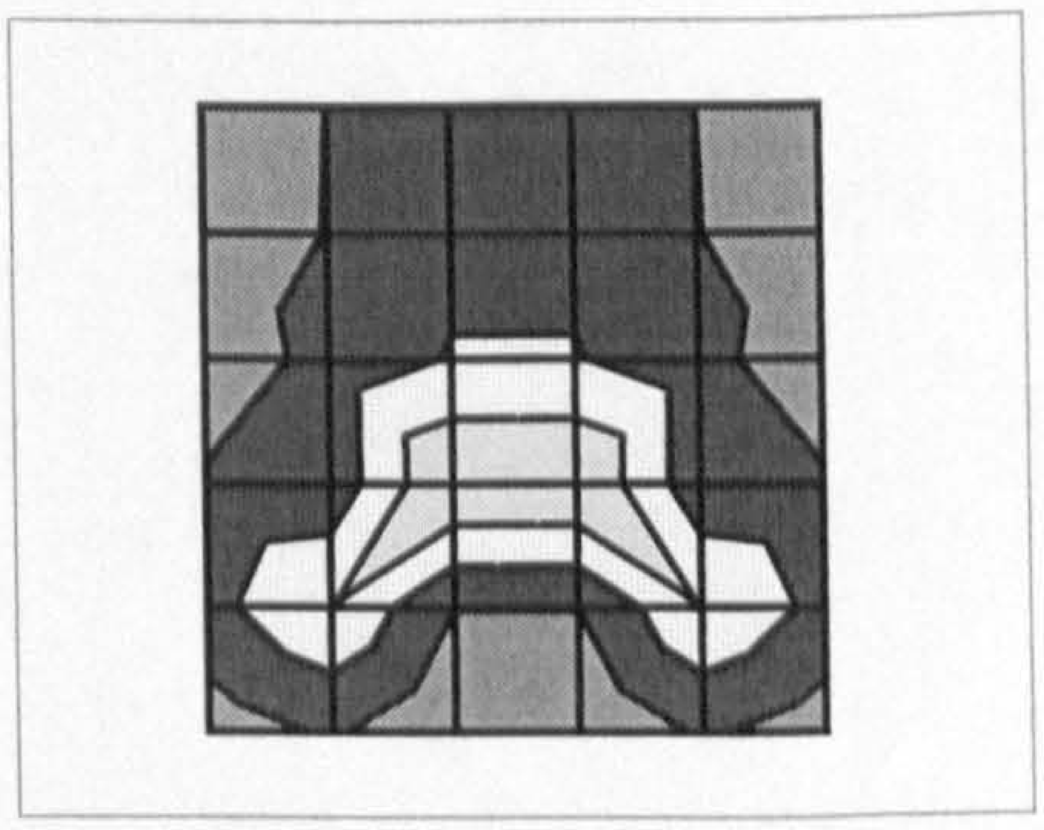
CRANE 1

	0	10	20	30	40	50
50	26.20	27.13	27.76	27.76	27.13	26.20
40	26.07	27.12	28.23	28.23	27.12	26.07
30	25.58	27.44	28.75	28.75	27.44	25.58
20	27.00	26.99	30.96	30.96	26.90	27.00
10	27.93	29.32	26.20	26.20	29.32	27.93
0	26.20	26.87	24.82	24.82	26.87	26.20



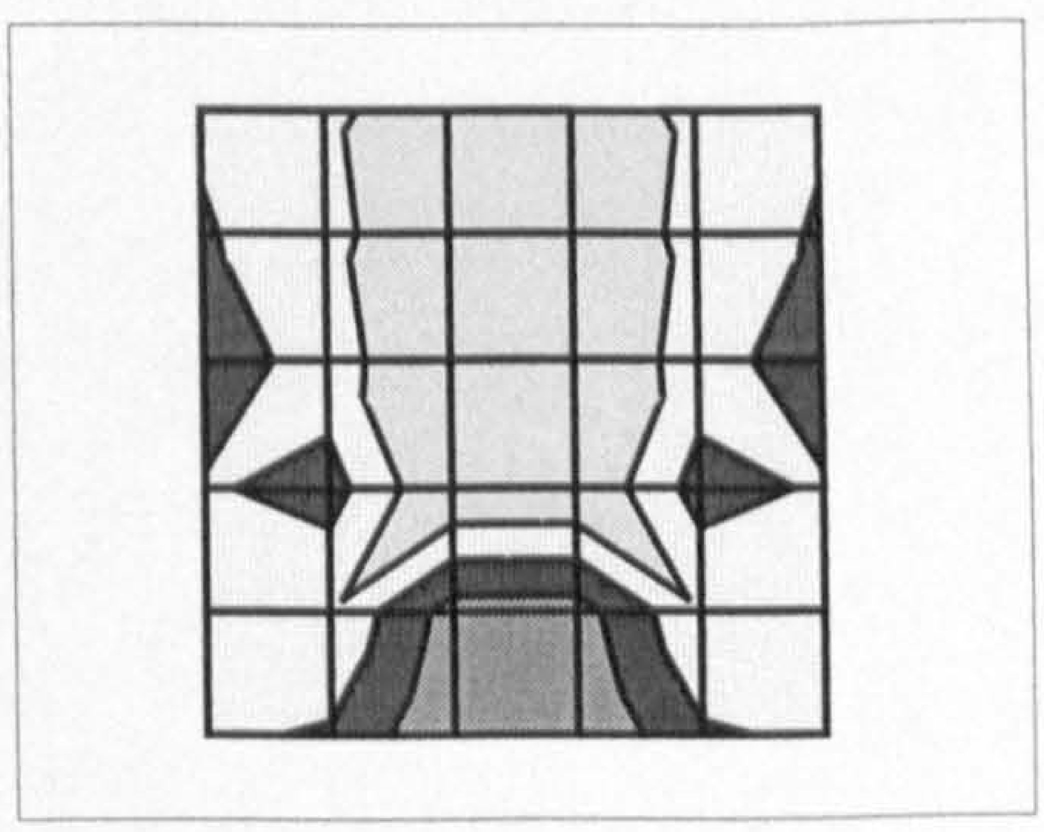
CRANE 2A

	0	10	20	30	40	50
50	89.76	90.72	91.36	91.36	90.72	89.76
40	89.74	90.76	91.90	91.90	90.76	89.74
30	89.41	91.35	92.53	92.53	91.35	89.41
20	90.98	91.30	95.77	95.77	91.30	90.98
10	91.92	94.01	90.75	90.75	94.01	91.92
0	89.76	90.93	89.03	89.03	90.93	89.76



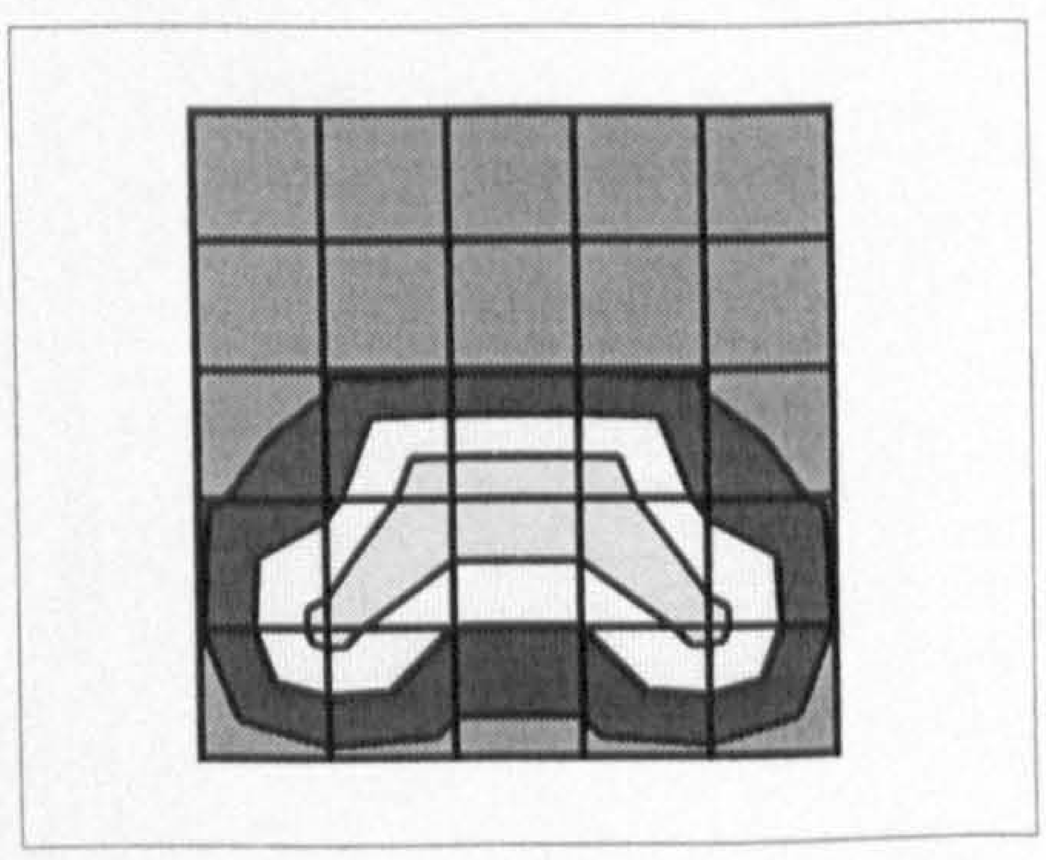
CRANE 2B

	0	10	20	30	40	50
50	94.84	96.57	97.74	97.74	96.57	94.84
40	94.13	96.35	98.43	98.43	96.35	94.13
30	92.52	95.89	99.08	99.08	95.89	92.52
20	94.72	93.42	99.32	99.32	93.42	94.72
10	96.57	96.59	90.88	90.88	96.59	96.57
0	94.84	94.13	89.50	89.50	94.12	94.84

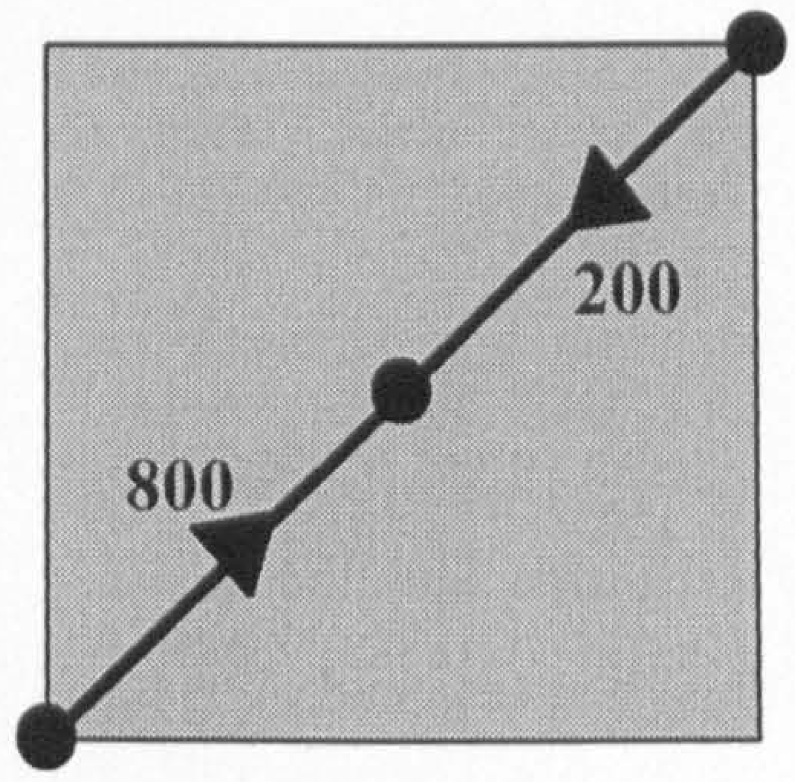


CRANE 3

	0	10	20	30	40	50
50	22.44	23.35	23.86	23.86	23.35	22.44
40	22.76	23.62	24.61	24.61	23.62	22.76
30	22.91	25.53	25.88	25.88	25.53	22.91
20	25.42	28.90	37.35	37.35	28.90	25.42
10	25.94	35.09	29.82	29.82	35.09	25.94
0	22.44	25.25	24.48	24.48	25.25	22.44

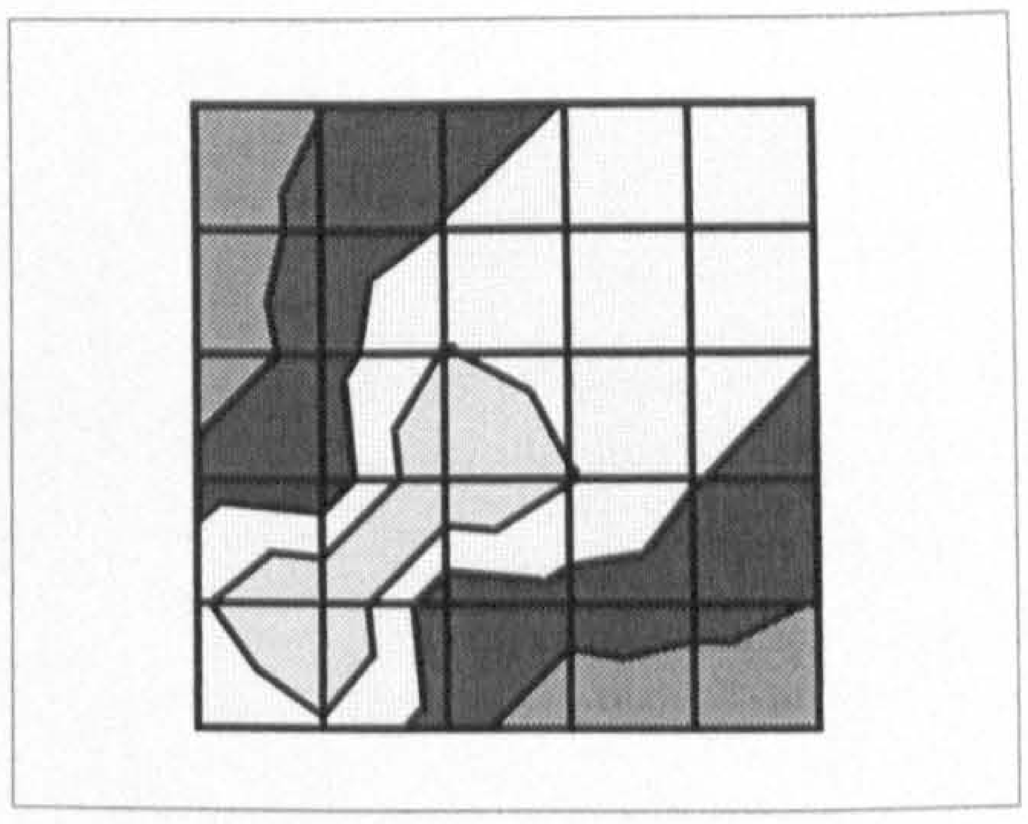


D.8 Layout 8



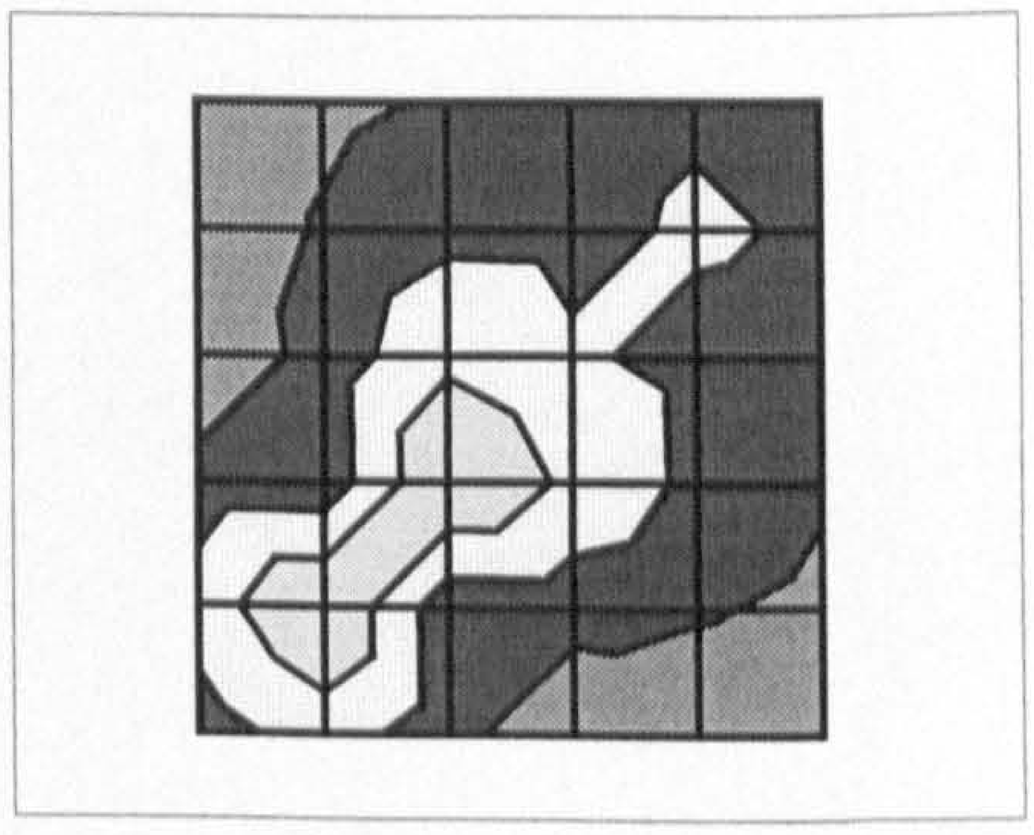
CRANE 1

50	24.55	25.78	26.60	27.74	28.38	27.86
40	24.50	26.39	27.80	27.85	28.74	28.38
30	23.99	26.84	29.65	28.74	27.85	27.74
20	26.83	26.37	31.38	29.65	27.80	26.60
10	29.33	31.38	26.37	26.84	26.39	25.78
0	27.86	29.33	26.83	23.99	24.50	24.55
	0	10	20	30	40	50



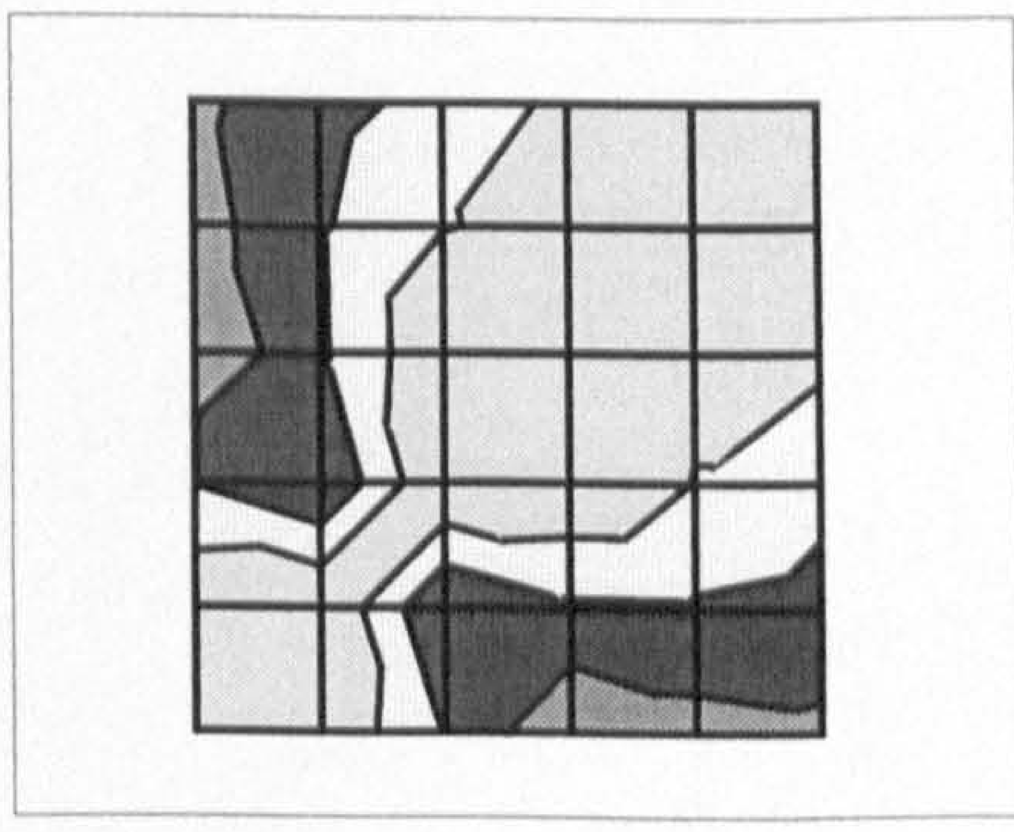
CRANE 2A

50	88.33	89.58	90.37	91.43	91.95	91.19
40	88.40	90.34	91.71	91.64	92.49	91.95
30	88.02	91.04	93.86	92.49	91.64	91.43
20	90.97	90.92	96.38	93.86	91.71	90.37
10	93.29	96.38	90.92	91.04	90.34	89.58
0	91.19	93.29	90.97	88.02	88.40	88.33
	0	10	20	30	40	50



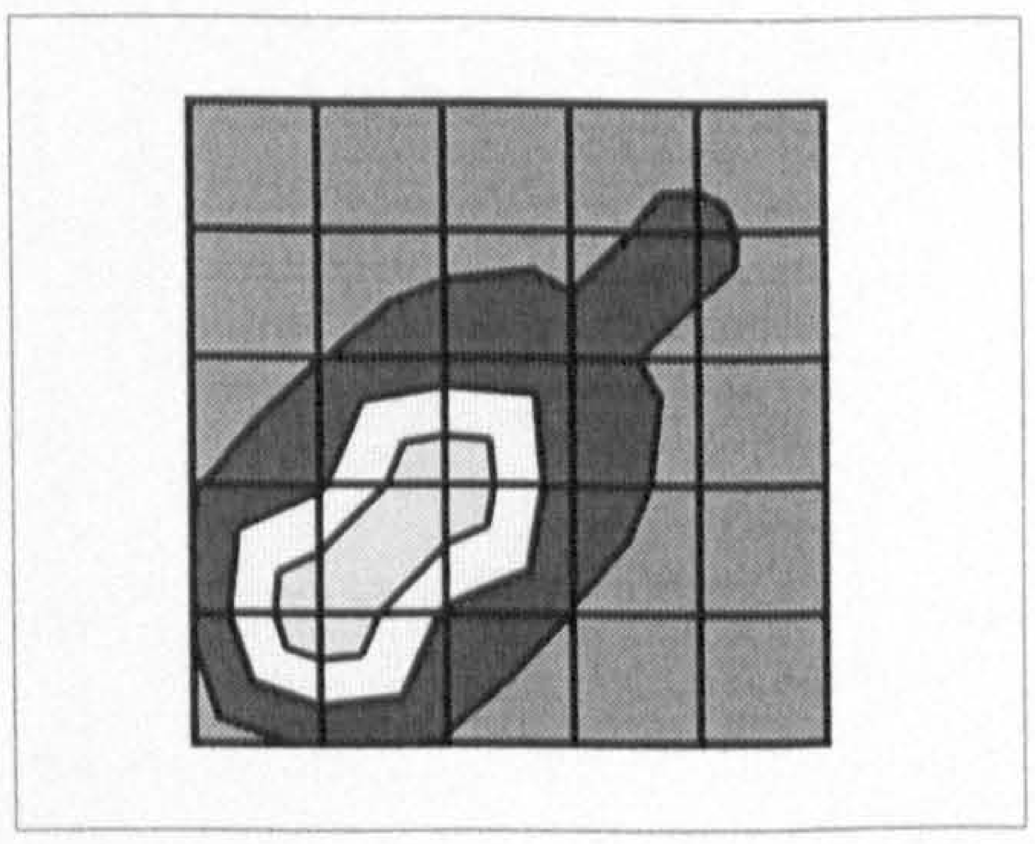
CRANE 2B

50	90.64	93.04	94.81	97.38	99.13	99.05
40	90.11	93.65	96.62	97.23	99.14	99.13
30	88.54	93.57	99.12	99.14	97.23	97.28
20	93.76	91.21	99.43	99.12	96.62	94.81
10	99.12	99.43	91.21	93.57	93.65	93.04
0	99.05	99.12	93.76	88.54	90.11	90.64
	0	10	20	30	40	50

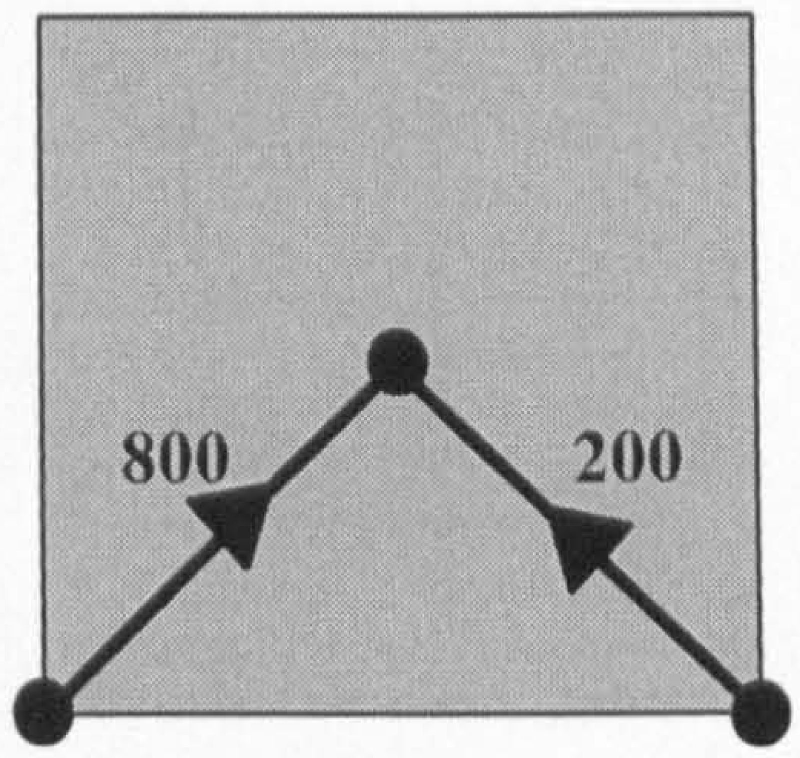


CRANE 3

50	21.80	22.96	23.54	24.42	24.54	23.08
40	22.25	24.17	25.47	25.84	27.66	24.54
30	22.40	26.56	28.69	27.66	25.84	24.42
20	26.30	30.99	41.42	28.69	25.47	23.54
10	27.65	41.42	30.99	26.56	24.17	22.96
0	23.08	27.65	26.30	22.40	22.25	21.80
	0	10	20	30	40	50

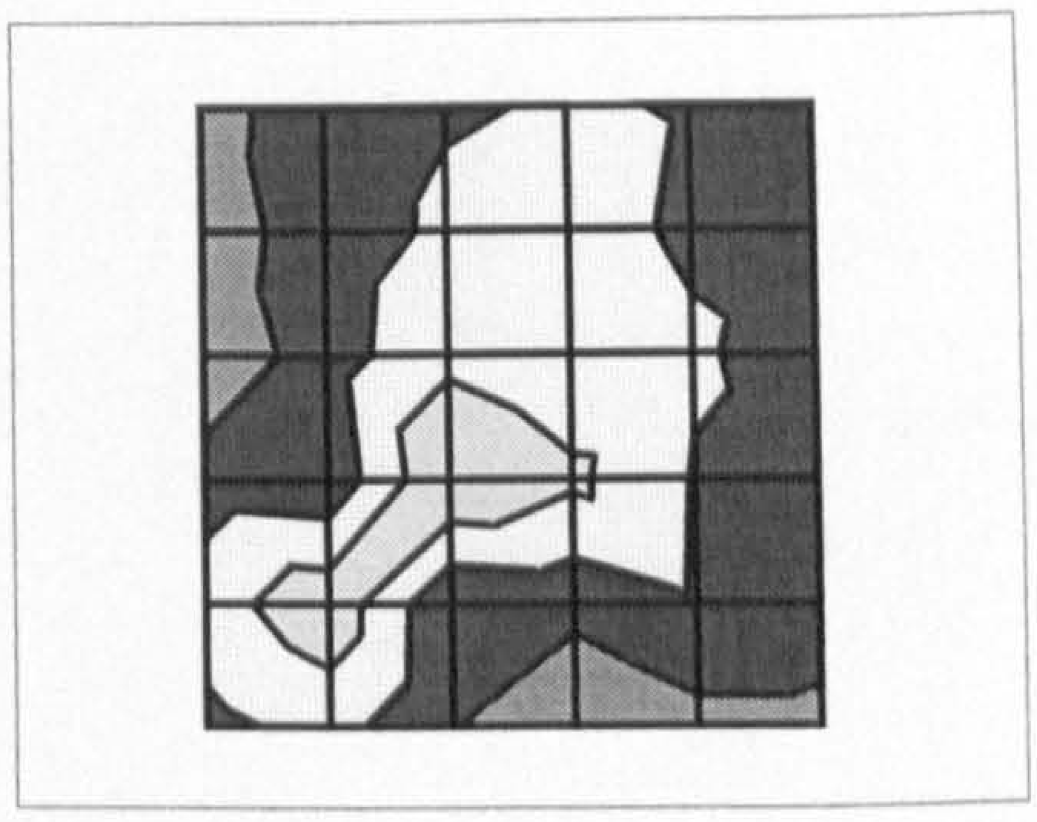


D.9 Layout 9



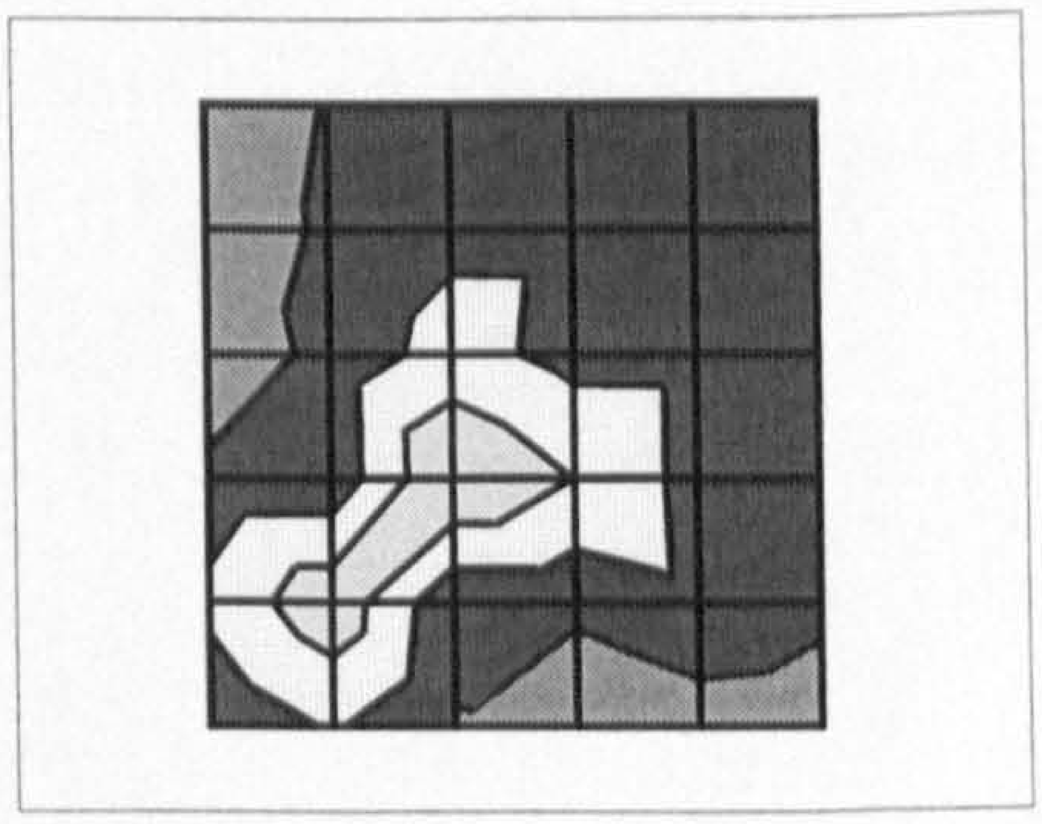
CRANE 1

	0	10	20	30	40	50
50	25.21	26.58	27.59	27.93	27.69	27.19
40	24.87	26.68	28.16	28.31	27.56	27.26
30	24.10	26.89	29.29	28.22	27.98	27.05
20	26.72	26.32	31.74	30.17	27.66	27.28
10	28.96	31.09	26.00	26.40	27.56	26.89
0	27.19	28.54	25.85	23.80	25.19	25.21



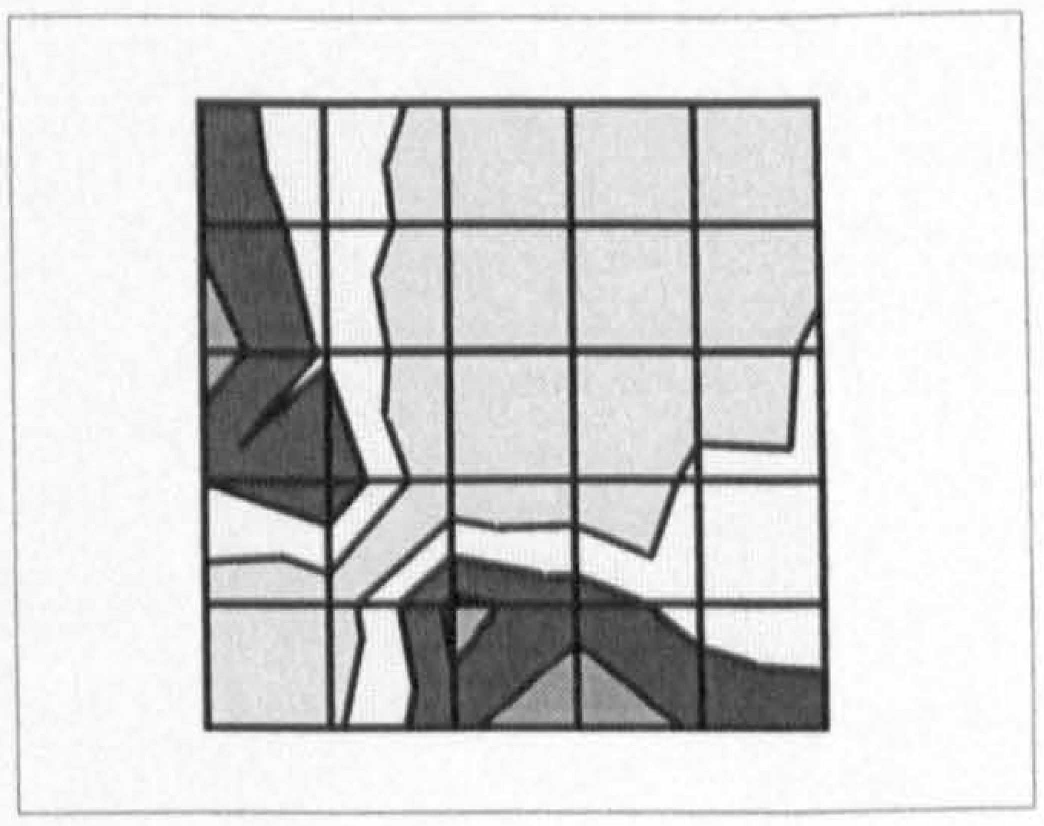
CRANE 2A

	0	10	20	30	40	50
50	88.89	90.27	91.24	91.49	91.17	90.62
40	88.70	90.51	91.92	91.89	91.02	90.78
30	88.10	91.03	93.33	91.72	91.67	90.71
20	90.88	90.93	96.91	94.63	91.68	91.08
10	93.08	96.21	90.70	90.79	91.80	90.75
0	90.62	92.69	90.10	87.95	89.17	88.90



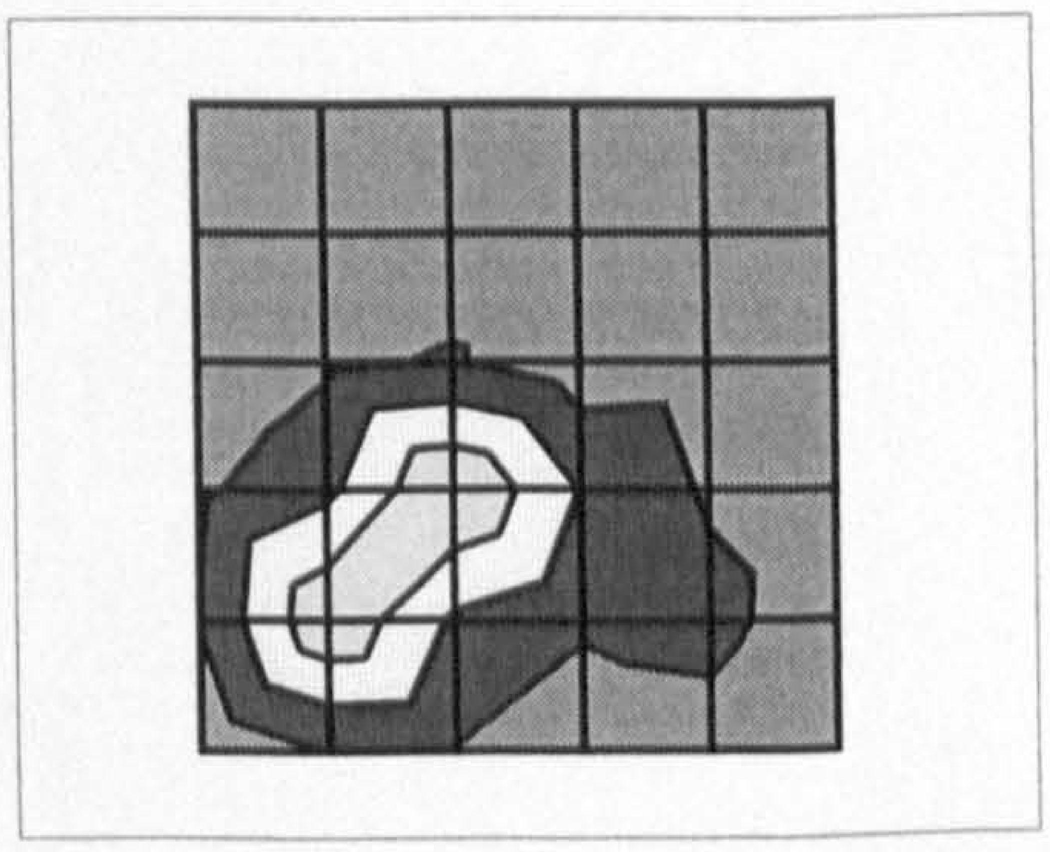
CRANE 2B

	0	10	20	30	40	50
50	92.32	95.04	97.24	98.25	98.11	97.36
40	91.13	94.73	97.95	98.92	97.97	97.13
30	88.88	93.89	99.10	99.06	97.90	96.16
20	93.42	90.89	99.44	99.20	95.95	96.03
10	98.10	98.35	89.88	91.88	94.83	95.04
0	97.36	97.12	91.33	87.67	91.13	92.32

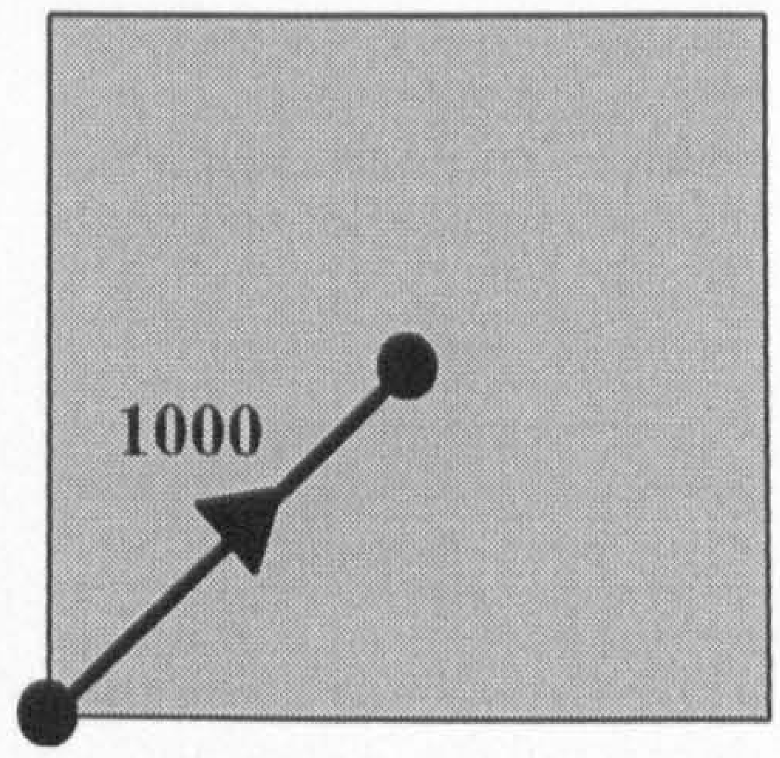


CRANE 3

	0	10	20	30	40	50
50	22.05	23.25	23.89	23.82	23.44	22.82
40	22.32	23.95	24.91	24.32	23.30	23.21
30	22.38	26.37	27.57	24.20	24.69	23.44
20	26.33	31.18	42.54	32.15	26.62	24.52
10	27.59	41.64	31.55	28.08	28.54	24.29
0	22.82	27.36	26.95	23.01	25.35	22.05

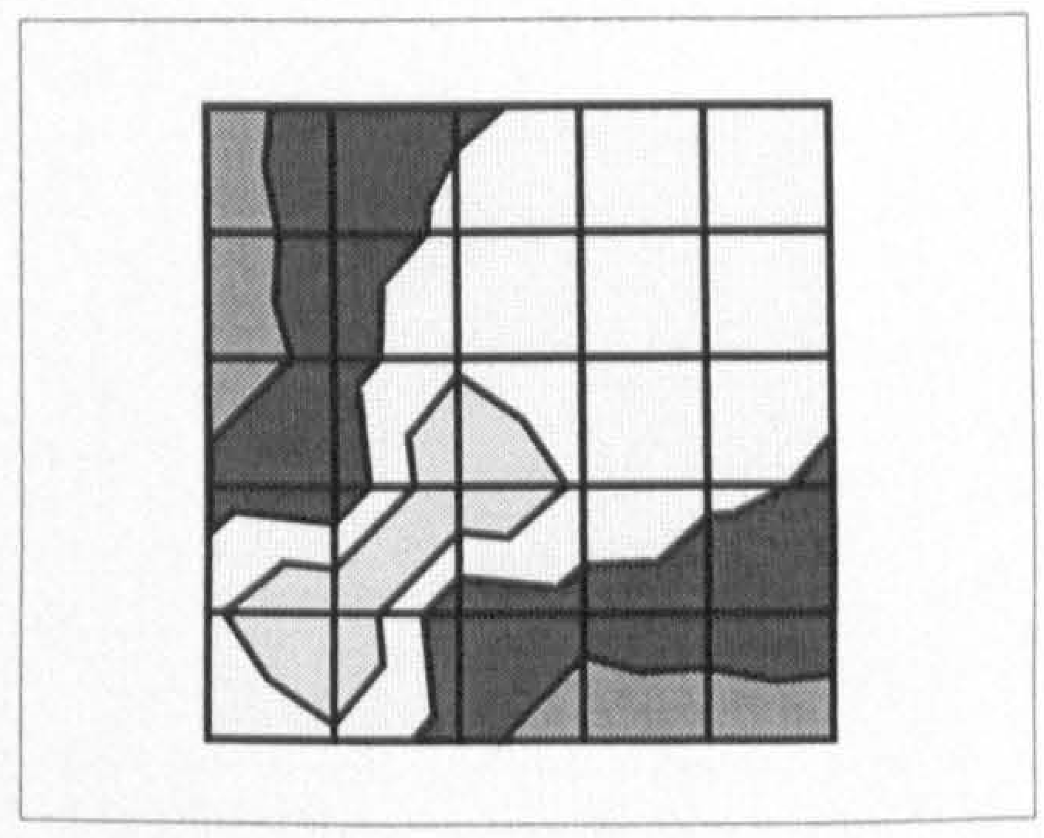


D.10 Layout 10



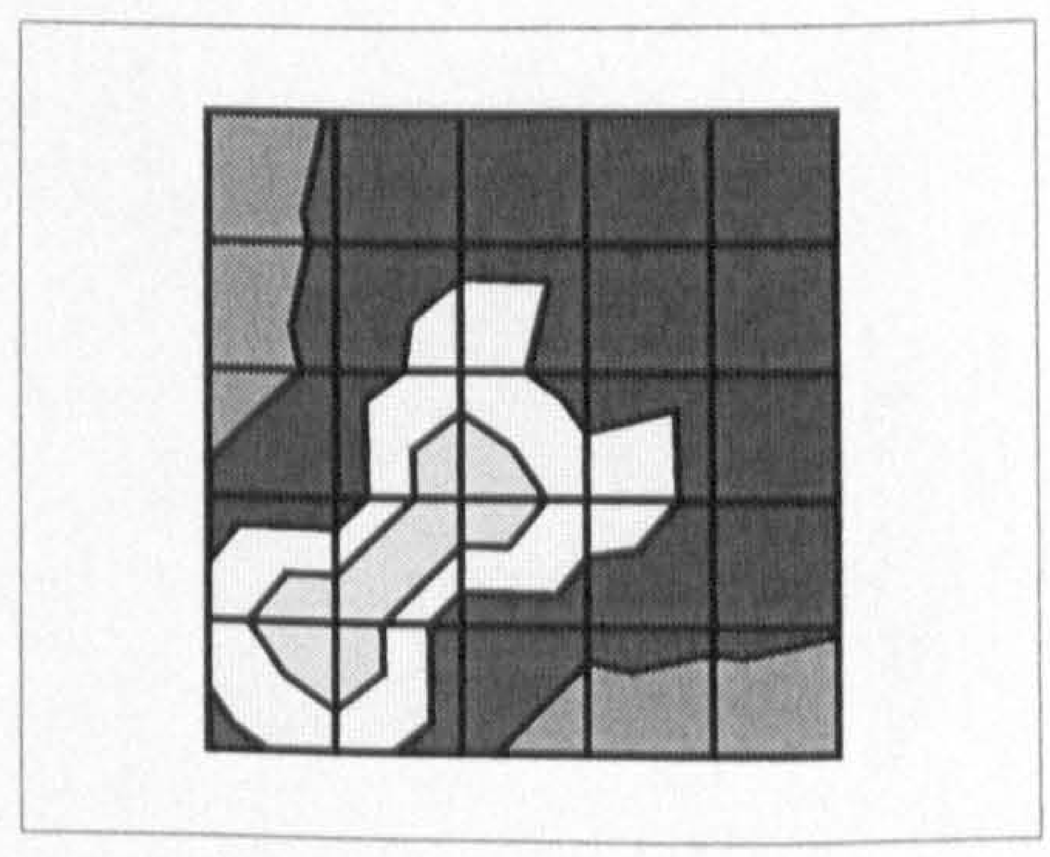
CRANE 1

50	24.55	26.21	27.47	28.04	28.06	27.86
40	24.08	26.39	28.11	28.35	27.86	28.06
30	23.12	26.53	29.65	27.86	28.35	28.04
20	26.53	25.87	32.26	29.65	28.11	27.47
10	29.65	32.26	25.87	26.53	26.39	26.21
0	27.86	29.65	26.53	23.12	24.08	24.55
	0	10	20	30	40	50



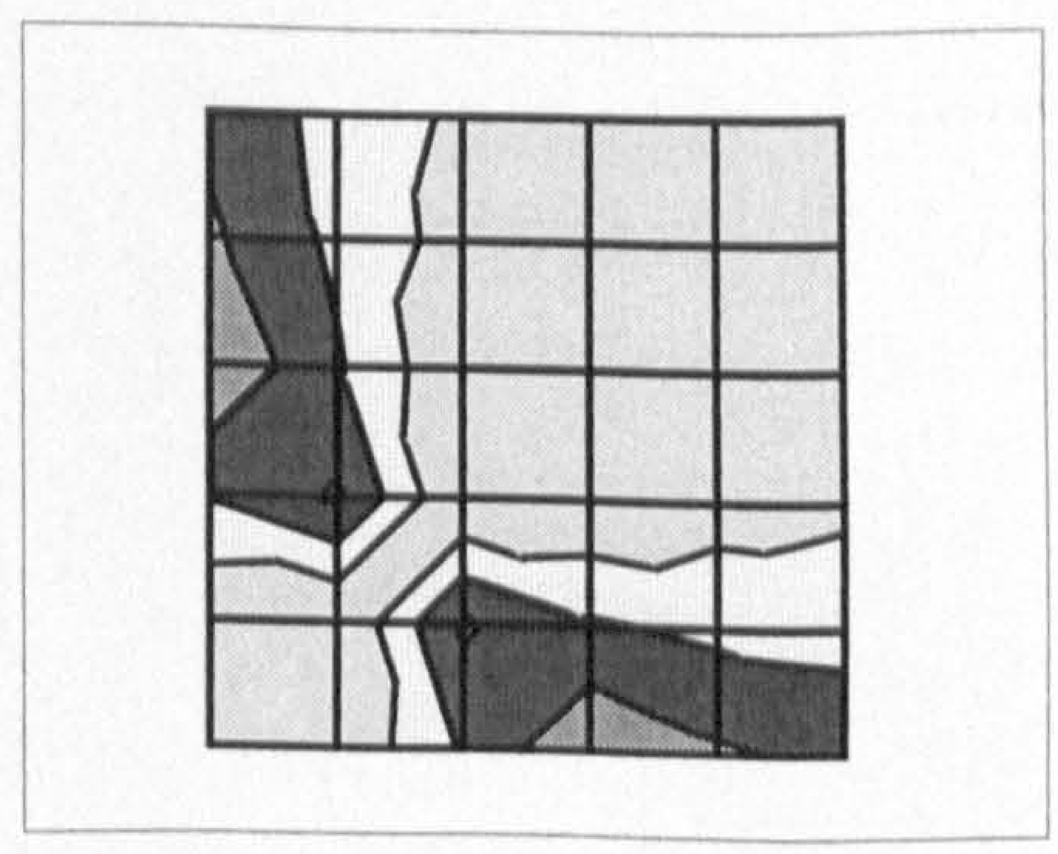
CRANE 2A

50	88.33	89.97	91.15	91.58	91.47	91.19
40	88.00	90.34	91.93	91.88	91.19	91.47
30	87.23	90.82	93.86	91.19	91.88	91.58
20	90.82	90.68	97.68	93.86	91.93	91.15
10	93.86	97.68	90.68	90.82	90.34	89.97
0	91.19	93.86	90.82	87.23	88.00	88.33
	0	10	20	30	40	50



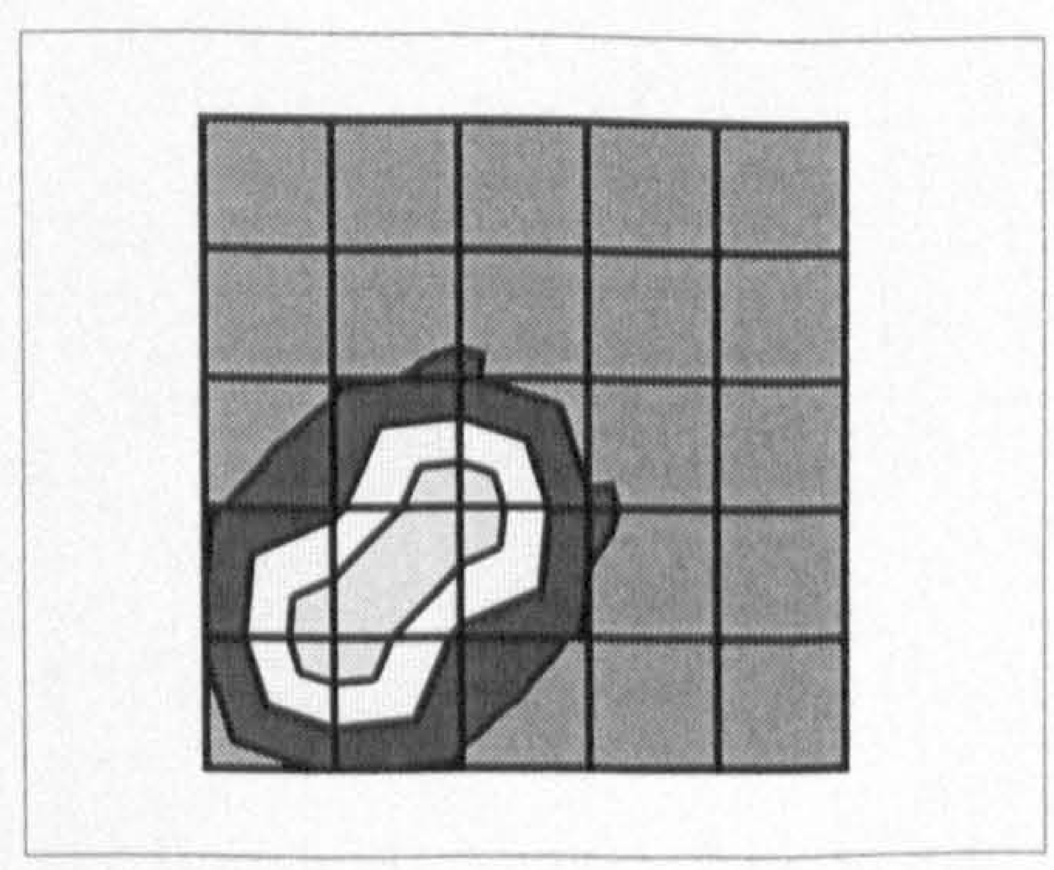
CRANE 2B

50	90.64	94.02	96.90	98.59	99.13	99.05
40	89.13	93.65	97.63	99.24	99.05	99.13
30	86.45	92.55	99.12	99.05	99.24	98.59
20	92.55	89.21	99.52	99.12	97.63	96.90
10	99.12	99.52	89.21	92.55	93.65	94.02
0	99.05	99.12	92.55	86.45	89.13	90.64
	0	10	20	30	40	50



CRANE 3

50	21.80	23.19	23.92	23.80	23.51	23.08
40	22.02	24.17	25.10	24.13	23.08	23.51
30	22.02	26.93	28.69	23.08	24.13	23.80
20	26.93	32.70	46.01	28.69	25.10	23.92
10	28.69	46.01	32.70	26.93	24.17	23.19
0	23.08	28.69	26.93	22.02	22.02	21.80
	0	10	20	30	40	50



APPENDIX E

SERIES B SIMULATIONS

The results of the Series B simulations are presented as follows, for each layout and for each crane at each height of the central moving facility between 0m and 30m in 5m increments:

- the minimum time (hours) to complete all movements
- the maximum time (hours) to complete all movements
- the absolute difference (hours) between the minimum and maximum times
- the difference between the minimum and maximum times, expressed as a percentage increase of the minimum time
- the co-ordinates of the crane associated with the minimum time
- the co-ordinates of the crane associated with the maximum time

E.1 Layout 1

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates				Maximum time co-ordinates			
0	14.69	20.30	5.61	38.19	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
5	16.08	21.69	5.61	34.89	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
10	17.47	23.08	5.61	32.11	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
15	19.20	24.47	5.27	27.45	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
20	21.28	25.86	4.58	21.52	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
25	23.58	27.65	4.07	17.26	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
30	26.20	29.86	3.66	13.97	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates				Maximum time co-ordinates			
0	25.62	32.34	6.72	26.23	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
5	32.76	38.13	5.37	16.39	(0,20) (0,30)	(20,0) (20,50)	(30,0) (30,50)	(50,20) (50,30)	(20,20)	(20,30)	(30,20)	(30,30)
10	43.46	47.85	4.39	10.10	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
15	55.04	59.43	4.39	7.98	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
20	66.61	71.00	4.39	6.59	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
25	78.18	82.57	4.39	5.62	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
30	89.76	94.15	4.39	4.89	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates								Maximum time co-ordinates			
0	32.96	41.90	8.94	27.12	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
5	39.51	47.69	8.18	20.70	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
10	48.20	54.29	6.09	12.63	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
15	58.90	64.48	5.58	9.47	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
20	70.47	76.06	5.59	7.93	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
25	82.05	87.63	5.58	6.80	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)
30	93.62	99.20	5.58	5.96	(0,20)	(0,30)	(20,0)	(20,50)	(30,0)	(30,50)	(50,20)	(50,30)	(20,20)	(20,30)	(30,20)	(30,30)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates				Maximum time co-ordinates			
0	14.36	25.04	10.68	74.37	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
5	15.46	26.14	10.68	69.08	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
10	16.55	27.23	10.68	64.53	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
15	17.65	28.33	10.68	60.51	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
20	19.15	29.42	10.27	53.63	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
25	20.79	30.52	9.73	46.80	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)
30	22.44	31.62	9.18	40.91	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(20,30)	(30,20)	(30,30)

E.2 Layout 2

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.18	21.03	7.85	59.56	(30,50)		(20,30)
5	14.57	22.42	7.85	53.88	(30,50)		(20,30)
10	15.95	23.81	7.86	49.28	(30,50)		(20,30)
15	17.86	25.19	7.33	41.04	(30,50)		(20,30)
20	20.22	26.58	6.36	31.45	(30,50)		(20,30)
25	22.75	28.30	5.55	24.40	(30,50)		(20,30)
30	25.50	30.24	4.74	18.59	(30,50)		(20,30)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	24.82	33.60	8.78	35.37	(0,0)	(50,50)	(20,30)
5	31.86	39.39	7.53	23.63	(30,50)		(20,30)
10	43.18	48.56	5.38	12.46	(0,0)	(50,50)	(20,30)
15	54.75	60.13	5.38	9.83	(0,0)	(50,50)	(20,30)
20	66.32	71.71	5.39	8.13	(0,0)	(50,50)	(20,30)
25	77.90	83.28	5.38	6.91	(0,0)	(50,50)	(20,30)
30	89.47	94.85	5.38	6.01	(0,0)	(50,50)	(20,30)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	28.88	42.60	13.72	47.51	(20,20)	(30,50)
5	35.86	48.39	12.53	34.94	(20,20)	(30,50)
10	45.70	54.81	9.11	19.93	(30,20)	(30,50)
15	56.86	64.54	7.68	13.51	(20,30)	(30,50)
20	68.44	76.12	7.68	11.22	(20,30)	(30,50)
25	80.01	87.69	7.68	9.60	(20,30)	(30,50)
30	91.58	99.27	7.69	8.40	(20,30)	(30,50)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	13.93	27.92	13.99	100.43	(0,0) (50,50)	(20,30)
5	15.03	29.01	13.98	93.01	(0,0) (50,50)	(20,30)
10	16.13	30.11	13.98	86.67	(0,0) (50,50)	(20,30)
15	17.22	31.21	13.99	81.24	(0,0) (50,50)	(20,30)
20	18.80	32.30	13.50	71.81	(0,0) (50,50)	(20,30)
25	20.56	33.40	12.84	62.45	(0,0) (50,50)	(20,30)
30	22.31	34.49	12.18	54.59	(0,0) (50,50)	(20,30)

E.3 Layout 3

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.39	20.72	7.33	54.74	(30,0)	(50,20)	(30,20)
5	14.78	22.11	7.33	49.59	(30,0)	(50,20)	(30,20)
10	16.17	23.50	7.33	45.33	(30,0)	(50,20)	(30,20)
15	18.01	24.89	6.88	38.20	(30,0)	(50,20)	(30,20)
20	20.33	26.28	5.95	29.27	(30,0)	(50,20)	(30,20)
25	22.93	28.21	5.28	23.03	(30,0)	(50,20)	(30,20)
30	25.65	30.52	4.87	18.99	(0,50)	(50,0)	(30,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	24.30	33.26	8.96	36.87	(0,50)	(50,0)	(30,20)
5	31.97	39.04	7.07	22.11	(30,0)	(50,20)	(30,20)
10	42.99	48.84	5.85	13.61	(0,50)	(50,0)	(30,20)
15	54.56	60.42	5.86	10.74	(0,50)	(50,0)	(30,20)
20	66.13	71.99	5.86	8.86	(0,50)	(50,0)	(30,20)
25	77.71	83.56	5.85	7.53	(0,50)	(50,0)	(30,20)
30	89.28	95.14	5.86	6.56	(0,50)	(50,0)	(30,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	29.42	43.07	13.65	46.40	(30,0)	(50,20)	(20,30)
5	36.23	48.86	12.63	34.86	(30,0)	(50,20)	(20,30)
10	45.88	54.64	8.76	19.09	(30,0)	(50,20)	(20,30)
15	57.25	64.53	7.28	12.72	(30,0)	(50,20)	(30,20)
20	68.28	76.11	7.83	11.47	(30,0)	(50,20)	(30,20)
25	80.39	87.68	7.29	9.07	(30,0)	(50,20)	(30,20)
30	91.97	99.25	7.28	7.92	(30,0)	(50,20)	(30,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.65	27.90	14.25	104.40	(0,50)	(50,0)	(30,20)
5	14.75	28.99	14.24	96.54	(0,50)	(50,0)	(30,20)
10	15.84	30.09	14.25	89.96	(0,50)	(50,0)	(30,20)
15	16.94	31.19	14.25	84.12	(0,50)	(50,0)	(30,20)
20	18.57	32.28	13.71	73.83	(0,50)	(50,0)	(30,20)
25	20.40	33.38	12.98	63.63	(0,50)	(50,0)	(30,20)
30	22.22	34.47	12.25	55.13	(0,50)	(50,0)	(30,20)

E.4 Layout 4

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	12.20	22.00	9.80	80.33	(20,0)	(50,30)	(30,20)
5	13.59	23.39	9.80	72.11	(20,0)	(50,30)	(30,20)
10	14.98	24.78	9.80	65.42	(20,0)	(50,30)	(30,20)
15	17.06	26.17	9.11	53.40	(20,0)	(50,30)	(30,20)
20	19.56	27.56	8.00	40.90	(20,0)	(50,30)	(30,20)
25	22.06	29.27	7.21	32.68	(20,0)	(50,30)	(30,20)
30	23.78	31.22	7.44	31.29	(20,0)	(50,30)	(30,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	24.12	35.41	11.29	46.81	(20,0)	(50,30)	(30,20)
5	31.23	41.20	9.97	31.92	(20,0)	(50,30)	(30,20)
10	42.52	49.86	7.34	17.26	(20,0)	(50,30)	(30,20)
15	54.10	61.43	7.33	13.55	(20,0)	(50,30)	(30,20)
20	65.67	73.00	7.33	11.16	(20,0)	(50,30)	(30,20)
25	77.24	84.58	7.34	9.50	(20,0)	(50,30)	(30,20)
30	88.82	96.15	7.33	8.25	(20,0)	(50,30)	(30,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	26.49	43.97	17.48	65.99	(20,0)	(50,30)	(20,30)
5	33.96	49.75	15.79	46.50	(20,0)	(50,30)	(20,30)
10	44.38	55.54	11.16	25.15	(20,0)	(50,30)	(20,30)
15	55.38	64.35	8.97	16.20	(20,0)	(50,30)	(30,20)
20	66.95	76.21	9.26	13.83	(20,0)	(50,30)	(30,20)
25	78.53	87.79	9.26	11.79	(20,0)	(50,30)	(30,20)
30	90.10	99.36	9.26	10.28	(20,0)	(50,30)	(30,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.93	32.54	18.61	133.60	(0,0)	(50,50)	(30,20)
5	15.03	33.60	18.57	123.55	(0,0)	(50,50)	(30,20)
10	16.13	34.70	18.57	115.13	(0,0)	(50,50)	(30,20)
15	17.22	35.79	18.57	107.84	(0,0)	(50,50)	(30,20)
20	18.80	36.89	18.09	96.22	(0,0)	(50,50)	(30,20)
25	20.55	37.98	17.43	84.82	(0,0)	(50,50)	(30,20)
30	22.31	39.08	16.77	75.17	(0,0)	(50,50)	(30,20)

E.5 Layout 5

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	11.71	22.00	10.29	87.87	(50,30)	(30,20)
5	13.10	23.39	10.29	78.55	(50,30)	(30,20)
10	14.49	24.78	10.29	71.01	(50,30)	(30,20)
15	16.60	26.17	9.57	57.65	(50,30)	(30,20)
20	19.24	27.56	8.32	43.24	(50,30)	(30,20)
25	21.88	29.27	7.39	33.78	(50,30)	(30,20)
30	24.63	31.22	6.59	26.76	(50,30)	(30,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	23.80	35.41	11.61	48.78	(50,30)	(30,20)
5	31.02	41.20	10.18	32.82	(50,30)	(30,20)
10	42.45	49.86	7.41	17.46	(50,30)	(30,20)
15	54.02	61.43	7.41	13.72	(50,30)	(30,20)
20	65.59	73.00	7.41	11.30	(50,30)	(30,20)
25	77.17	84.58	7.41	9.60	(50,30)	(30,20)
30	88.74	96.15	7.41	8.35	(50,30)	(30,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	24.98	43.97	18.99	76.02	(50,30)	(20,30)
5	32.49	49.75	17.26	53.12	(50,30)	(20,30)
10	43.48	55.54	12.06	27.74	(50,30)	(20,30)
15	54.77	64.64	9.87	18.02	(50,30)	(30,20)
20	66.35	76.21	9.86	14.86	(50,30)	(30,20)
25	77.92	87.79	9.87	12.67	(50,30)	(30,20)
30	89.50	99.36	9.86	11.02	(50,30)	(30,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.93	32.50	18.57	133.31	(0,0)	(50,50)	(30,20)
5	15.03	33.60	18.57	123.55	(0,0)	(50,50)	(30,20)
10	16.13	34.70	18.57	115.13	(0,0)	(50,50)	(30,20)
15	17.22	35.79	18.57	107.84	(0,0)	(50,50)	(30,20)
20	18.80	36.89	18.09	96.22	(0,0)	(50,50)	(30,20)
25	20.55	37.98	17.43	84.82	(0,0)	(50,50)	(30,20)
30	22.31	39.08	16.77	75.17	(0,0)	(50,50)	(30,20)

E.6 Layout 6

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates			
0	10.64	21.49	10.85	101.97	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
5	12.02	22.88	10.86	90.35	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
10	13.43	24.27	10.84	80.71	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
15	16.21	25.65	9.44	58.24	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
20	18.99	27.04	8.05	42.39	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
25	21.77	28.43	6.66	30.59	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
30	24.55	30.06	5.51	22.44	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates			
0	21.64	34.13	12.49	57.72	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
5	30.46	39.91	9.45	31.02	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
10	42.03	48.14	6.11	14.54	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
15	53.60	59.71	6.11	11.40	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
20	65.18	71.29	6.11	9.37	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
25	76.75	82.86	6.11	7.96	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
30	88.33	94.43	6.10	6.91	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates			
0	26.70	45.32	18.62	69.74	(0,50)	(50,0)	(0,0)	(50,50)		
5	32.76	51.10	18.34	55.98	(0,50)	(50,0)	(0,0)	(50,50)		
10	44.34	56.89	12.55	28.30	(0,50)	(50,0)	(0,0)	(50,50)		
15	55.91	64.56	8.65	15.47	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
20	67.49	76.14	8.65	12.82	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
25	79.06	87.71	8.65	10.94	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
30	90.64	99.29	8.65	9.54	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates			
0	12.22	27.97	15.75	128.89	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
5	13.32	29.06	15.74	118.17	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
10	14.41	30.16	15.75	109.30	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
15	15.51	31.25	15.74	101.48	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
20	17.41	32.35	14.94	85.81	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
25	19.61	33.45	13.84	70.58	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)
30	21.80	34.54	12.74	58.44	(0,50)	(50,0)	(10,10)	(20,20)	(30,30)	(40,40)

E.7 Layout 7

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	11.63	21.52	9.89	85.04	(20,0)	(30,0)	(20,20)	(30,20)
5	13.02	22.91	9.89	75.96	(20,0)	(30,0)	(20,20)	(30,20)
10	14.41	24.30	9.89	68.63	(20,0)	(30,0)	(20,20)	(30,20)
15	16.49	25.69	9.20	55.79	(20,0)	(30,0)	(20,20)	(30,20)
20	19.27	27.08	7.81	40.53	(20,0)	(30,0)	(20,20)	(30,20)
25	22.05	28.87	6.82	30.93	(20,0)	(30,0)	(20,20)	(30,20)
30	24.82	30.96	6.14	24.74	(20,0)	(30,0)	(20,20)	(30,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	23.93	34.60	10.67	44.59	(20,0)	(30,0)	(20,20)	(30,20)
5	31.16	40.39	9.23	29.62	(20,0)	(30,0)	(20,20)	(30,20)
10	42.73	49.47	6.74	15.77	(20,0)	(30,0)	(20,20)	(30,20)
15	54.30	61.05	6.75	12.43	(20,0)	(30,0)	(20,20)	(30,20)
20	65.88	72.62	6.74	10.23	(20,0)	(30,0)	(20,20)	(30,20)
25	77.45	84.20	6.75	8.72	(20,0)	(30,0)	(20,20)	(30,20)
30	89.03	95.77	6.74	7.57	(20,0)	(30,0)	(20,20)	(30,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	24.31	43.63	19.32	79.47	(20,0)	(30,0)	(20,30)	(30,30)
5	31.63	49.42	17.79	56.24	(20,0)	(30,0)	(20,30)	(30,30)
10	43.21	55.20	11.99	27.75	(20,0)	(30,0)	(20,30)	(30,30)
15	54.78	64.60	9.82	17.93	(20,0)	(30,0)	(20,20)	(30,20)
20	66.35	76.17	9.82	14.80	(20,0)	(30,0)	(20,20)	(30,20)
25	77.93	87.75	9.82	12.60	(20,0)	(30,0)	(20,20)	(30,20)
30	89.50	99.32	9.82	10.97	(20,0)	(30,0)	(20,20)	(30,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates				Maximum time co-ordinates	
0	14.36	30.77	16.41	114.28	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
5	15.46	31.87	16.41	106.14	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
10	16.55	32.96	16.41	99.15	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
15	17.65	34.06	16.41	92.97	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
20	19.15	35.16	16.01	83.60	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
25	20.79	36.25	15.46	74.36	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)
30	22.44	37.35	14.91	66.44	(0,0)	(0,50)	(50,0)	(50,50)	(20,20)	(30,20)

E.8 Layout 8

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	10.62	22.95	12.33	116.10	(0,40)	(40,0)	(10,10)	(20,20)
5	12.01	24.34	12.33	102.66	(0,40)	(40,0)	(10,10)	(20,20)
10	13.43	25.73	12.30	91.59	(0,50)	(50,0)	(10,10)	(20,20)
15	16.04	27.12	11.08	69.08	(0,30)	(30,0)	(10,10)	(20,20)
20	18.54	28.51	9.97	53.78	(0,30)	(30,0)	(10,10)	(20,20)
25	21.21	29.90	8.69	40.97	(0,30)	(30,0)	(10,10)	(20,20)
30	23.99	31.38	7.39	30.80	(0,30)	(30,0)	(10,10)	(20,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	21.64	36.84	15.20	70.24	(0,50)	(50,0)	(10,10)	(20,20)
5	30.21	42.63	12.42	41.11	(0,30)	(30,0)	(10,10)	(20,20)
10	41.72	50.08	8.36	20.04	(0,30)	(30,0)	(10,10)	(20,20)
15	53.29	61.66	8.37	15.71	(0,30)	(30,0)	(10,10)	(20,20)
20	64.87	73.23	8.36	12.89	(0,30)	(30,0)	(10,10)	(20,20)
25	76.44	84.81	8.37	10.95	(0,30)	(30,0)	(10,10)	(20,20)
30	88.02	96.38	8.36	9.50	(0,30)	(30,0)	(10,10)	(20,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	24.03	45.32	21.29	88.60	(0,30)	(30,0)	(0,0)	(50,50)
5	31.95	51.10	19.15	59.94	(0,30)	(30,0)	(0,0)	(50,50)
10	42.37	56.89	14.52	34.27	(0,30)	(30,0)	(0,0)	(50,50)
15	53.82	64.71	10.89	20.23	(0,30)	(30,0)	(10,10)	(20,20)
20	65.39	76.28	10.89	16.65	(0,30)	(30,0)	(10,10)	(20,20)
25	76.97	87.85	10.88	14.14	(0,30)	(30,0)	(10,10)	(20,20)
30	88.54	99.43	10.89	12.30	(0,30)	(30,0)	(10,10)	(20,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	12.22	34.84	22.62	185.11	(0,50)	(50,0)	(10,10)	(20,20)
5	13.32	35.94	22.62	169.82	(0,50)	(50,0)	(10,10)	(20,20)
10	14.41	37.04	22.63	157.04	(0,50)	(50,0)	(10,10)	(20,20)
15	15.51	38.13	22.62	145.84	(0,50)	(50,0)	(10,10)	(20,20)
20	17.41	39.23	21.82	125.33	(0,50)	(50,0)	(10,10)	(20,20)
25	19.60	40.33	20.73	105.77	(0,50)	(50,0)	(10,10)	(20,20)
30	21.80	41.42	19.62	90.00	(0,50)	(50,0)	(10,10)	(20,20)

E.9 Layout 9

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	10.40	22.97	12.57	120.87	(30,0)	(20,20)
5	11.79	24.35	12.56	106.53	(30,0)	(20,20)
10	13.17	25.74	12.57	95.44	(30,0)	(20,20)
15	15.47	27.13	11.66	75.37	(30,0)	(20,20)
20	18.24	28.52	10.28	56.36	(30,0)	(20,20)
25	21.02	30.07	9.05	43.05	(30,0)	(20,20)
30	23.80	31.74	7.94	33.36	(30,0)	(20,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates	Maximum time co-ordinates
0	22.58	37.03	14.45	63.99	(30,0)	(20,20)
5	30.08	42.82	12.74	42.35	(30,0)	(20,20)
10	41.65	50.62	8.97	21.54	(30,0)	(20,20)
15	53.23	62.19	8.96	16.83	(30,0)	(20,20)
20	64.80	73.77	8.97	13.84	(30,0)	(20,20)
25	76.38	85.34	8.96	11.73	(30,0)	(20,20)
30	87.95	96.91	8.96	10.19	(30,0)	(20,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	21.80	44.64	22.84	104.77	(30,0)		(30,30)
5	29.80	50.43	20.63	69.23	(30,0)		(30,30)
10	41.38	56.21	14.83	35.84	(30,0)		(30,30)
15	52.95	64.72	11.77	22.23	(30,0)		(20,20)
20	64.52	76.29	11.77	18.24	(30,0)		(20,20)
25	76.10	87.87	11.77	15.47	(30,0)		(20,20)
30	87.67	99.44	11.77	13.43	(30,0)		(20,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates
0	13.08	35.97	22.89	175.00	(0,50)	(50,0)	(20,20)
5	14.17	37.06	22.89	161.54	(0,50)	(50,0)	(20,20)
10	15.27	38.16	22.89	149.90	(0,50)	(50,0)	(20,20)
15	16.37	39.26	22.89	139.83	(0,50)	(50,0)	(20,20)
20	18.11	40.35	22.24	122.81	(0,50)	(50,0)	(20,20)
25	20.08	41.45	21.37	106.42	(0,50)	(50,0)	(20,20)
30	22.05	42.54	20.49	92.93	(0,50)	(50,0)	(20,20)

E.10 Layout 10

Crane1

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	9.57	23.93	14.36	150.05	(0,30)	(30,0)	(10,10)	(20,20)
5	10.96	25.32	14.36	131.02	(0,30)	(30,0)	(10,10)	(20,20)
10	12.35	26.71	14.36	116.28	(0,30)	(30,0)	(10,10)	(20,20)
15	14.79	28.10	13.31	89.99	(0,30)	(30,0)	(10,10)	(20,20)
20	17.56	29.48	11.92	67.88	(0,30)	(30,0)	(10,10)	(20,20)
25	20.34	30.87	10.53	51.77	(0,30)	(30,0)	(10,10)	(20,20)
30	23.12	32.26	9.14	39.53	(0,30)	(30,0)	(10,10)	(20,20)

Crane2a

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	21.50	38.65	17.15	79.77	(0,40)	(40,0)	(10,10)	(20,20)
5	29.36	44.44	15.08	51.36	(0,30)	(30,0)	(10,10)	(20,20)
10	40.94	51.38	10.44	25.50	(0,30)	(30,0)	(10,10)	(20,20)
15	52.51	62.96	10.45	19.90	(0,30)	(30,0)	(10,10)	(20,20)
20	64.08	74.53	10.45	16.31	(0,30)	(30,0)	(10,10)	(20,20)
25	75.66	86.10	10.44	13.80	(0,30)	(30,0)	(10,10)	(20,20)
30	87.23	97.68	10.45	11.98	(0,30)	(30,0)	(10,10)	(20,20)

Crane2b

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	20.13	45.32	25.19	125.14	(0,30)	(30,0)	(0,0)	(50,50)
5	28.58	51.10	22.52	78.80	(0,30)	(30,0)	(0,0)	(50,50)
10	40.16	56.89	16.73	41.66	(0,30)	(30,0)	(0,0)	(50,50)
15	51.73	64.80	13.07	25.27	(0,30)	(30,0)	(10,10)	(20,20)
20	63.30	76.38	13.08	20.66	(0,30)	(30,0)	(10,10)	(20,20)
25	74.88	87.95	13.07	17.45	(0,30)	(30,0)	(10,10)	(20,20)
30	86.45	99.52	13.07	15.12	(0,30)	(30,0)	(10,10)	(20,20)

Crane3

Height of central facility	Minimum time (hours)	Maximum time (hours)	Maximum - Minimum	% increase	Minimum time co-ordinates		Maximum time co-ordinates	
0	12.22	39.43	27.21	222.67	(0,50)	(50,0)	(10,10)	(20,20)
5	13.32	40.53	27.21	204.28	(0,50)	(50,0)	(10,10)	(20,20)
10	14.41	41.62	27.21	188.83	(0,50)	(50,0)	(10,10)	(20,20)
15	15.51	42.72	27.21	175.44	(0,50)	(50,0)	(10,10)	(20,20)
20	17.41	43.82	26.41	151.69	(0,50)	(50,0)	(10,10)	(20,20)
25	19.61	44.92	25.31	129.07	(0,50)	(50,0)	(10,10)	(20,20)
30	21.80	46.01	24.21	111.06	(0,50)	(50,0)	(10,10)	(20,20)

APPENDIX F

SERIES C SIMULATIONS

The results of the Series C simulations are presented as follows:

- a diagrammatic representation of the layout

- a grid giving times (hours) to complete all the movements for 121 (less those where the moving facility coincides with a fixed facility) different positions of the moving central facility, based on 5m intervals within a 50m by 50m grid. The horizontal axis represents the x axis and the vertical axis represents the y axis. The co-ordinates associated with the lowest and highest minimum times to complete all movements are annotated as follows:

  co-ordinates associated with lowest minimum time

  co-ordinates associated with the highest minimum time

  Note that where more than one set of moving facility co-ordinates associated with any layout, only one solution (and the corresponding crane position) is depicted graphically.

- a surface contour plot, based on the grid referred to above. Again, the horizontal axis represents the x axis and the vertical axis represents the y axis and the grid is 50m by 50m. The key is:

0% - 25% of the range from lowest minimum value to highest minimum value

25% - 50% of the range from lowest minimum value to highest minimum value

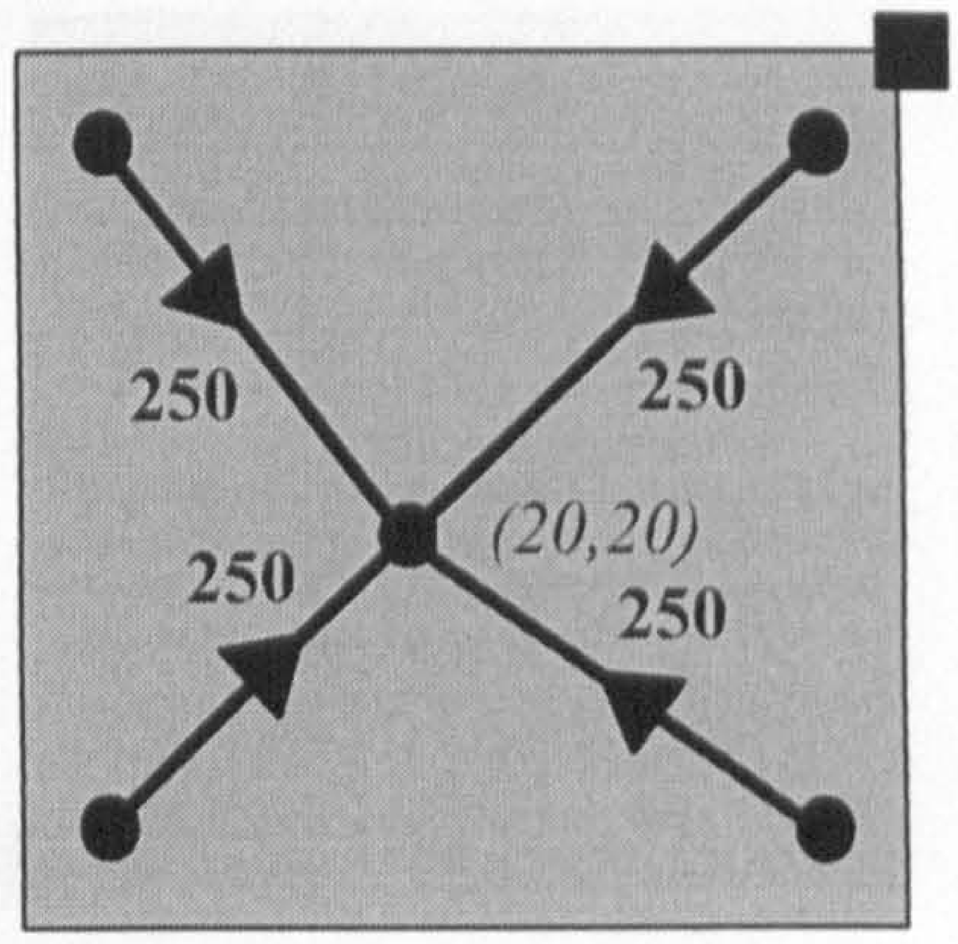
50% - 75% of the range from lowest minimum value to highest minimum value

75% - 100% of the range from lowest minimum value to highest minimum value

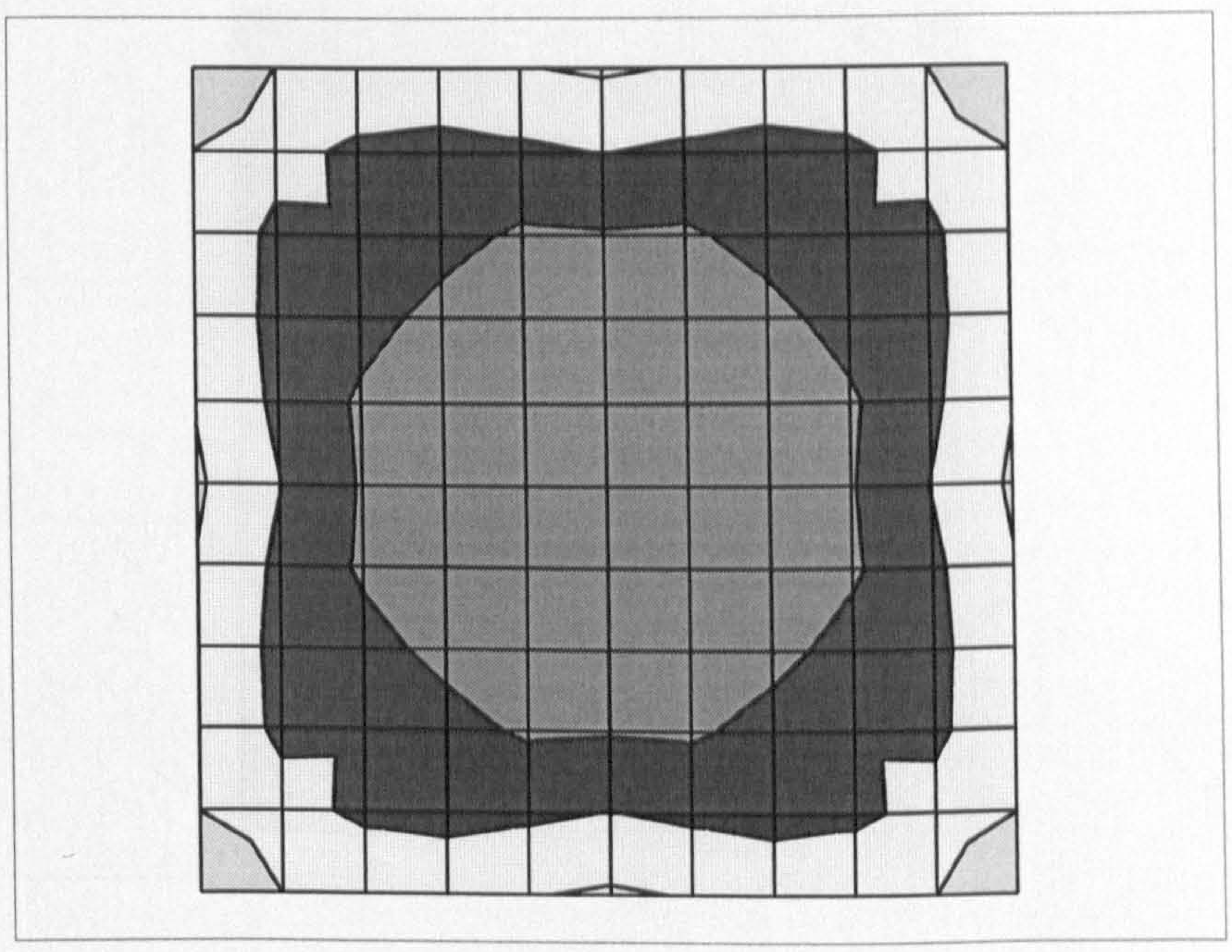
- a surface contour plot, based on the grid referred to above. Again, the horizontal axis represents the x axis and the vertical axis represents the y axis and the grid is 50m by 50m. The key is:

  - 0% - 25% of the range from lowest minimum value to highest minimum value
  - 25% - 50% of the range from lowest minimum value to highest minimum value
  - 50% - 75% of the range from lowest minimum value to highest minimum value
  - 75% - 100% of the range from lowest minimum value to highest minimum value

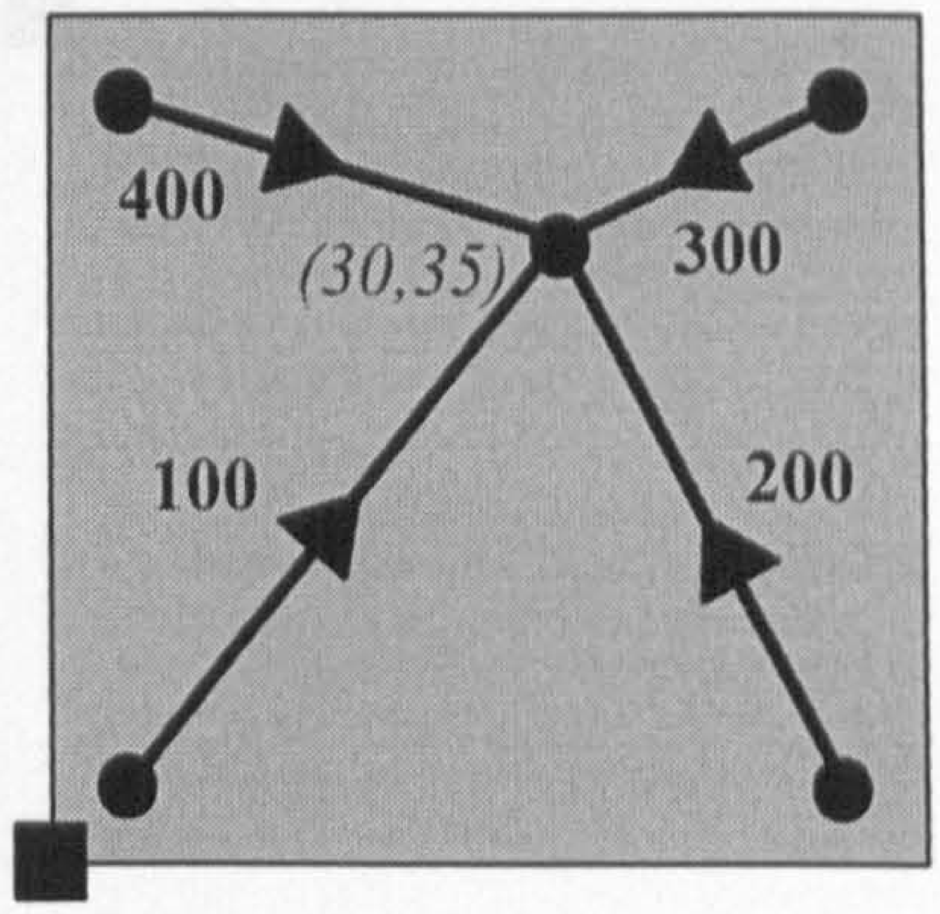
F.1 Layout 1



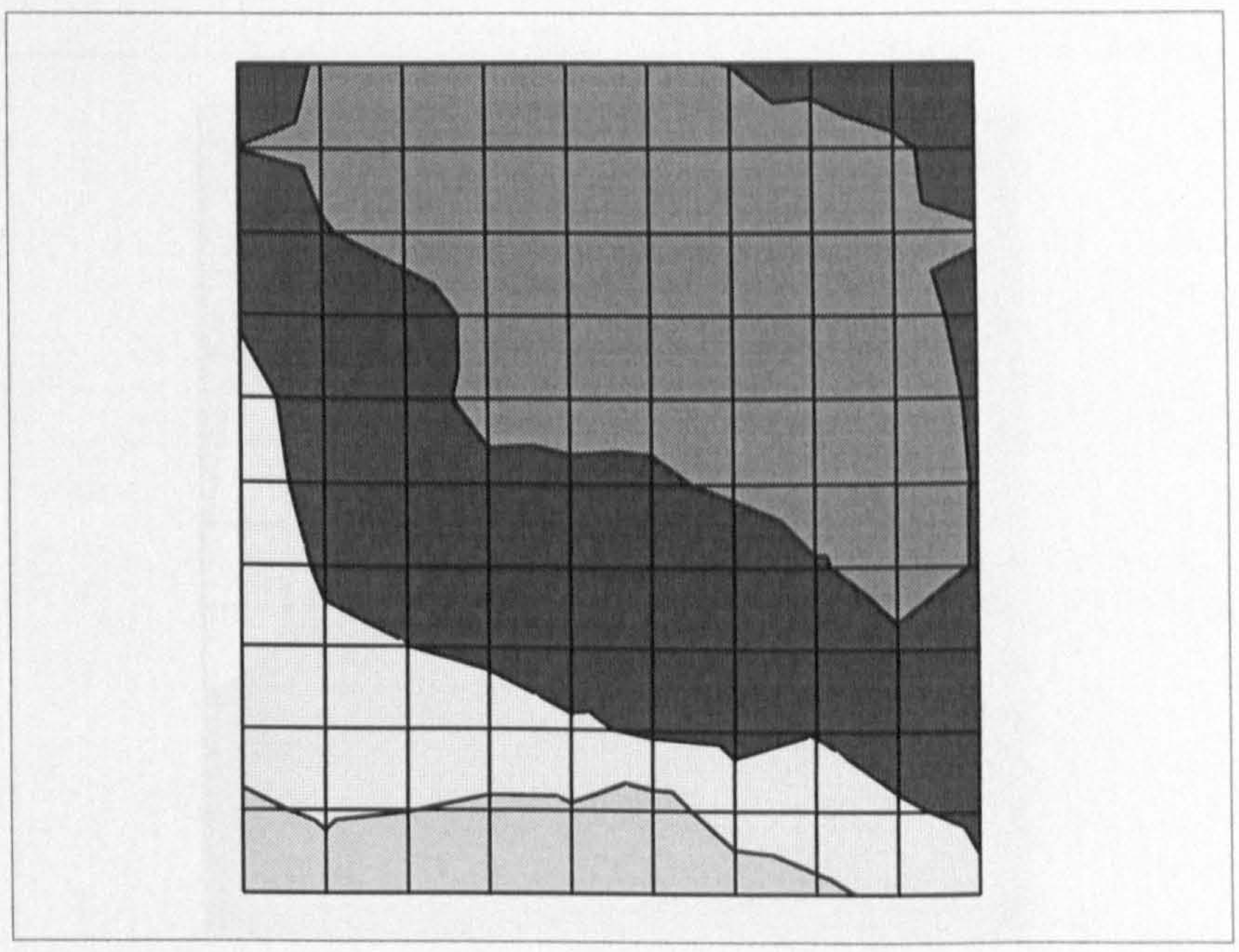
50	25.28	24.43	24.38	24.32	24.39	24.55	24.39	24.32	24.38	24.43	25.28
45	24.43		23.40	23.27	23.44	23.62	23.44	23.27	23.40		24.43
40	24.38	23.40	23.42	23.03	22.63	22.69	22.63	23.03	23.42	23.40	24.38
35	24.32	23.37	23.03	22.52	22.09	22.32	22.09	22.52	23.03	23.37	24.32
30	24.39	23.44	22.63	22.09	21.91	22.36	21.91	22.09	22.63	23.44	24.39
25	24.55	23.62	22.69	22.32	22.36	22.44	22.36	22.32	22.69	23.62	24.55
20	24.39	23.44	22.63	22.09	21.91	22.36	21.91	22.09	22.63	23.44	24.39
15	24.32	23.37	23.03	22.52	22.09	22.32	22.09	22.52	23.03	23.37	24.32
10	24.38	23.40	23.42	23.03	22.63	22.69	22.63	23.03	23.42	23.40	24.38
5	24.43		23.40	23.27	23.44	23.62	23.44	23.27	23.40		24.43
0	25.28	24.43	24.38	24.32	24.39	24.55	24.39	24.32	24.38	24.43	25.28
	0	5	10	15	20	25	30	35	40	45	50



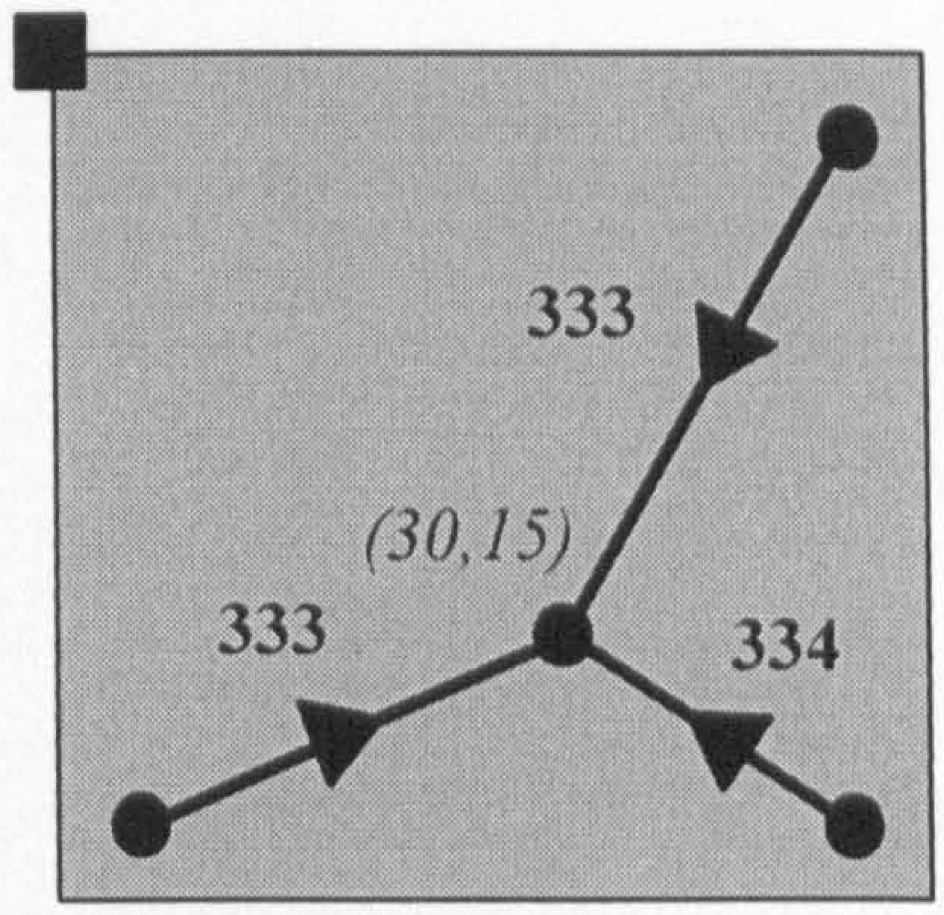
F.2 Layout 2



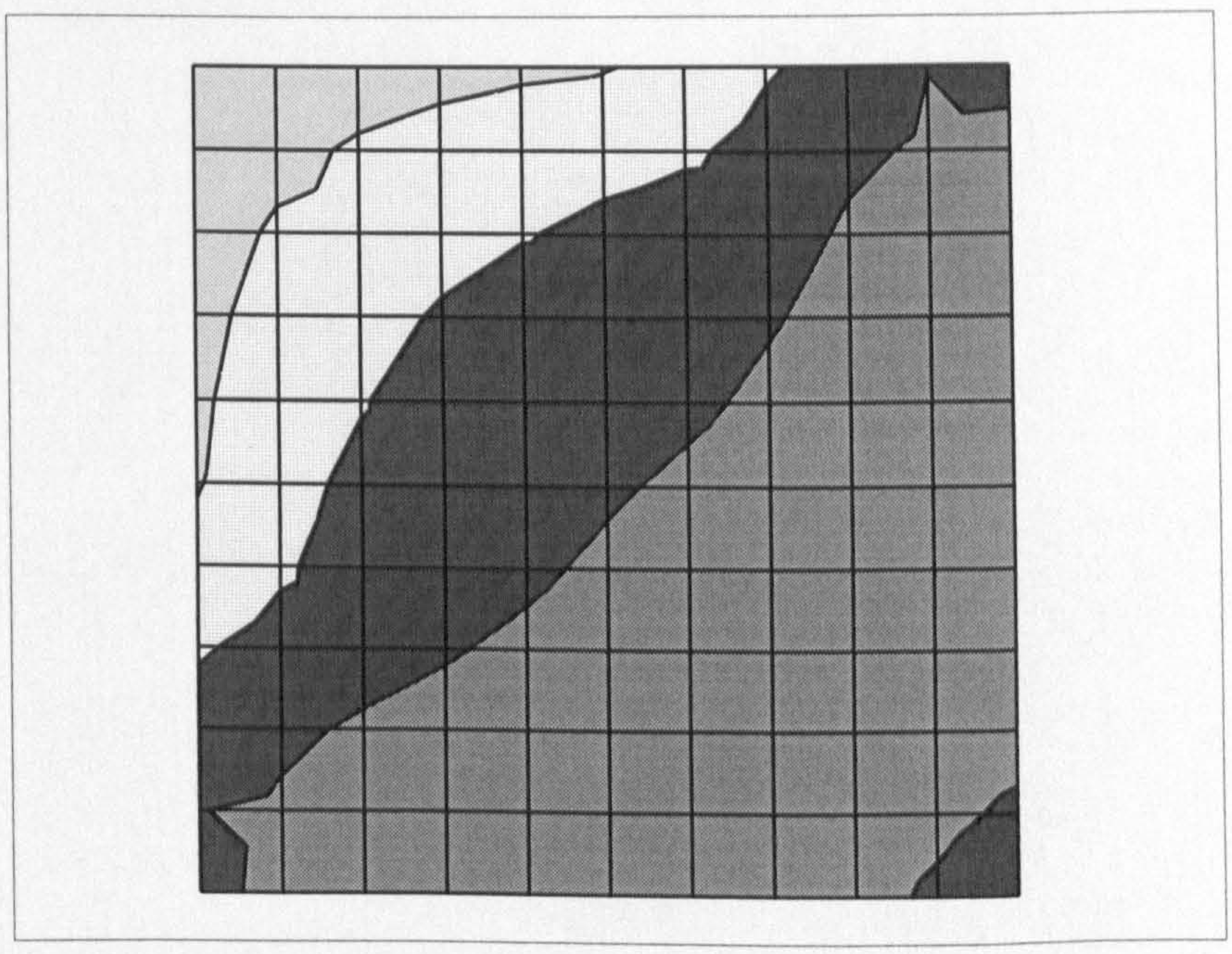
50	22.62	22.01	21.85	21.87	21.98	22.04	22.10	22.35	22.67	22.98	23.70
45	22.08		21.20	21.26	21.38	21.55	21.79	21.72	21.95		22.92
40	22.90	22.15	21.77	21.39	20.94	20.97	21.23	21.54	21.88	22.03	22.58
35	23.43	22.78	22.50	21.86	21.63	21.06	20.68	21.02	21.68	22.33	22.70
30	23.77	23.15	22.39	21.86	21.73	21.66	20.99	20.84	21.53	22.21	22.88
25	23.86	23.24	22.60	22.26	22.28	22.31	21.86	21.41	21.45	22.15	22.83
20	24.01	23.40	22.87	22.33	22.10	22.47	23.00	22.20	21.62	22.15	22.84
15	24.22	23.63	23.51	23.17	22.50	22.61	23.00	22.95	22.30	22.24	22.92
10	24.54	23.94	24.14	24.37	23.76	23.26	23.07	23.45	22.91	22.41	23.12
5	25.05		24.89	25.04	25.03	25.49	24.27	24.09	23.66		23.57
0	25.71	25.28	25.77	25.74	26.32	25.92	25.63	25.18	24.61	23.75	24.28
	0	5	10	15	20	25	30	35	40	45	50



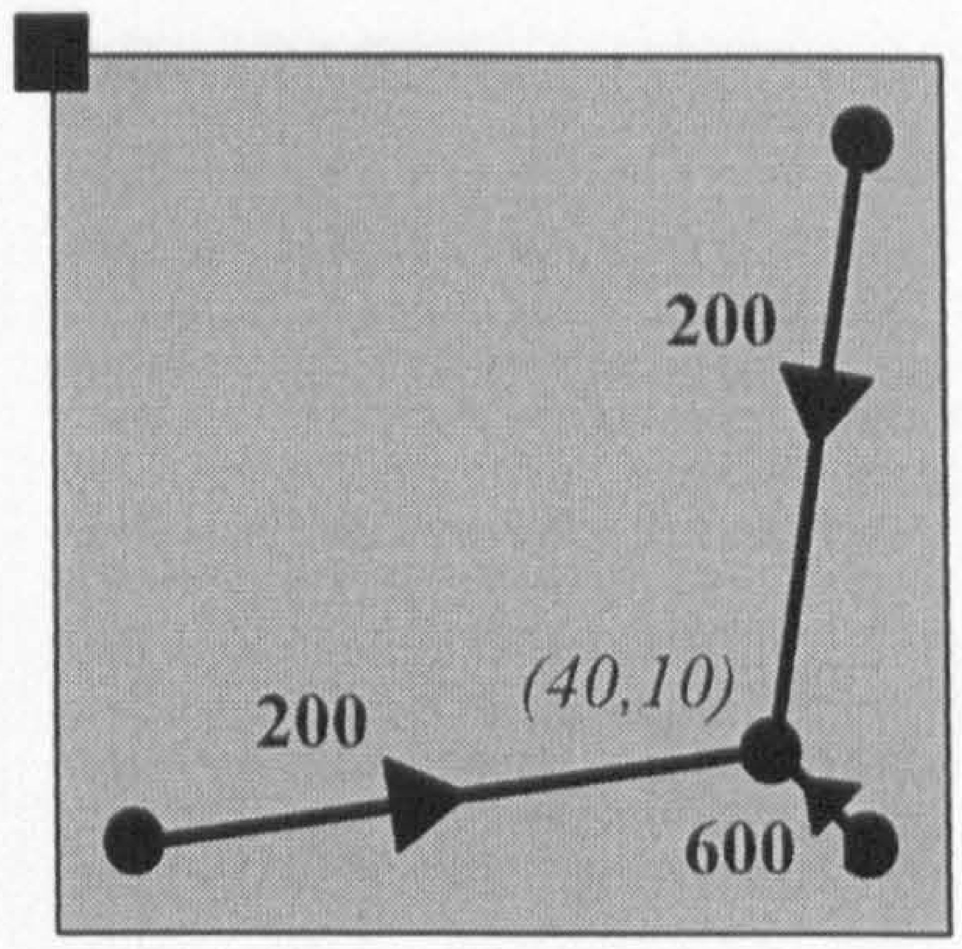
F.3 Layout 3



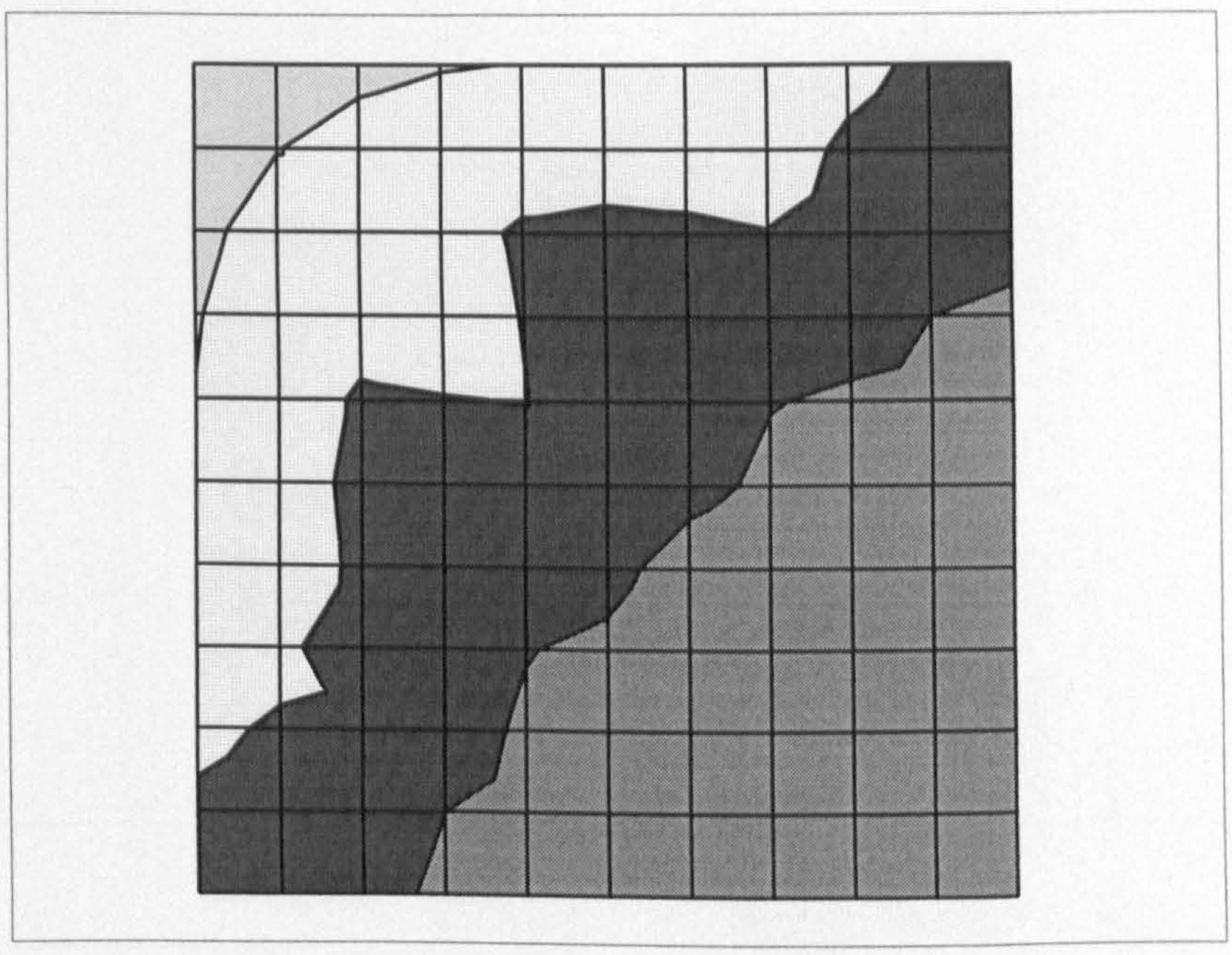
50	27.86	27.09	26.62	26.28	26.08	25.97	25.39	24.09	23.14	21.91	22.23
45	27.09	26.30	25.67	25.34	25.12	24.75	24.18	23.21	22.23		21.54
40	26.62	25.67	25.40	24.79	24.03	23.25	22.80	22.68	21.62	20.75	21.22
35	26.28	25.34	24.79	23.61	22.63	22.52	22.70	22.09	21.06	20.67	21.11
30	26.08	25.12	24.03	22.63	22.23	22.39	22.35	21.36	20.38	20.65	21.09
25	25.97	24.75	23.25	22.52	22.39	22.22	21.36	20.52	20.23	20.67	21.05
20	25.39	24.18	22.80	22.70	22.35	21.36	20.37	19.88	20.31	20.70	21.13
15	24.09	23.21	22.68	22.09	21.36	20.52	19.88	20.02	20.43	20.84	21.26
10	23.14	22.23	21.62	21.06	20.38	20.23	20.31	20.43	20.59	20.99	21.35
5	21.91		20.75	20.67	20.65	20.67	20.70	20.84	20.99		22.13
0	22.23	21.54	21.22	21.11	21.09	21.05	21.13	21.26	21.35	22.13	22.90
	0	5	10	15	20	25	30	35	40	45	50



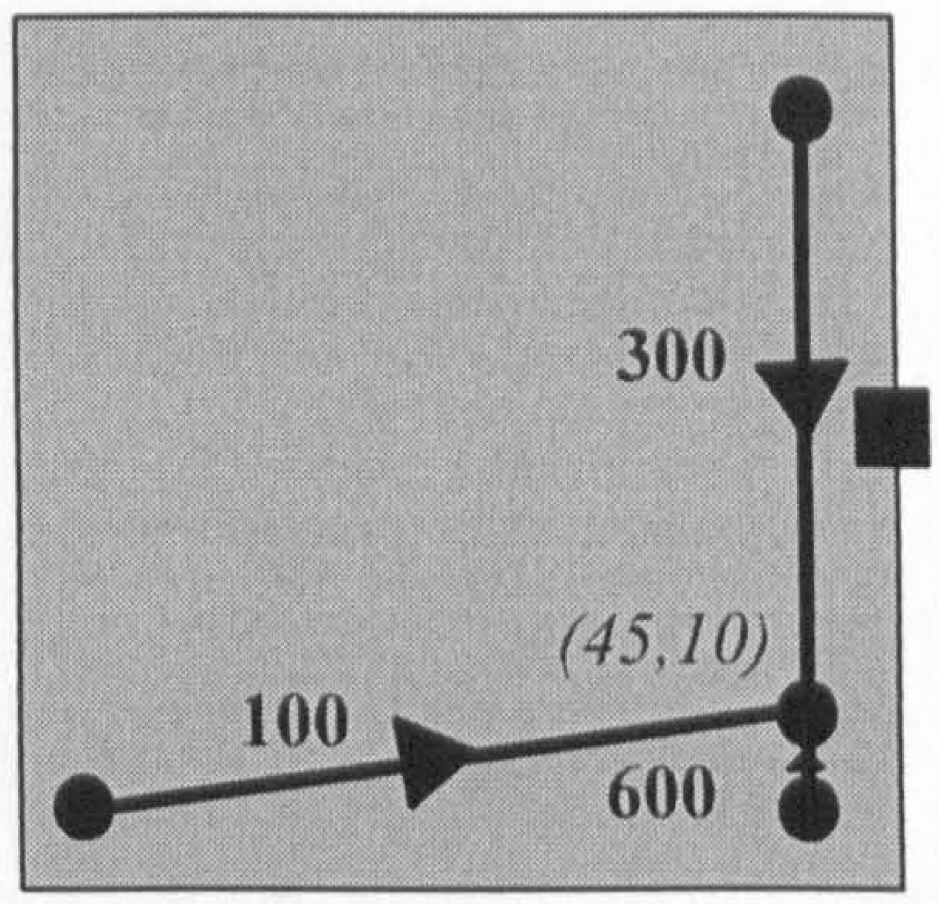
F.4 Layout 4



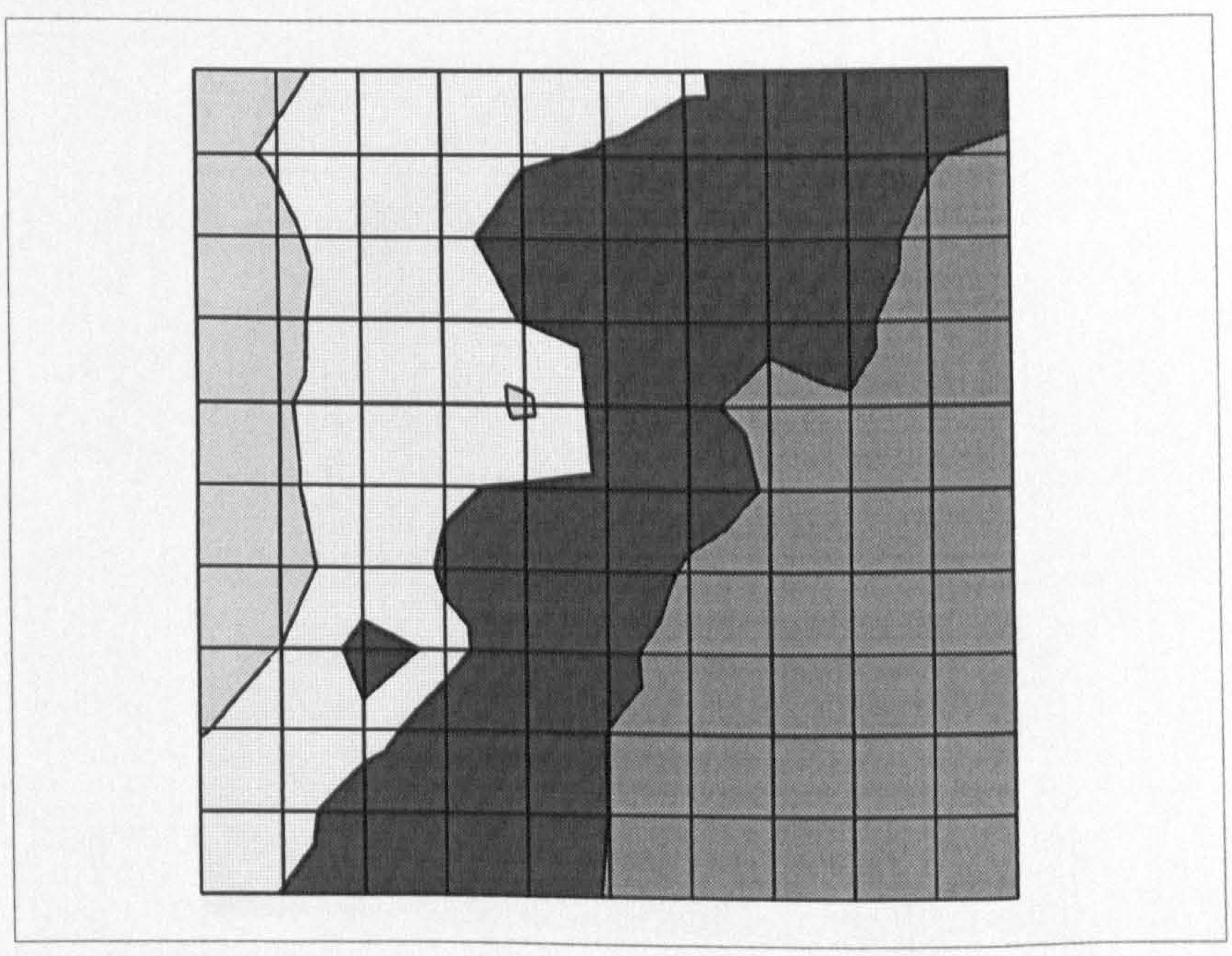
	0	5	10	15	20	25	30	35	40	45	50
50	27.06	26.16	25.58	25.24	25.09	25.02	25.09	24.06	23.68	22.90	22.66
45	26.16	25.19	24.44	24.15	23.99	23.96	24.01	23.95	22.95		22.01
40	25.58	24.44	24.53	23.78	23.03	22.84	22.94	23.16	22.63	21.68	21.53
35	25.24	24.15	23.78	23.99	23.16	22.36	21.83	22.09	21.90	21.29	21.15
30	25.09	23.99	23.03	23.16	23.25	22.36	21.54	21.34	21.08	20.89	20.79
25	25.02	23.96	22.84	22.36	22.36	22.31	21.73	21.00	20.55	20.50	20.42
20	25.09	24.01	22.94	21.83	21.54	21.73	20.62	20.12	20.14	20.11	20.06
15	24.06	23.95	21.34	22.09	21.34	21.00	20.12	19.71	19.74	19.74	19.70
10	23.68	22.95	22.63	21.90	21.08	20.55	20.14	19.74	19.36	19.37	19.47
5	22.90		21.68	21.29	20.89	20.50	20.11	19.74	19.37		20.04
0	22.66	22.01	21.53	21.15	20.79	20.42	20.06	19.70	19.47	20.04	20.75



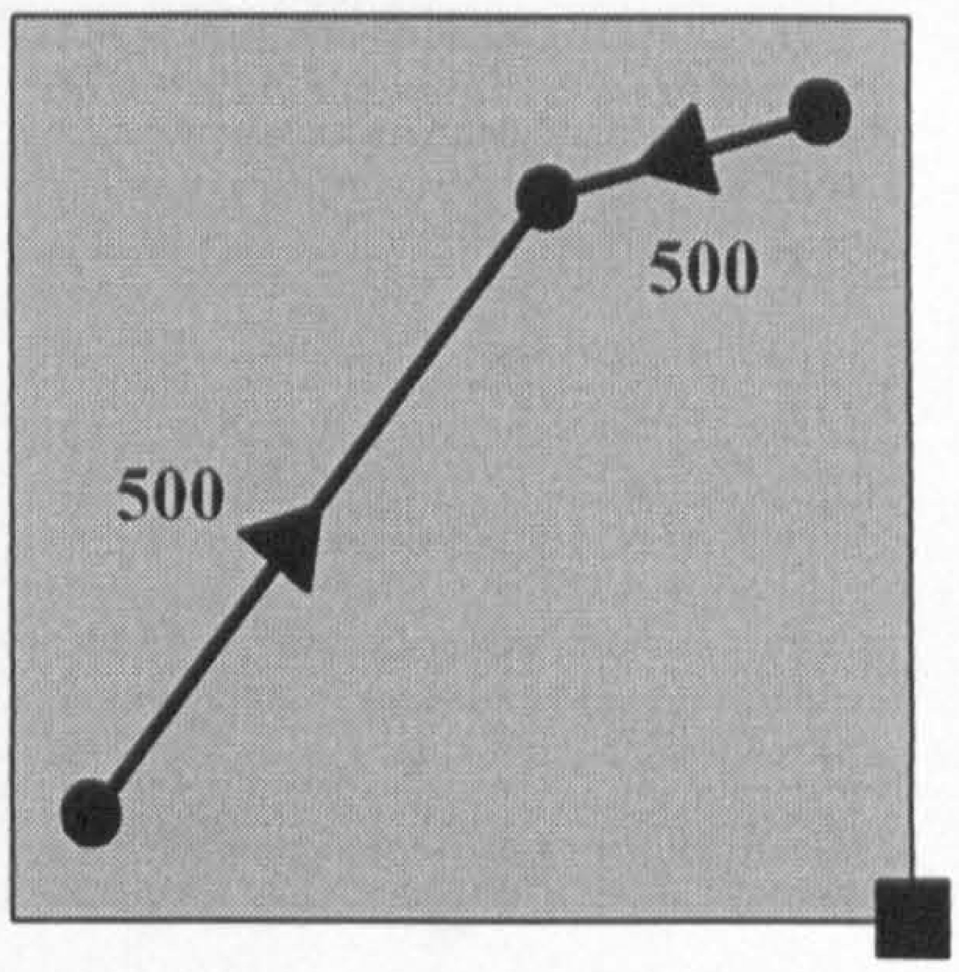
F.5 Layout 5



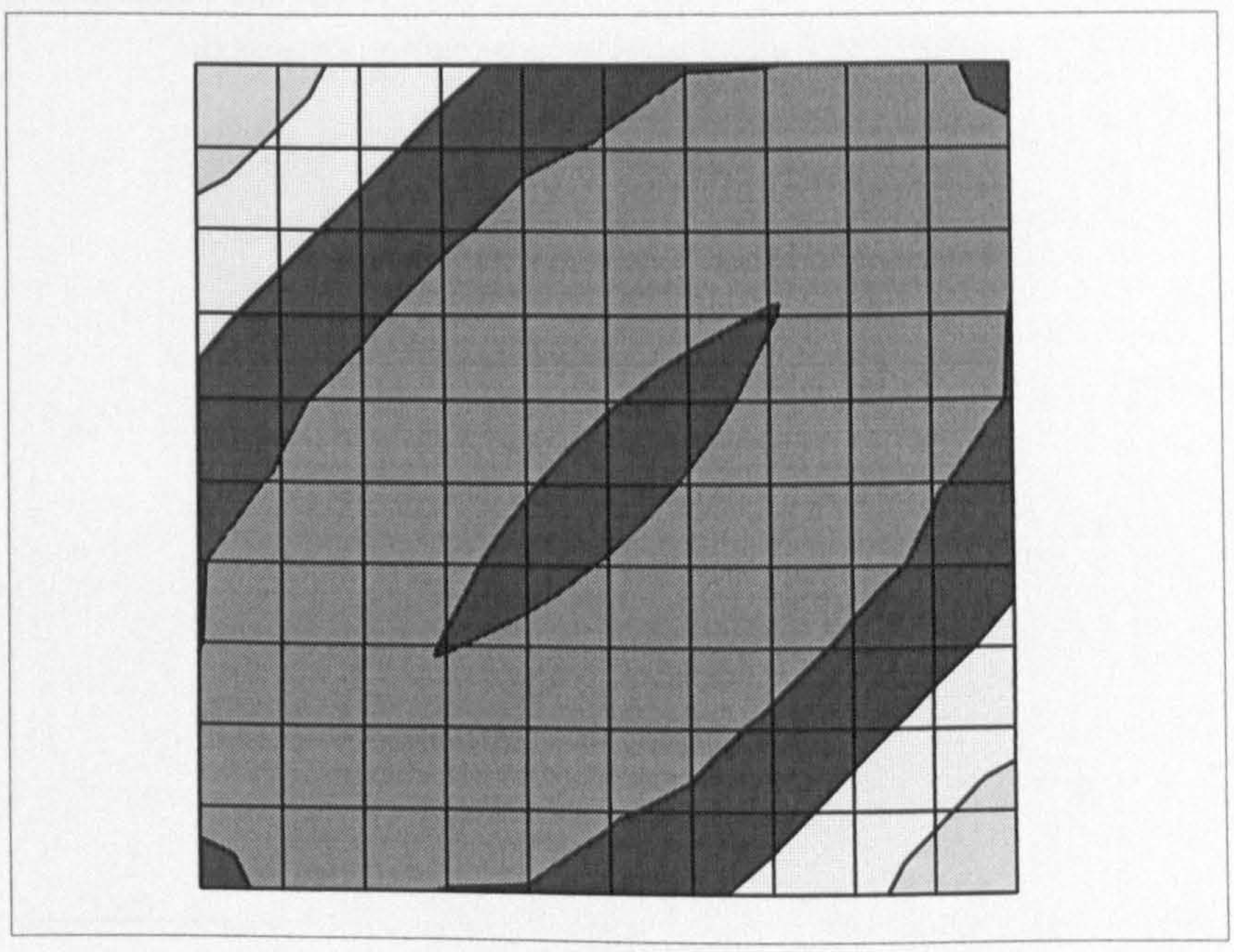
	0	5	10	15	20	25	30	35	40	45	50
50	25.95	25.13	24.39	23.96	23.63	23.18	23.08	22.14	21.75	21.17	21.41
45	25.41	24.63	23.61	23.22	22.93	22.74	22.26	22.23	21.05		20.60
40	26.27	25.16	24.06	23.20	22.30	21.93	21.83	21.44	21.12	20.64	20.19
35	25.52	25.07	24.36	23.67	22.76	21.76	21.01	21.02	21.10	20.21	19.97
30	26.49	25.05	23.75	23.56	25.18	22.05	20.99	20.52	20.74	20.20	19.72
25	26.60	25.18	23.74	22.96	22.66	22.31	21.47	20.71	20.31	19.97	19.44
20	26.84	25.45	24.06	22.66	22.10	21.83	20.62	20.04	19.92	19.57	19.18
15	25.65	24.81	22.17	23.12	22.17	21.17	20.20	19.55	19.51	19.09	19.13
10	24.95	24.09	23.20	22.36	21.42	20.79	20.29	19.55	19.20	18.80	19.35
5	23.79		22.29	21.78	21.28	20.80	20.20	19.71	18.97		19.54
0	23.49	22.79	22.17	21.68	21.22	20.76	20.29	19.81	19.15	19.42	20.17



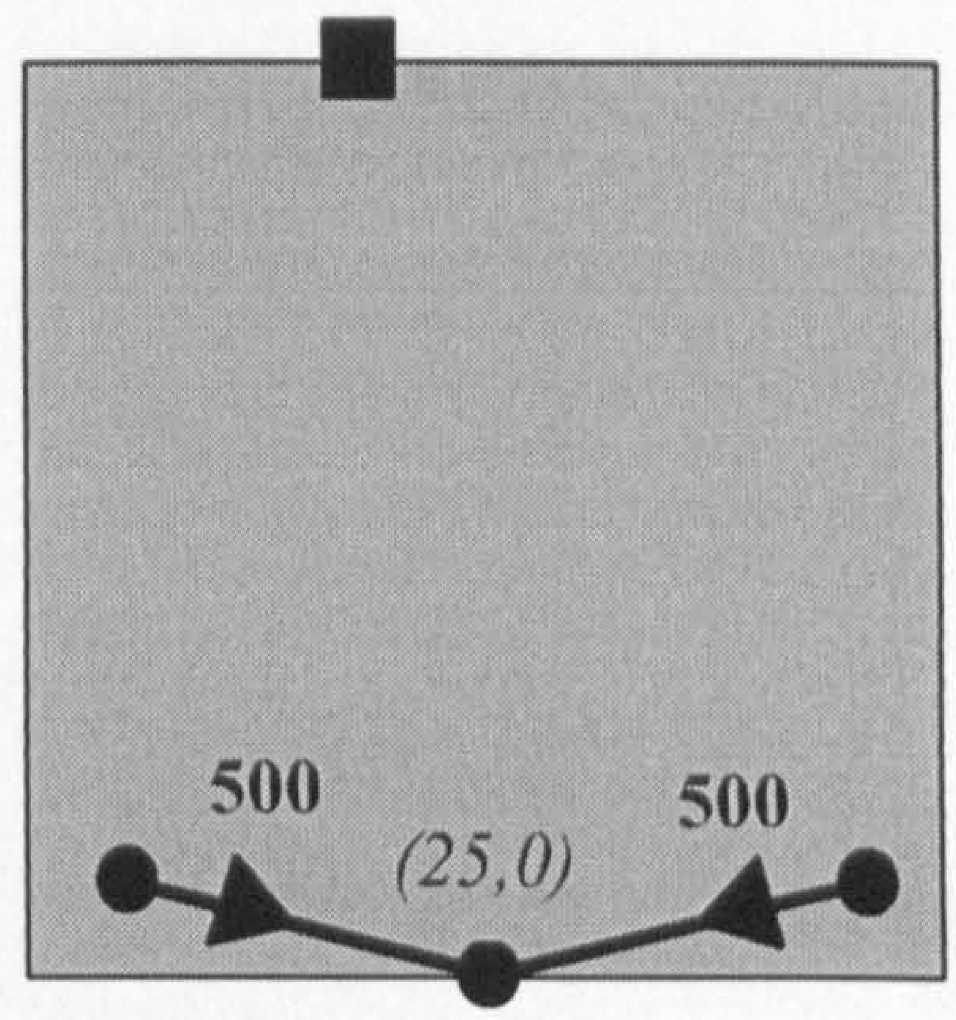
F.6 Layout 6



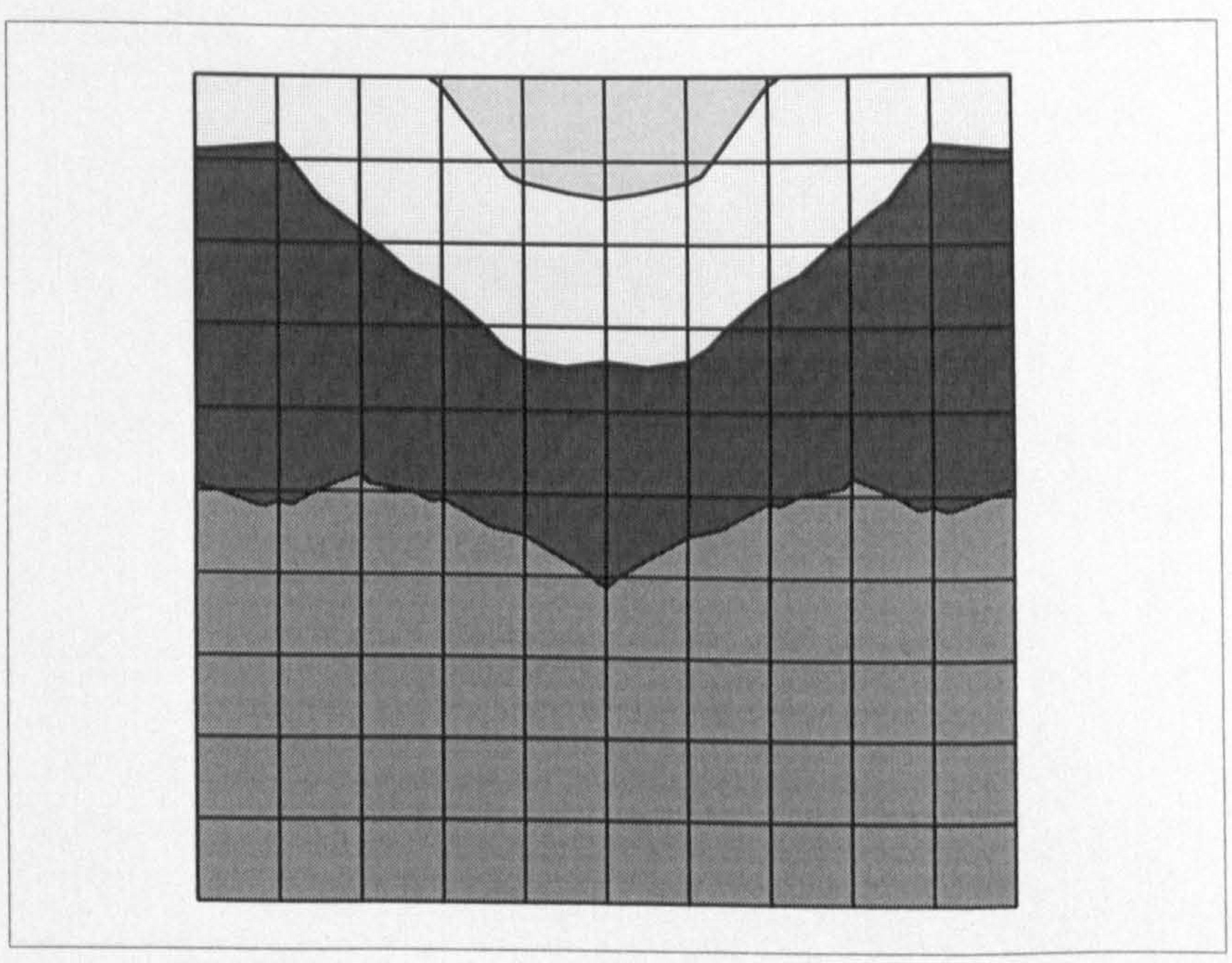
	0	5	10	15	20	25	30	35	40	45	50
50	25.60	24.75	23.60	22.97	22.24	21.55	21.09	21.06	20.83	20.60	21.69
45	24.74	23.87	22.97	22.12	21.29	20.89	20.34	19.89	19.57		20.60
40	23.60	22.97	22.13	21.29	20.52	19.83	19.50	19.99	20.36	19.57	20.83
35	22.97	22.12	21.29	20.40	19.57	19.92	20.58	21.13	19.99	19.89	21.06
30	22.24	21.29	20.52	19.57	20.06	20.89	21.63	20.58	19.50	20.34	21.09
25	21.55	20.89	19.83	19.92	20.89	21.80	20.89	19.92	19.83	20.89	21.55
20	21.09	20.34	19.50	20.58	21.63	20.89	20.06	19.57	20.52	21.29	22.24
15	21.06	19.89	19.99	21.13	20.58	19.92	19.57	20.40	21.29	22.12	22.97
10	20.83	19.57	20.36	19.99	19.50	19.83	20.52	21.29	22.13	22.97	23.60
5	20.60		19.57	19.89	20.34	20.89	21.29	22.12	22.97	23.87	24.75
0	21.69	20.60	20.83	21.06	21.09	21.55	22.24	22.97	23.60	24.75	25.60



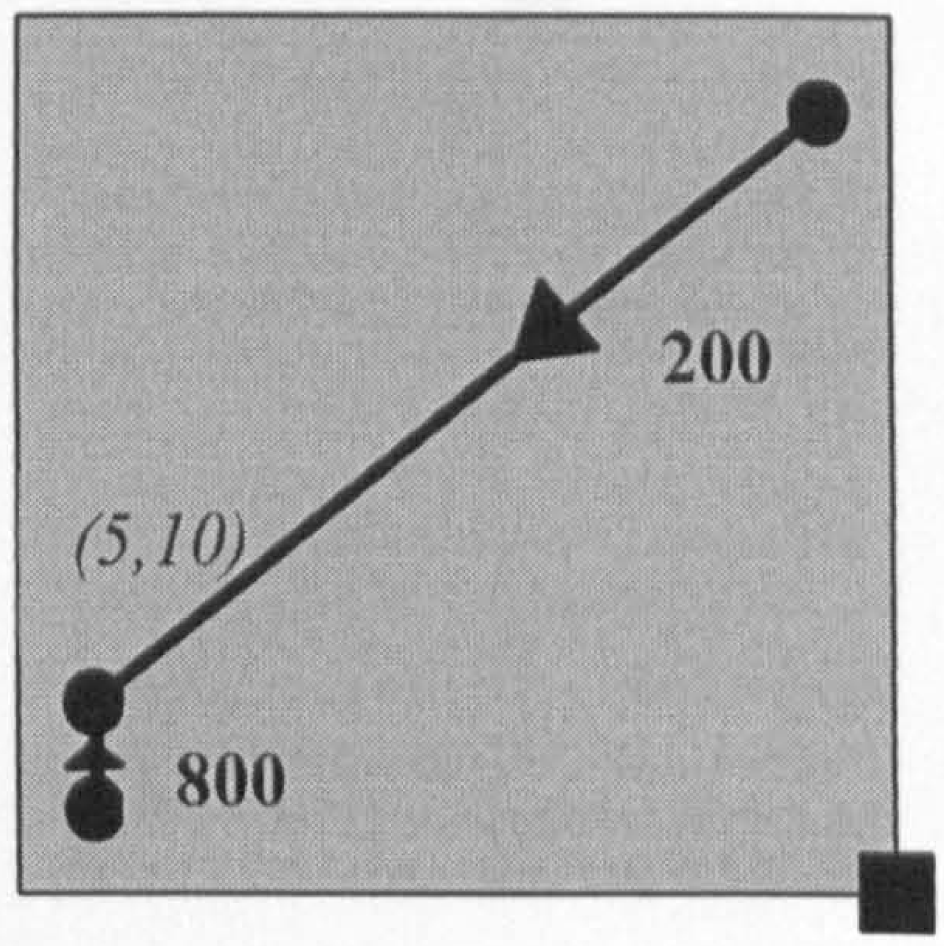
F.7 Layout 7



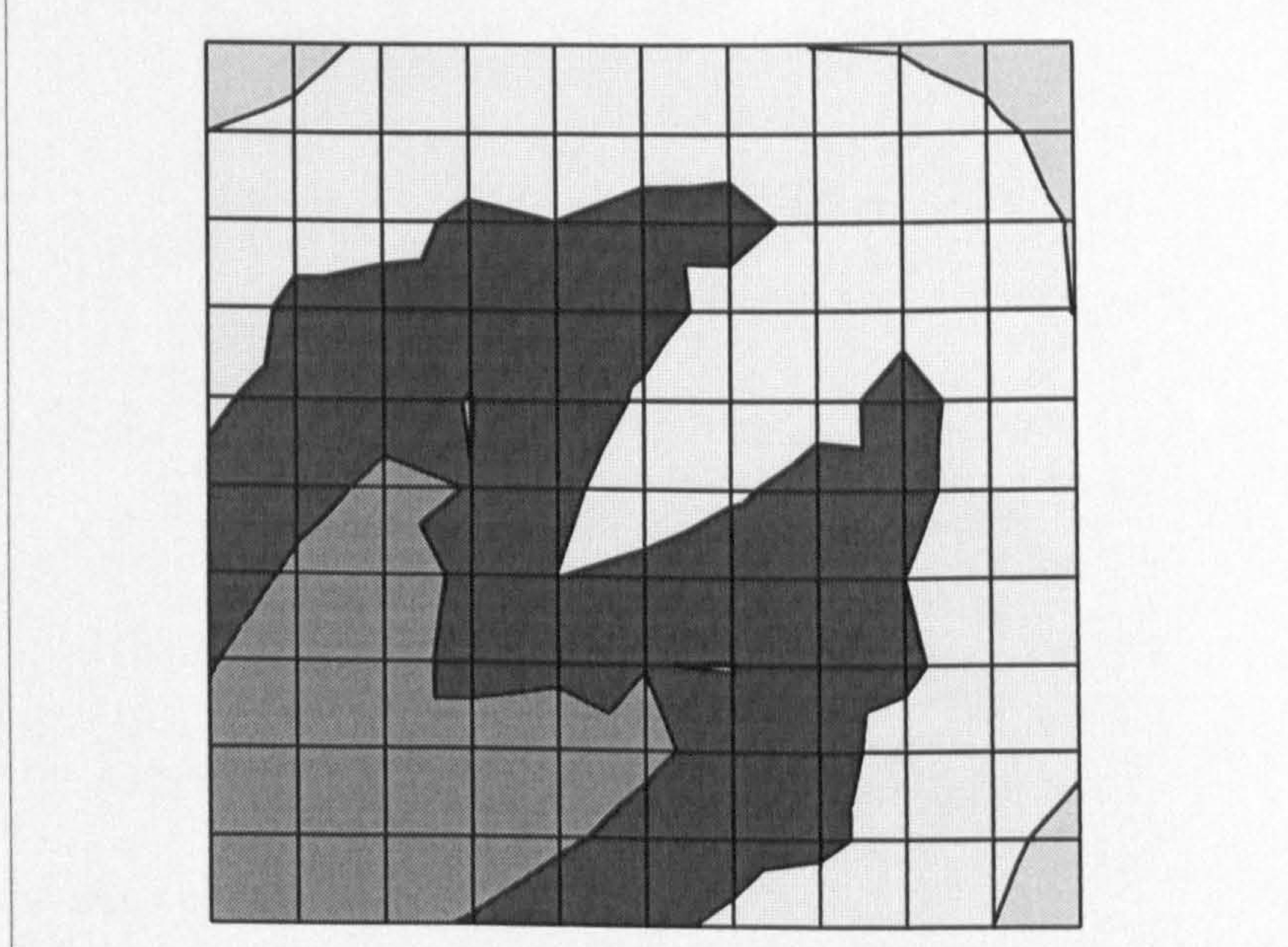
	0	5	10	15	20	25	30	35	40	45	50
50	24.58	24.65	25.87	26.70	27.96	29.27	27.96	26.70	25.87	24.65	24.58
45	23.78	23.70	24.81	25.61	27.01	27.41	27.01	25.61	24.81	23.70	23.78
40	23.01	22.84	23.69	24.57	25.29	25.55	25.29	24.57	23.69	22.84	23.01
35	22.45	22.29	22.72	23.36	24.36	24.25	24.36	23.36	22.72	22.29	22.45
30	21.77	21.77	21.67	22.46	23.19	23.37	23.19	22.46	21.67	21.77	21.77
25	21.13	21.30	21.03	21.26	21.83	22.44	21.83	21.26	21.03	21.30	21.13
20	20.68	20.34	20.58	20.23	20.52	21.30	20.52	20.23	20.58	20.34	20.68
15	19.88	19.93	19.52	19.83	19.83	20.38	19.83	19.83	19.52	19.93	19.88
10	19.20	18.82	19.14	19.27	19.41	19.83	19.41	19.27	19.14	18.82	19.20
5	18.99		18.48	18.48	18.81	19.01	18.81	18.48	18.48		18.99
0	19.37	18.66	18.48	18.48	18.48	18.48	18.48	18.48	18.48	18.66	19.37



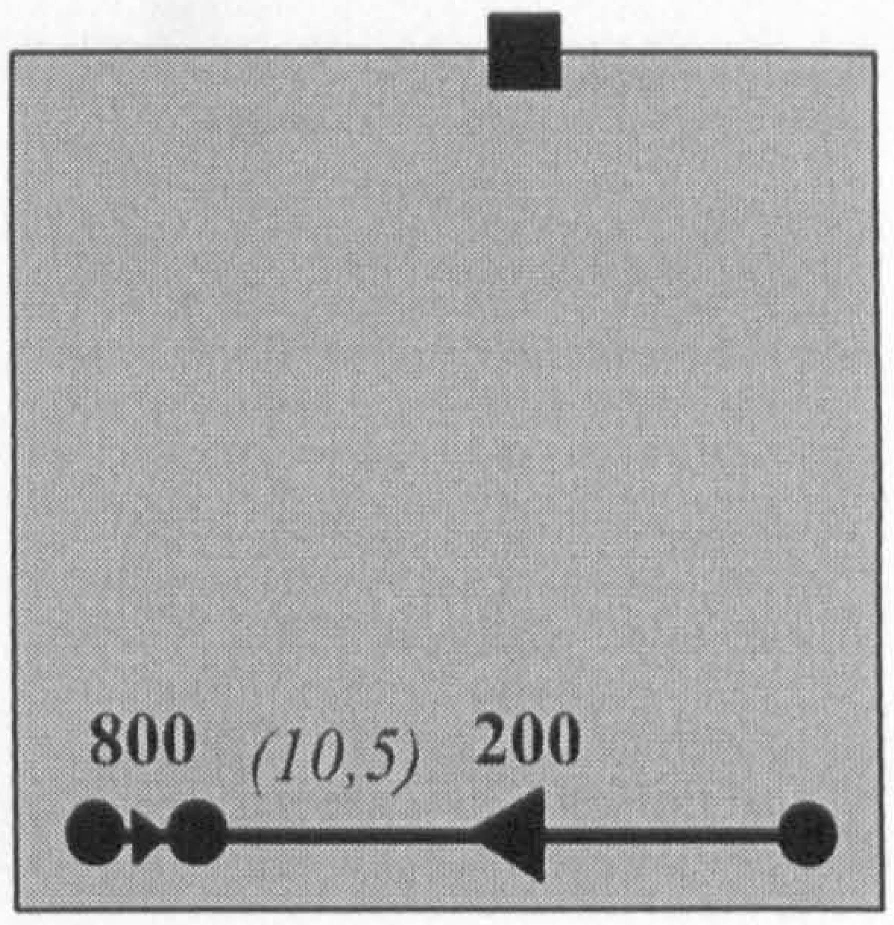
F.8 Layout 8



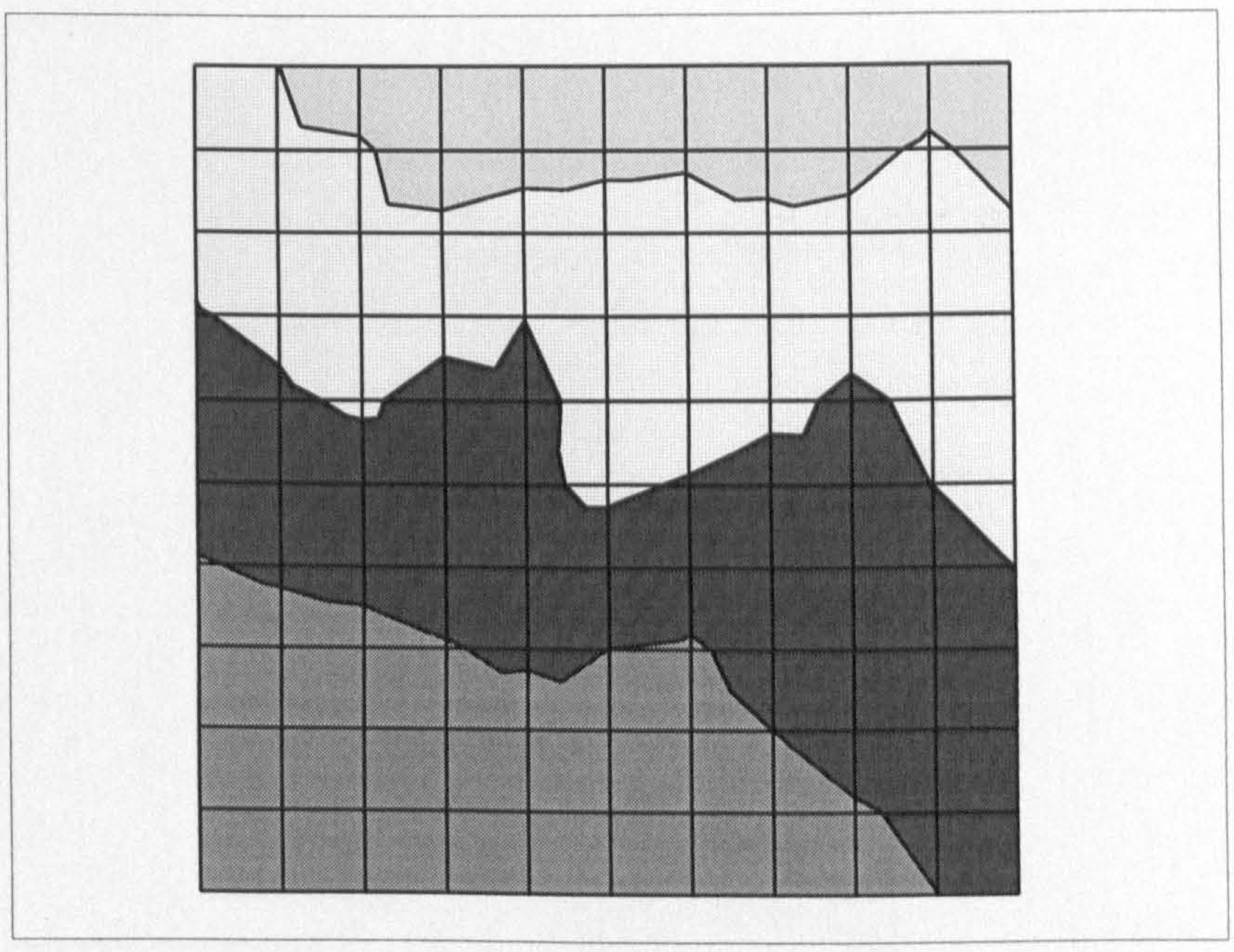
	0	5	10	15	20	25	30	35	40	45	50
50	23.35	23.00	22.36	22.14	22.37	21.94	21.86	22.63	22.73	23.10	24.19
45	22.59	22.29	21.50	21.79	21.20	21.62	21.51	21.37	21.38		23.10
40	22.12	21.46	21.46	20.71	20.97	20.55	20.53	21.35	22.08	21.38	22.73
35	21.78	20.71	20.50	20.40	19.81	20.45	21.43	22.20	21.35	21.37	22.63
30	21.18	20.56	19.82	19.32	20.06	21.18	22.25	21.43	20.53	21.51	21.86
25	20.73	19.81	19.11	19.39	20.60	21.80	21.18	20.45	20.55	21.62	21.94
20	20.18	19.15	18.48	19.73	21.00	20.60	20.06	19.81	20.97	21.20	22.37
15	19.49	18.42	18.63	19.92	19.73	19.39	19.32	20.40	20.71	21.79	22.14
10	18.92	17.76	18.64	18.63	18.48	19.11	19.82	20.50	21.46	21.50	22.36
5	18.11		17.76	18.42	19.15	19.81	20.56	20.71	21.46	22.29	23.00
0	19.20	18.11	18.92	19.49	20.18	20.73	21.18	21.78	22.12	22.59	23.35



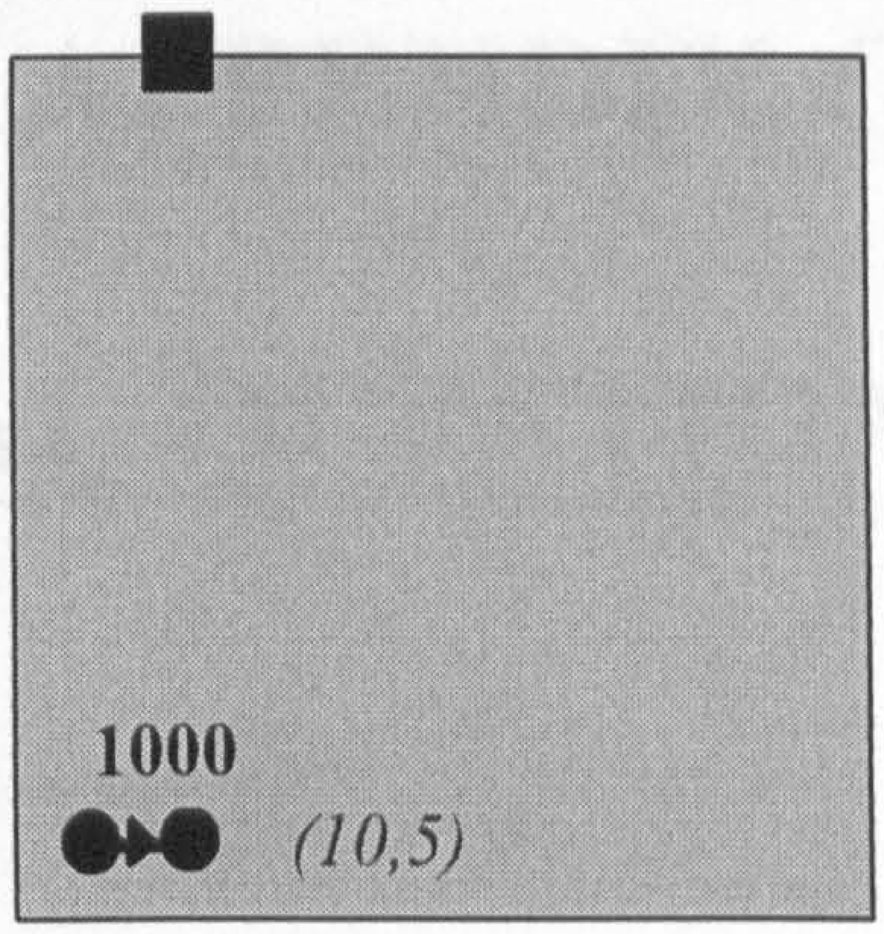
F.9 Layout 9



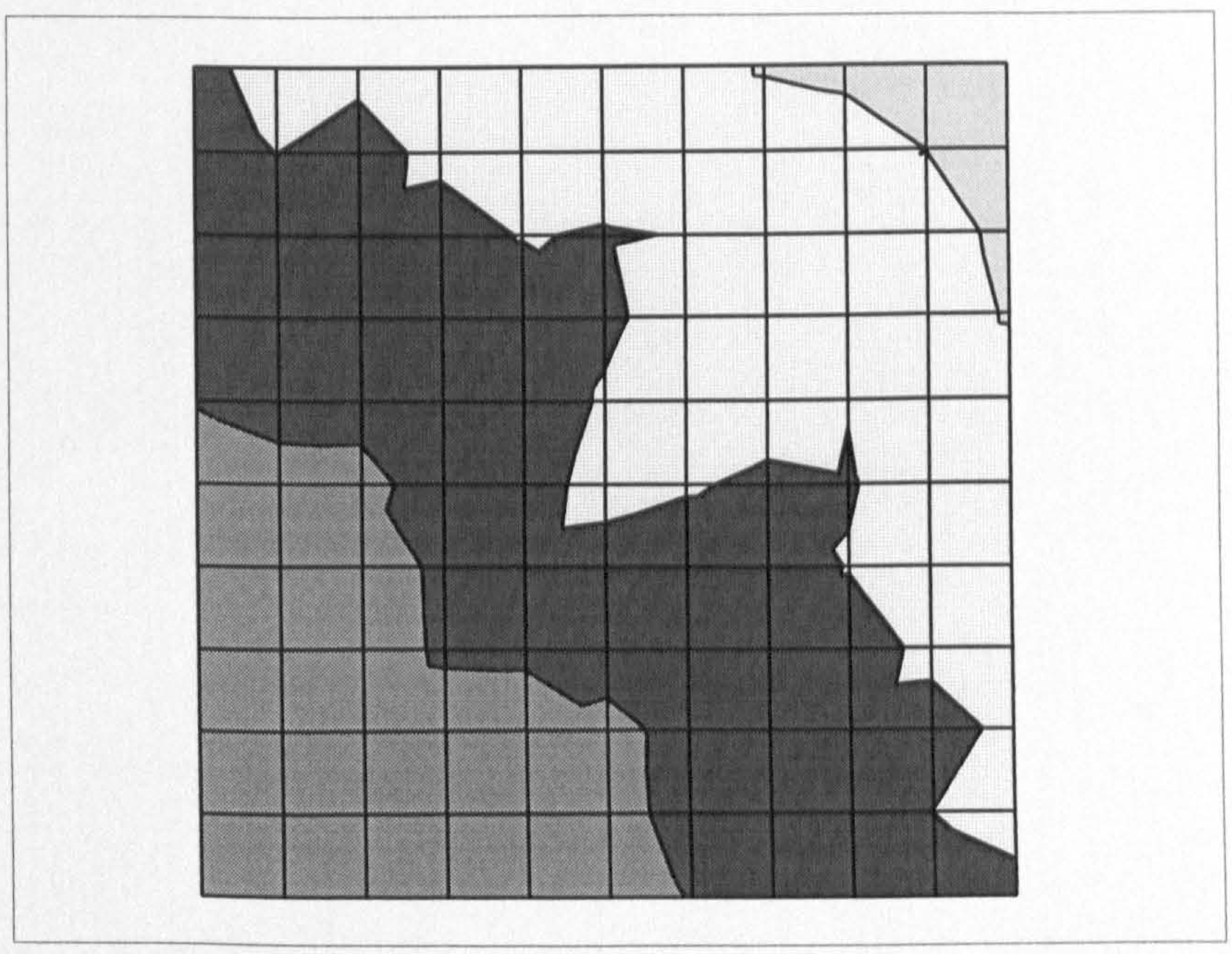
	0	5	10	15	20	25	30	35	40	45	50
50	23.51	23.80	24.76	24.74	25.77	25.45	25.61	25.74	25.95	24.72	25.35
45	22.84	23.45	23.63	24.64	24.34	24.38	24.20	24.17	24.34	23.59	24.43
40	22.14	22.99	23.39	23.52	23.22	22.84	22.84	23.59	23.41	22.68	23.61
35	21.63	22.08	22.90	22.32	21.73	22.18	22.98	23.06	22.44	22.33	23.19
30	20.99	21.47	21.95	21.08	21.36	22.17	22.82	22.18	21.39	22.08	22.14
25	20.25	20.67	20.92	20.78	21.40	22.05	21.56	20.98	21.03	21.73	21.78
20	19.49	19.85	20.11	20.39	20.80	20.79	20.25	20.08	20.99	20.82	21.74
15	18.71	18.94	19.04	19.48	19.92	19.58	19.43	20.06	20.01	20.92	20.90
10	17.80	17.80	18.26	18.82	18.66	19.11	19.14	19.59	20.03	19.84	20.60
5	17.64		17.47	17.88	18.35	18.77	18.91	18.91	19.48		20.34
0	18.35	17.73	17.78	17.73	17.92	18.34	18.69	18.98	19.18	19.58	20.39



F.10 Layout 10



50	21.08	21.24	21.54	21.58	22.45	22.21	22.38	23.68	24.01	24.77	25.86
45	20.20	21.17	20.52	21.57	21.15	21.97	22.29	22.35	22.58	23.53	24.77
40	19.64	20.15	20.62	20.33	21.24	21.03	21.21	22.26	23.22	22.58	24.01
35	19.31	19.20	19.80	20.20	19.97	20.80	21.99	22.86	22.26	22.35	23.68
30	18.84	18.98	18.97	19.16	20.06	21.35	22.57	21.99	21.21	22.29	22.38
25	18.25	18.61	18.63	19.04	20.41	21.80	21.35	20.80	21.03	21.97	22.21
20	17.55	17.73	17.79	19.17	20.58	20.41	20.06	19.97	21.24	21.15	22.45
15	17.10	16.96	17.73	19.11	19.17	19.04	19.16	20.40	20.33	21.57	21.58
10	16.47	16.44	17.49	17.73	17.70	18.63	18.97	19.80	20.62	20.52	21.54
5	16.44		16.44	16.96	17.73	18.61	18.98	19.20	20.15	21.17	21.24
0	17.52	16.44	16.47	17.10	17.55	18.25	18.84	19.31	19.64	20.20	21.08
	0	5	10	15	20	25	30	35	40	45	50



APPENDIX G

POSTAL QUESTIONNAIRE

The following information is provided:

G.1 Covering letter

Date

Company name
Address
Address
Address
Address
Address

Dear Sir or Madam

Please find enclosed a questionnaire about the use of tower cranes on construction sites. I would be very grateful if you could pass this on to an appropriate person in your company, preferably someone involved in site planning.

This questionnaire forms an integral part of research being carried out in the Department of Civil and Construction Engineering at UMIST. Its purpose is to ascertain the view of planners, and other construction professionals, involved in decisions relating to materials handling, and in particular, the selection and location of tower cranes. The views of practitioners obtained from this questionnaire are invaluable and will be used to corroborate the ideas and concepts gained from other sources.

No specific details of the responding companies are required and hence all replies will be treated in the strictest confidence.

If you have any queries about this questionnaire, please do not hesitate to ring me on 0161 200 4234 or email me at margaret.emsley@umist.ac.uk.

Thank you for your co-operation in this matter, which is greatly appreciated.

Yours faithfully

Margaret W Emsley
Lecturer

G.2 Questionnaire

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UMIST

TOWER CRANE QUESTIONNAIRE

This questionnaire forms an integral part of research being carried out in the Department of Civil and Construction Engineering at UMIST.

The purpose of this questionnaire is to ascertain the view of planners, and other construction professionals, involved in decisions relating to materials handling, and in particular, the selection and location of tower cranes. The views of practitioners obtained from this questionnaire are invaluable and will be used to corroborate the ideas and concepts gained from other sources.

Margaret Emsley
Lecturer

Please note that all references to tower cranes refer to towe r cranes that are fixed in position and exclude mobile cranes of any type.

1. **Personal details**
Please give your job title

[ ]

2. **Company details**
Company annual turnover:
Please tick one box as appropriate

Less than £1 million ☐ **£1 =10 million** ☐

£10 – 100 million ☐ **Greater than £100 million** ☐

3. **Is your company either currently, or has been during the past year, involved in contracts where tower cranes are used on construction sites?**
Please tick one box as appropriate

Yes ☐ *Please go to Question 4* **No** ☐ *Please go to Question 7*

4. **How many contracts are your company currently involved with where:**

Please tick one box as appropriate

a) **There is one tower crane on site?**

1 – 2 ☐ **3 – 5** ☐

6 – 10 ☐ **More than 10** ☐

b) **There are more than one tower crane on site?**

1 – 2 ☐ **3 – 5** ☐

6 – 10 ☐ **More than 10** ☐

5. **Is your company either currently, or has been during the past year, involved in deciding whether or not to use a tower crane (or cranes) on a particular construction site?**
Please tick one box as appropriate

Yes ☐ **No** ☐

6. **Is your company either currently, or has been during the past year, involved in deciding where to locate a tower crane (or cranes) on a particular construction site?**
Please tick one box as appropriate

Yes ☐ **No** ☐

7. **As a general rule, and given that there are no constraints which prohibit your choice, which of the following, in your opinion, is the best strategy when considering where to locate a tower crane?**
Please rank from 1 to 4, with 1 representing the most favoured strategy and 4 representing the least favoured strategy

Place inside the structure in a lift shaft, court yard or other opening	☐	**Place inside the structure where 'making good' later is required**	☐
Place outside the structure but sufficiently close so that it can be tied to the structure	☐	**Place away from the structure**	☐

8. **How important do you consider the location of the tower crane to be?**
Please tick one box as appropriate

Of great importance	☐	**Of some importance**	☐
Of little importance	☐	**Of no impo rtance**	☐

9. **What is this view, expressed in Question 8, based upon?**

10. **In your opinion, how important are the following factors that may be taken into account when deciding where to locate a tower crane (or cranes)?**
Please rate each factor as follows: *Of great importance 1 Of some importance 2 Of little importance 3 Of no importance 4*

Ease of erection	☐	**The need to provide a base**	☐
The need to ensure the crane can reach the whole site	☐	**The need to avoid over-swing onto adjacent property/roads**	☐
The need to avoid locating where 'making good' later is required	☐	**Ease of disamantling**	☐
Other *(please specify)* ________________	☐	**Other** *(please specify)* ________________	☐

11. **What method (or methods) do you use in deciding where to locate a tower crane?**
Please tick as many boxes as appropriate

Common sense ☐ **Past experience** ☐

Company 'system' ☐ **Graphical methods** ☐

Computer methods (such as expert systems) ☐

Other *(please specify)* ☐

____

12. **When considering the use of tower cranes, how important, in your opinion, are the following considerations?**

Please rate each factor as follows:	*Of great importance 1*	*Of some importance 2*
	Of little importance 3	*Of no importance 4*

The need to place the crane centrally and so use a crane with the shortest possible jib length ☐

The need to ensure that the crane is fully utilized ☐

The need to ensure that the crane works efficiently (that is does not experience any undue delays) ☐

13. **Some research has shown that placing the crane on the site perimeter could result in time savings in respect of the time to complete crane-related activities. Would you consider placing the crane at the perimeter, even though this would require a crane with a longer jib length than if the crane centrally located?**
Please tick one box as appropriate

Would seriously consider ☐ **May consider** ☐

Unlikely to consider ☐ **Would not consider** ☐

Not sure/don't know ☐

14. **Any other comments about tower crane location?**

Thank you for your co-operation.
Please return the questionnaire (in the envelope supplied) to:
Margaret Emsley, Lecturer, Department of Civil and Construction Engineering, UMIST, PO Box 88, Manchester, M60 1QD.

G.3 Summary of responses

Respondent	1	2	3	4	5
Background and experience					
Job Title	Planner	Contract Manager	Planner	Planner	General Manager
Annual Turnover	>£100M	£1 - £10M	>£100M	>£100M	>£100M
Recent experience of using cranes	Yes	No	Yes	Yes	Yes
No. sites with 1 crane	3-5		1-2	3-5	>10
No. sites with more than 1 crane	0		1-2	1-2	3-5
Decision to use cranes	Yes		Yes	Yes	Yes
Decision to locate cranes	Yes		Yes	Yes	Yes
Preferred location strategy					
Inside but utilizing an opening	3	3	1	3	
Inside with 'making good' later	4	4	4	4	1
Outside but tied to structure	2	2	3	2	
Outside away from the structure	1	1	2	1	
Location importance	1	1	1	1	1
Factors influening location					
Ease of erection	2	4	2	1	1
Need for base	2	3	3	1	2
Need to reach	1	1	2	2	1
Avoid overswing	2	2	2	2	1
Avoid making good	2	3	3	3	3
Ease of dismantling	2	3	2	1	1
Crane type	2				
Accessibility of pick up			2		
Ground conditions				2	
Obstructions					
Crane capacity					
Minimize radius for heavy loads			2		
Operator visibility					
Methods used to locate cranes					
Common sense	✓	✓	✓		
Past experience	✓	✓	✓		
Company system			✓		
Graphical methods	✓		✓	✓	
Computer methods					✓
Considerations when using cranes					
Crane uses shortest possible jib	3	3	2	2	2
Crane is fully utilized	1	1	2	1	1
Crane works efficiently	1	1	2	1	1
Likely to place crane at perimeter					
Seriously consider	✓	✓		✓	
May consider			✓		✓
Unlikely to consider					
Would not consider					
Not sure/don't know					

Respondent	6	7	8	9	10
Background and experience					
Job Title	Planner	Plant Manager	Chief Engineer	Plant Manager	Safety Officer
Annual Turnover	>£100M	£10-100M	>£100M	£10-100M	£10-100M
Recent experience of using cranes	Yes	No	Yes	Yes	Yes
No. sites with 1 crane	3-5			1-2	1-2
No. sites with more than 1 crane	0			0	0
Decision to use cranes	Yes		Yes	Yes	Yes
Decision to locate cranes	Yes		Yes	Yes	Yes
Preferred location strategy					
Inside but utilizing an opening		2	1		2
Inside with 'making good' later		3	2		4
Outside but tied to structure	2	1	3	1	3
Outside away from the structure	1	4	4		1
Location importance	2	1	1	1	1
Factors influening location					
Ease of erection	2		2	1	2
Need for base	1		3		2
Need to reach	1		2	1	1
Avoid overswing	2		2	1	1
Avoid making good	2		2		2
Ease of dismantling	2		1	1	2
Crane type					
Accessibility of pick up			1		
Ground conditions					
Obstructions					
Crane capacity					
Minimize radius for heavy loads					
Operator visibility					
Methods used to locate cranes					
Common sense	✓	✓	✓	✓	✓
Past experience		✓	✓		✓
Company system					
Graphical methods			✓		
Computer methods		✓			
Considerations when using cranes					
Crane uses shortest possible jib	1		2	1	2
Crane is fully utilized	2		2	1	1
Crane works efficiently	2		2	1	1
Likely to place crane at perimeter					
Seriously consider				✓	✓
May consider	✓		✓		
Unlikely to consider		✓			
Would not consider					
Not sure/don't know					

Respondent	11	12	13	14	15
Background and experience					
Job Title	Director	Engiineer	Safety Officer	Director	Director
Annual Turnover	£10-100M	>£100M	£1-10M	£10-100M	£1-£10M
Recent experience of using cranes	No	Yes	No	No	No
No. sites with 1 crane		>10			
No. sites with more than 1 crane		>10			
Decision to use cranes		Yes			
Decision to locate cranes		Yes			
Preferred location strategy					
Inside but utilizing an opening	1				1
Inside with 'making good' later					2.5
Outside but tied to structure			1	1	2.5
Outside away from the structure					4
Location importance	1	1	1	1	1
Factors influening location					
Ease of erection	2	2	1	2	2
Need for base	4	1	1	3	3
Need to reach	1	1	1	1	1
Avoid overswing	1	1	1	2	2
Avoid making good	3	2	3	3	2
Ease`of dismantling	2	2	1	1	2
Crane type					
Accessibility of pick up					
Ground conditions					
Obstructions					
Crane capacity					
Minimize radius for heavy loads					
Operator visibility					
Methods used to locate cranes					
Common sense		✓			✓
Past experience		✓	✓	✓	✓
Company system					
Graphical methods		✓			
Computer methods	✓				
Considerations when using cranes					
Crane uses shortest possible jib	1	2	3	2	1
Crane is fully utilized	1	1	1	1	1
Crane works efficiently	3	1	2	2	2
Likely to place crane at perimeter					
Seriously consider		✓	✓		✓
May consider	✓				
Unlikely to consider				✓	
Would not consider					
Not sure/don't know					

Respondent	16	17	18	19	20
Background and experience					
Job Title	Chief Estimator	Safety Officer	Planner	Director	Bid Manager
Annual Turnover	£10-100M	£10-100M	£10-100M	£1-£10M	>£100M
Recent experience of using cranes	No	Yes	Yes	No	No
No. sites with 1 crane		1-2	1-2		
No. sites with more than 1 crane		1-2	0		
Decision to use cranes	Yes	No	Yes		
Decision to locate cranes		No	Yes		
Preferred location strategy					
Inside but utilizing an opening		1		4	1
Inside with 'making good' later				3	2
Outside but tied to structure	1			1	3
Outside away from the structure			1	2	4
Location importance	1	1	1	1	1
Factors influening location					
Ease of erection	4	2	2	2	2
Need for base	4	1	3	2	1
Need to reach	1	1	1	1	1
Avoid overswing	2	1	2	3	2
Avoid making good	2	3	2	3	2
Ease of dismantling	4	2	2	2	2
Crane type					
Accessibility of pick up					
Ground conditions					
Obstructions					
Crane capacity					
Minimize radius for heavy loads			1		
Operator visibility			1		
Methods used to locate cranes					
Common sense			✓		✓
Past experience		✓	✓	✓	✓
Company system		✓			
Graphical methods	✓	✓	✓		✓
Computer methods	✓	✓			
Considerations when using cranes					
Crane uses shortest possible jib	2	1	2	2	1
Crane is fully utilized	1	1	2	1	2
Crane works efficiently	2	1	2	1	1
Likely to place crane at perimeter					
Seriously consider	✓		✓		✓
May consider				✓	
Unlikely to consider					
Would not consider					
Not sure/don't know		✓			

Respondent	21	22	23	24	25
Background and experience					
Job Title	Engineer	Planner	Planner	Planner	Business Manager
Annual Turnover	>£100M	£10-100M	£10-100M	£10-100M	£10-100M
Recent experience of using cranes	Yes	Yes	Yes	Yes	Yes
No. sites with 1 crane	3-5	1-2	3-5	3-5	6-10
No. sites with more than 1 crane	>10	1-2	0	1-2	1-2
Decision to use cranes	Yes	Yes	Yes	Yes	Yes
Decision to locate cranes	Yes	Yes	Yes	Yes	Yes
Preferred location strategy					
Inside but utilizing an opening		2	2	4	1.5
Inside with 'making good' later		4	3	3	4
Outside but tied to structure		3	4	2	1.5
Outside away from the structure	1	1	1	1	3
Location importance	1	1	1	1	1
Factors influening location					
Ease of erection	2	3	1	2	2
Need for base	3	1	4	4	2
Need to reach	1	2	2	1	1
Avoid overswing	1	3	2	1	3
Avoid making good	3	2	3	3	3
Ease of dismantling	2	2	2	2	1
Crane type					
Accessibility of pick up					
Ground conditions					
Obstructions				2	
Crane capacity				2	
Minimize radius for heavy loads					
Operator visibility					
Methods used to locate cranes					
Common sense		✓	✓	✓	✓
Past experience	✓	✓	✓	✓	✓
Company system					
Graphical methods		✓			✓
Computer methods					
Considerations when using cranes					
Crane uses shortest possible jib	4	3	2	1	1
Crane is fully utilized	2	1	1	1	2
Crane works efficiently	1	2	2	1	1
Likely to place crane at perimeter					
Seriously consider	✓				
May consider		✓	✓	✓	✓
Unlikely to consider					
Would not consider					
Not sure/don't know					

Respondent	26	27	28	29
Background and experience				
Job Title	Managing Director	Estimator	Contract Manager	Planner
Annual Turnover	£10-100M	£10-100M	£1-10M	>£100M
Recent experience of using cranes	No	Yes	No	Yes
No. sites with 1 crane		0		3-5
No. sites with more than 1 crane		3-5		1-2
Decision to use cranes		No		Yes
Decision to locate cranes		No		Yes
Preferred location strategy				
Inside but utilizing an opening	1	1	2	2
Inside with 'making good' later		2	3	1
Outside but tied to structure		3	1	3
Outside away from the structure		4	4	4
Location importance	1	1	1	1
Factors influening location				
Ease of erection	3	2	2	2
Need for base	2	2	2	
Need to reach	1	1	2	4
Avoid overswing	2	2	1	1
Avoid making good	2	2	3	2
Ease of dismantling	3	2	3	2
Crane type				
Accessibility of pick up				
Ground conditions				
Obstructions				
Crane capacity				
Minimize radius for heavy loads				
Operator visibility			3	
Methods used to locate cranes				
Common sense	✓			✓
Past experience		✓		✓
Company system				
Graphical methods	✓	✓	✓	
Computer methods				
Considerations when using cranes				
Crane uses shortest possible jib	1	2	2	3
Crane is fully utilized	1	1	1	2
Crane works efficiently	1	1	3	1
Likely to place crane at perimeter				
Seriously consider	✓			✓
May consider		✓		
Unlikely to consider			✓	
Would not consider				
Not sure/don't know				