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An investigation of the flexibility properties of the location set covering problem.

Michael Kenneth. Cooke
University of Windsor

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An Investigation of the Flexibility Properties of the Location Set Covering Problem

by

MICHAEL KENNETH COOKE

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ABSTRACT

An Investigation of the Flexibility Properties
of the Location Set Covering Problem

by

Michael Kenneth Cooke

In recent years, there has been a marked rise in the interest of how facilities which serve the public might be best arranged in a community. The Location Set Covering Problem (L.S.C.P.) is one method that has been brought forth to assist decision-makers. It seeks to identify the minimum number and location of facilities that are required to serve citizens within a specified distance. The L.S.C.P. uses linear programming techniques and, therefore, offers seemingly inflexible optimal solutions. The purpose of this study was to determine how the L.S.C.P. might be used to provide flexible strategies to the decision-making process in public facility planning.

The nature of flexibility and the offerings of the L.S.C.P. were discussed and the findings suggested that it would do well to look at the approach in a broader aspect. Strategies that deviated from the standard answers of the

L.S.C.P. were developed with the hope that flexibility might be induced. Sample cases for the location of fire stations, schools, ambulance depots, and day care centres considered these strategies and were found to offer alternatives to decision-makers. In this regard, this study has demonstrated that the L.S.C.P. can assist in the planning of public facilities by providing flexible alternatives.

In memory of my mother.

ACKNOWLEDGEMENTS

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Finally, I owe thanks to my family and friends for their patience and support during the final stages of this work.

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Chapter I

INTRODUCTION

1.1 Background

1.1.1 Change and Flexibility

Cities and the systems that operate within them are frequently subjected to change. It is the concern of decision-makers to identify any influence that change might bring to the performance of a system and also suggest how it might be accommodated. In some instances change may take place without forewarning and the immediate effect of its presence will be unknown. Considering the complexity of city systems, the task of managing them is not an easy one. The need for the decision-making process to render itself capable of effectively responding to instability is therefore an important one.

A decision-making process that oversees the siting of public facility systems is not exempt from the presence of change. The desire to examine public facility arrangements is inspired by the belief that they share a common interest - to provide all members of a community with adequate levels of service. An alteration in demand for a service, in the funding available for a service, or in the caliber of service, could represent forces acting on a system which might require modification to maintain its goals.

Considering the potential influence that change can have on the performance of a system and the safekeeping of the goals of a system, decision-makers might be assisted by flexibility. The value of this property is that if flexible strategies can be implemented, then the modification of the system might occur with ease and with a greater likelihood of acceptable outcome. As an example, if a city's budget for the operation of libraries is increased to permit the construction of a new one, decision-makers would prefer to have more than one site from which to choose.

1.1.2 Mathematical Approaches

The literature indicates that mathematical methods have been widely applied to obtain solutions to facility location problems (Yeates 1963, Gould 1966, Holmes 1972, Dear 1974, Massam 1981). While many mathematical approaches can be of assistance by providing solutions that select one facility arrangement from many, they are deterministic and therefore offer seemingly inflexible answers. Most of these studies utilize some form of linear programming to identify facility patterns.

Using information that describes the location and magnitude of demand areas and the location of possible facility sites, the decision-maker might want to consider certain constraints. Among the constraints most common are:

the number of facilities to be provided; a specified distance or time that no user is to be farther from a facility; minimizing the average distance between all users and facilities; or serving the greatest percentage of the population with the fewest facilities.

In linear programming, the solutions are optimal in that all factors or constraints are efficiently directed towards the achievement of a desired objective (Lapin 1985). Focusing on a single objective is likely, however, to pose a restriction on the alternative choices available given the mathematical rigidity of optimal solutions. In some applications the optimal answer may be all that the decision-maker seeks, but the planners of facility systems would generally value the flexibility associated with having a number of choices.

The location set covering problem (L.S.C.P.) is one approach that is frequently used to solve public facility location problems. Since its introduction, the L.S.C.P. has been applied to determine the locations of a broad range of public facilities such as hospitals (Ali 1984), ambulance depots (Toregas et. al. 1971, Eaton et. al. 1985), fire stations (ReVelle and Swain 1970), and day care facilities (Holmes et. al. 1972). Given the number of applications of the covering problem it may be considered to be the fundamental approach taken in facility location problems.

No previous discussions of the L.S.C.P. have, however, examined the types or levels of flexibility offered. The purpose of this study will be to determine how this approach can provide flexible strategies to the decision-making process of public facility planning.

1.2 Relevant Literature

The L.S.C.P. is of particular value to the planning of public facilities since it does not distinguish between areas that demand service. All areas are served by the type of facility ~~planned.~~ within a distance specified by the planner. This goal differs from the interests of facility planning in the private sector which generally seeks arrangements that maximize profit.

The L.S.C.P. is able to identify the minimum number and arrangement of facilities in a system whereby all points of demand are within some specified distance or time. In the context of the L.S.C.P. this specified distance is refered to as the maximal service distance. The method identifies, for each facility required, the set of demand points that it can "cover" and, in effect, the service area of each facility.

If the number of facilities is to remain minimized, then only those identified as possible sites can be chosen. In this regard the standard solution might be viewed as inflexible. Decision-makers cannot depart from the standard answer by substituting potential sites for those identified.

Toregas, Swain, ReVelle and Bergman (1971) applied the L.S.C.P. to the State of New York to identify possible arrangements of emergency medical facilities. Given distances between thirty possible facility sites, they applied linear programming techniques to determine the location of facilities based on a range of response times for ambulances.

The relationship between the number of service facilities required as a function of the service distance was displayed in graphical form. The value of a maximal service distance or time was summarized as being:

> a prime factor in the location of public service facilities, since it tends to reflect well the decision process of those who would be using these facilities, and offers the decision-maker a quantifiable indicator on which he may base a decision (Toregas, ReVelle 1972).

This view supports the belief that the L.S.C.P. appeals to the planners of facilities to be used by all members of the public.

A model based on the logic of the L.S.C.P. was constructed by Holmes, Williams and Brown (1972) to locate day care centres in Columbus, Ohio. For a range of service distances their concern was to identify arrangements that considered the construction of new centres combined with the keeping of some of the existing facilities. The results provided decision-makers with choices in the level of service that might be useful under a constrained budget.

Chapter II

RESEARCH DESIGN

The nature of the L.S.C.P. makes it a useful tool for public facility planners. This chapter will outline how the approach will be assessed to identify the measure and types of flexibility that the L.S.C.P. might offer. The procedure shown in Figure 1 illustrates the steps that will be taken.

(1) Chapter 3 will be a discussion of types of flexibility and how they might be induced in decision-making. The intent is to provide a framework that will be central to an assessment of the manner in which flexible solutions might be obtained for problems normally handled by the L.S.C.P.

(2) The L.S.C.P. is characteristically able to provide certain answers to facility location problems. If a planner is to consider a set of potential facility sites, the L.S.C.P. can identify the minimal number, and also which of the sites are required to serve a population within a specified service distance. The approach utilizes zero-one linear programming techniques to solve the problem.

Definition of Flexibility as
Recognized in the Literature

↓

Identify the Types and Measures
of Flexibility Offered in the
Standard and Alternate Solutions

↓

Illustrate Parallel and Serial Flexibility
in Facility Location Problems

↓

Identify the Value of the
L.S.C.P. to Decision-making

Figure 1: Research Methodology

The program is of the form:

Define $X_j = 1$ if a facility is located at node j, or 0 if no facility is located at node j. Given the distances between potential sites, one must minimize

$$Z = \sum_{j=1}^{n} X_j$$

as the number of facilities. However, each area must have a facility within a maximum distance S, hence, the constraints

$$\sum_{j \in N_i} X_j \geqslant 1$$

for all nodes i, where N_i is equal to the set of nodes within the maximum distance S, of node i. Formally defined as

$$N_i = \{ j \mid d_{ji} \leqslant S \}$$

In Chapter 4 the methodology of the L.S.C.P. is examined to identify the types and measures of flexibility offered. Alternative strategies with some objective in mind are developed.

(3) Chapter 5 will illustrate cases in which the planner might use the types of flexibility discussed in Chapter 4 to provide decision-makers with alternative strategies. The chapter will seek to determine how the L.S.C.P. might be used to provide some types of flexibility not offered in the standard answer.

(4) The final chapter will assess the flexibility properties of the L.S.C.P. The results will be used to

determine the utility of the procedure in developing flexible decision-making strategies for the location of public facilities.

Chapter III

AN APPROACH TO FLEXIBILITY

3.1 Flexibility as a Desirable Property

Flexibility may be seen as the capability of decision-makers to evaluate a range of possible solutions to a problem and to make adjustments to the structure of the system so as to ensure the attainment of the goals of the system (MacKinnon 1968, Eilon 1972). Central to this definition of flexibility is the opportunity provided for a decision-maker to choose from more than one option. The reasons that may suggest one of these options is "better" than another are not of interest. Instead the focus is to accept flexibility as a desirable property and that a decision-maker might strive to maximize it by selecting methods for which the types and measures of flexibility are known.

No system with any level of complexity is able to operate without being influenced by the elements of change. Of particular interest to decision-makers are changes that require a response to be taken. Seen in this light, flexibility might be interpreted as a response capability, that is, "it occurs in situations where a critical change can be perceived and an appropriate response can be selected and implemented" (MacKinnon 1968).

The existence and measure of flexibility offered under present circumstance is often a function of decisions made at an earlier stage. Therefore, it may not always be present. To ensure flexibility, it can be incorporated into planning strategies as an operational criterion for the selection of alternatives (Morlok 1969). The intent is to ready or prepare the system, and to make decisions in the present so that planners will not be faced with restricted choice in the future. This suggests that flexibility is a potential source of assistance for decision-makers that might be best utilized in times of critical change.

The question to consider is - if flexibility is a desirable property, to what lengths should decision-makers go to obtain or increase it? If, for example, a greater range of options can be considered by accepting a lesser goal, should such an action be taken? Since no set penalty may be borne immediately by a strategy that offers little or no flexibility, a decision-maker may be uncertain if lowering the goals of a system to provide more alternatives is a worthy exercise.

3.2 Decision-Making Under Uncertainty

Decision-makers may seek to identify flexible strategies when faced with uncertainty. The clear advantage is to avoid a full concentration of efforts on a plan which might eventually prove to be misleading or incorrect. By selecting strategies with full recognition that situations are subject to uncertainty, a more neutral and yet assuring commitment is likely.

Three types of variables taken together reflect the presence of uncertainty in decision-making:

> (1) Action or decision variables refer to those decisions that a planning and control system can directly determine.
>
> (2) State-of-nature variables are "the set of exogenous factors over which a planning and control system has little, if any, control, but which must be considered in order to take appropriate actions".
>
> (3) Outcome variables are the product of decision and state-of-nature variables. (MacKinnon 1968)

Flexibility could be interpreted in terms of the size of the action variable space. If a decision-maker is able to increase the set of action variables, then the level of uncertainty regarding the nature of the system will decrease. This would allow the decision-maker to be more informed and, therefore, better able to select a flexible strategy.

The ability of a system to respond effectively to state-of-nature variables is also a measure of its flexibility. These variables are not simply those which the decision-maker is unable to control, but also those of which he/she may be totally unaware.

Uncertainty, then, may arise in decision-making out of: (1) an inability to predict or even observe which state-of-nature will best describe reality at any given time; (2) a failure to know the complete set of feasible actions or the full set of possible states-of-nature at any time; or (3) a failure to know the functional relationships which describe and predict the interaction of state-of-nature and action variables.

Conrath (1967) adds that even in cases where the state-of-nature set is revealed through perfect forecasting, the decision-maker must still decide the course of action that ought to be taken. It is in these situations of critical change, where future action is unknown, that a decision-maker may be hard pressed to select a strategy to satisfy predetermined goals. Whether the strategy suggests an immediate or a deferred action, it is most desirable to provide the system with a range of potential actions, and this implies the existence of some measure of flexibility.

3.3 The Role of Planners and Controllers

The terms planner and controller are generally applied to those persons who oversee the decision-making of changing systems. While the terms are not always mutually exclusive and may often refer to the same person, it is important to differentiate between the two when considering decision-making in relation to different periods of time.

Controllers are recognized as being those persons who make decisions that influence the status of a system for a short period of time. Starr (1966) considered the role of the controller to be closely tied to the repetitive features of a particular system and the execution of policy. He defined policies as "pre-planned, deferred decisions waiting to be activated by the occurrence of specific situations for which they were designed". It is the function of the controller to operationalize policy and then monitor its behaviour in a static time frame.

Planners, on the other hand, tend to be concerned with dynamic strategies and types of decisions that alter the structure of a system in a more permanent manner. These decisions may involve implementing plans that follow extensive research and are characterized by high capital and infrastructure expenditure. Flexibility ought to be examined with the distinction between these terms in mind.

3.4 Operational and Developmental Flexibility

MacKinnon (1968) defined operational flexibility as

> the capability of controllers to make adjustments to the status of the system in response to relatively short-term fluctuations in system and/or environmental variables.

Central to this definition are the notions of adjustments and short-term fluctuations. An adjustment to a system is the way in which controllers modify the system in the face of transitory change. An attractive feature of the adjustment process is that it may be able to provide flexibility by yielding decisions that are easily changed in light of their short-term commitment.

In contrast, developmental flexibility is concerned with decisions of a planner that imply a long-term commitment. The critical nature of the temporal stream in developmental planning contrasts with its unimportance in static decision situations (Starr 1966). While the distinction between operational and developmental flexibility may be somewhat arbitrary, developmental decisions imply a capability of the system to adapt in a more permanent fashion.

3.5 Inducing Flexibility

Decision-makers may be able to induce flexibility by modifying specific components or elements of a system. This action can be obtained through either a parallel or a serial relationship.

Parallel flexibility occurs when a decision-maker is able to directly change the status of component A in a system (Figure 2). Change might increase, decrease or terminate the contribution of an active system component or, assign responsibility to a previously dormant component.

Even though this type of flexibility appears to segment the function of components, it does not overlook the value of comprehensive system planning. The complex interrelationships of components within a system seldom allow for only a single one to be modified. Thus, parallel flexibility permits substitution or reassignment and a general interchangeability of the roles and activities of a number of elements in the same stage of decision-making.

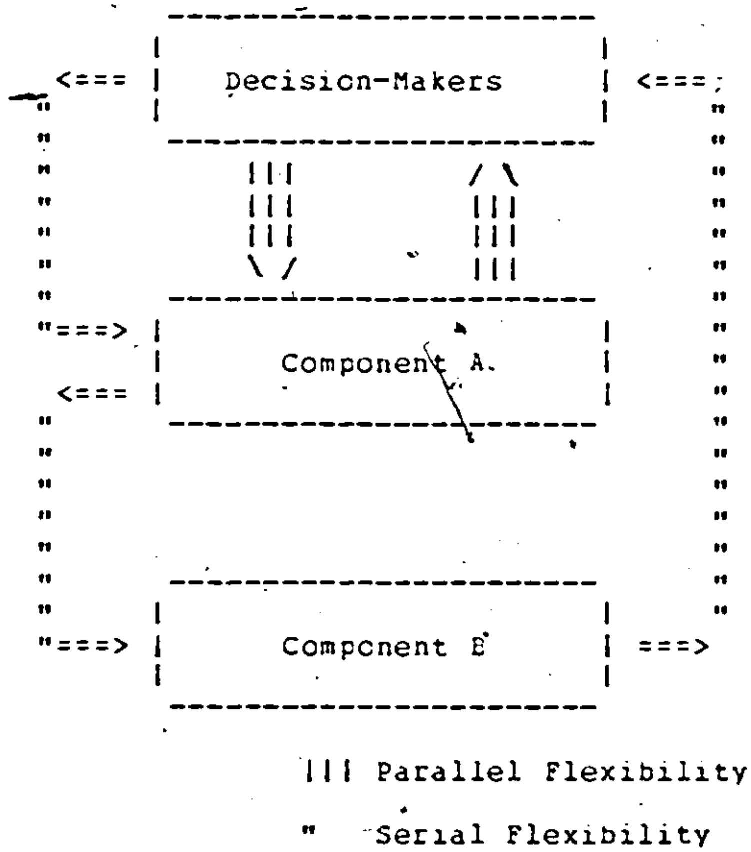


Figure 2: Inducing Flexibility

The nature of parallel flexibility suggests that it satisfies the goals of a system over short periods of time. This is because a decision-maker implements change by adjusting the system and anticipates that additional change may soon be required. This is the realm of controllers.

Serial flexibility is encountered when a component or subsystem allows a decision-maker to change the status of another component. Figure two illustrates this in the situation that a decision-maker is assisted by component A to change component B. This type of flexibility is related to the long-term planning of a system. Decisions are made in the interest of maintaining the goals of the system in the future and is therefore in the realm of the planner.

3.6 Strategies in the Decision-Making Process

There are strategies planners and controllers of public facility systems can employ that are directly related to the decision-making process. The crux of these strategies is the value of what can be learned over a period of time about the behaviour of a system undergoing change.

Sequential planning processes avoid full commitment to one fixed plan by deferring critical decisions. In the context of uncertianty the longer a decision can be deferred, the greater the chance that more can be learned about the state-of-nature variables acting on the system. The sequential process determines from a set of feasible alternatives those characteristics which are common. The effect of this is that the final decision between the total range of plans can be postponed until decision-makers are more certain (MacKinnon 1968).

Research and Development (R+D) strategies for example, consider the value of delaying critical decisions until more information can be obtained. The essence is to operationalize two or more desirable plans and to discontinue those that seem less favourable as more information becomes available. The favourability of a particular plan can be determined by evaluating new information that may be bought or learned by the unfolding of a plan. The underlying principle of R+D is that the value of learning will offset the additional costs of initiating and developing more than one plan - until a time when a single plan must be chosen.

3.7 Flexibility in the L.S.C.P.

The L.S.C.P. is a deterministic optimization procedure. By identifying facility sites based upon the single objective criterion that their numbers be minimized, the method would appear to be restricted to providing unique, inflexible answers.

For the facility planner, the L.S.C.P. identifies from a number of potential sites those which ought to be chosen given some limiting constraint. This direct application always indicates the location and number of facilities for any specified problem, and such answers are inflexible in that the standard arrangement is always the sole specified. The notion of flexibility, however, entails a consideration of solutions that hold when viewed from more than one standpoint. Therefore, if the standard arrangement is known, are there any alternative arrangements? And if so, how might they be compared with the standard? To ask such a question is to seek parallel flexibility, under which some degree of freedom to interchange components between the standard and any alternative arrangement is granted. Clearly such a feature is related only to short-term solutions.

The complexity of interrelationships between human beings, the facilities that serve them, and the environment, all act as a precursor to change. Since static solutions are often unable to respond effectively, it may be desirable for the facility planner to be aware of dynamic strategies. The L.S.C.P. approach will be examined to determine if it is able to provide serial flexibility, and through it long-term strategies.

3.8 Summary

Parallel and serial are two types of flexibility that have been discussed from a theoretical standpoint in this chapter. Planners and controllers are more likely to maintain the goals of a system that has been faced with change if they are able to induce either of these types.

Public facility problems can be viewed from the demand side, where the distance or time between citizens and facilities is stressed, or from the supply side, where the number of facilities provided is most important. Combining these standpoints and the offerings of short-term and long-term flexibility, the following figure represents a framework for facility planning which seeks flexible strategies.

Flexibility

Standpoint		Parallel	Serial
	Demand	X	XX
	Supply	X	XX

Figure 3: Theoretical Standpoints on Flexibility

Chapter IV

PARALLEL AND SERIAL FLEXIBILITY

This chapter seeks to identify the different types and measures of flexibility that can be developed out of the L.S.C.P. approach.

4.1 Initial L.S.C.P. Offerings

The degree of parallel flexibility may vary over a range of service distances. If the service distance is set at zero, no two points of demand can share the same service facility and therefore, it would be essential that each demand site be designated a facility site. The decision-maker is given no alternative arrangement, and in this regard, no flexibility.

Parallel flexibility will continue to remain absent for all service distances greater than zero until at least two demand points can be reached from each other. At this distance the decision-maker is able to choose one or the other as a site that can serve both.

All service distances that follow may not, however, provide a choice for the decision-maker. The number of combinations of potential servers will tend to be a function of the spatial arrangement of the demand points. No general pattern describing the relationship between the number of possible facility arrangements and the value of the service distance can be identified.

It is possible, however, to note a measure of parallel flexibility that is clearly in all applications of the L.S.C.P. if larger service distances are considered. When the service distance reaches a value that enables a single facility to provide coverage to all others it may initially permit no choice. Beyond this critical service distance, more points will become eligible to provide complete coverage. When the service distance equals the diameter of the demand surface all points will become eligible to provide complete coverage and the decision-maker has the flexibility to choose any one. This form of parallel flexibility can always be cperationalized at a service distance whose absolute magnitude will be a function of the spatial arrangement of the points.

4.2 Seeking_Alternatives_to_Induce_Flexibility

Generally, the greater the number of facility patterns that offer a choice between potential servers, the greater the chance new and flexible strategies might be identified. One way a decision-maker can increase the number of arrangements from which to choose is to consider answers other than the standard solution.

The nature of the L.S.C.P. makes it possible to consider at least two initial strategies. The first accepts the service distance as the criterion for facility siting. This strategy may be best suited, but not limited to, those types of services which operate under crucial time or distance restrictions. Fire stations, ambulance depots, and hospitals are the most common examples of such services. The decision-maker can select a maximal service distance and the L.S.C.P. will identify the minimum number and location of potential sites required to provide service to all within that given distance. This is equivalent to approaching decisions from the **demand** side.

A second strategy considers the number of facilities to be a priority. A decision-maker seeking a prescribed number of facilities might use the L.S.C.P. to identify a set of potential servers. This emphasis on the number of facilities might be utilized by the decision-maker who is financially restricted and can only consider a set number of facilities. The difference here is that the decision-maker places no interest on the size of the service distance directly, but rather, an arrangement for the desired number of facilities. This strategy focuses on the **supply** side of decision-making.

Under either strategy a decision-maker might want to identify arrangements that are possible if a constraint is relaxed. If a service distance or a number of facilities is specified, can flexibility be gained or even created by considering an arrangement other than the standard one? If flexibility can be induced, decision-makers might want to examine the merits of changes in comparison to the costs which must be borne.

4.3 Seeking Flexible Strategies

Parallel flexibility might be present in situations where a run of the L.S.C.P. identifies two or more combinations of facilities. Under such conditions the decision-maker is given the freedom to select one of the arrangements. When the number of facilities or the maximal distance is at acceptable measures, and there are at least two possible facility arrangements, the planner can benefit from parallel flexibility by employing one of two strategies.

4.3.1 Minimizing Distance in a Facility Arrangement

The first strategy would be to seek the pattern of facilities that minimizes the total service distance between all users and their nearest server. By measuring the distance between each user and the nearest facility for each combination of facilities, the total service distance for each pattern could be identified. The arrangement that offers the lowest average distance might be considered the most desirable. This strategy could be considered an approach from the demand side.

The greater the number of facility patterns that offer a choice between potential servers, the greater the chance the average service distance for the entire set will be reduced. One means of increasing the number of arrangements possible is to increase the service distance. A decision-maker who is able to consider larger service values might reveal new combinations with the same number of facilites. While the number of facilities required in the L.S.C.P. characteristically decreases with significant increases in the service distance, it might also be possible to decrease the average service distance without changing the number of facilities.

Consider the set of nodes in Figure 4. The first node which is able to singly provide coverage to the complete demand surface is A at a service distance of 12 units. This arrangement offers an average service distance of 7.4 units. Increasing the service distance to 13 units allows the decision-maker to choose either node A or B as the single site. If B is chosen then the average distance can be decreased considerably to 5.8 units. Had the planner been instructed to seek the location of a single facility with no specified service distance, he would have the flexibility to choose any one of the five. However, node B offers coverage to all with the smallest average distance, and could be viewed as the best choice under this criterion.

Using the same data another situation would be one in which a service distance had been specified. If no demand was to be farther than 12 units from a facility, the

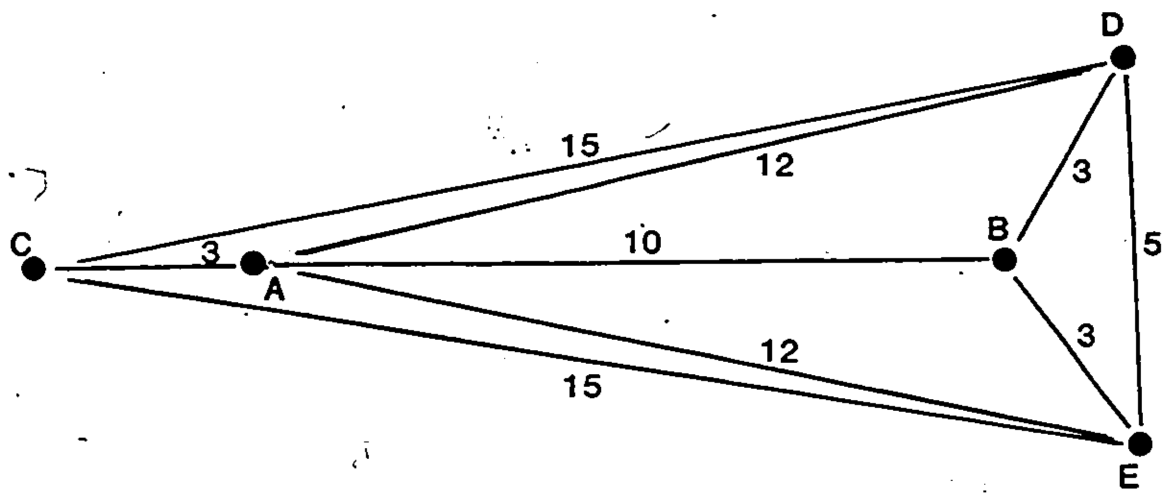


Figure 4: Minimizing Distance.

standard solution would identify node A as the only, and therefore, essential choice. In an effort to gain flexibility the planner might advise decision-makers on the alternatives available. For example, increasing the service distance to 13 units would allow node B to become a candidate site. Decision-makers may want to determine if the penalty incurred by increasing the service distance by one unit would be outweighed by the lower average service distance that a facility at B would permit.

The examples above all seek a single facility under different service distances. An alternative approach would be to increase or decrease the number of facilities required. Here too the possibility may exist for new arrangements to be created and examined.

If two facilities could be considered, one located at B and another at either A or C would be possible at a service distance of 3 units. The average distance to a facility would be 1.8 units which is the lowest possible with only two facilities. The questions to be answered would include - Are two facilities necessary? Is a maximal distance of 3 units, or an average distance of 1.8 units more desirable?

The "ideal" or most flexible situation might be considered to occur when each demand point is a potential server regardless of the number of facilities required or the service distance specified. The decision-maker might then select any combination of facilities.

4.3.2 Popularity of Potential Servers

A second strategy centers on the frequency particular nodes are identified as potential servers. It may be assumed the more frequently a node appears in a solution as a candidate facility site, the more likely it will contribute a vital role in any arrangement. By the same token, a node which seldom emerges as a candidate site could be considered unpopular and, therefore, less significant to the system as a server.

The popularity of a node as a possible site can be measured and compared with other nodes by the use of ratios. The ratio of the number of times a node is selected - to the total number of runs conducted (for the full range of service distances possible) could in turn be expressed as a percentage. This value would indicate the potential ability of a node to act as a server among the full range of service distances. The decision-maker may be interested in the popularity of a node in planning from the supply side.

A decision-maker searching for an arrangement containing a precise number of facilities or specified service distance may decide instead to accept an arrangement other than the standard which offers a node(s) identified as being a popular server. The trade-off here is to accept an alternate arrangement to gain flexibility in the long-run. The advantage of including or substituting any one or more servers within a standard rrangement is that the system can be assured of coverage among a greater range of service distances should change occur.

4.4 The Distribution of Demand

Identifying standard arrangements over a range of service distances can describe for the decision-maker the relationship between the spatial arrangement of potential facility sites and the L.S.C.P. constraints. A range of distances from zero up to the diameter of the set could be considered. A decision-maker might then use this information to select serially flexible strategies for the siting of facilities.

4.4.1 Maximizing the Number of Demands Covered

The premise of this strategy is the potential overlapping of covering sets that might occur if certain servers are selected. When more than one arrangement of facilities is possible the decision-maker might wish to choose the one which covers the greatest number of demand points. Making such a choice would enable some demand points to be serviceable by more than one facility in a demand side approach. By providing some demand points with at least double coverage then those demand points would remain serviced if conditions should change, or if facilities are out of operation temporarily.

There may be circumstances, however, wherein the arrangement that serves the greatest number of demands is not the desired choice. Instead, a decision-maker might want to select the combination of servers that provides the greatest number of different demand points with coverage by more than one server.

To identify the arrangement providing the most points or the greatest number of different points with double coverage would require that all combinations of servers and the points they cover be noted. Under either objective the collection of servers that resulted in the greatest degree of double coverage might then be chosen.

Under the goal of double coverage the most desirable arrangements might be found in solutions other than the standard one. Figures 5 and 6 show the covering sets of three facilities at service distances of 4.7 units and 5.3 units respectively. The standard solution for three facilities is offered when the service distance equals 4.7 units. If 4.7 was the specified service distance then 6 demands would have at least double coverage (1,2,4,7,9,12). By considering an alternate solution at 5.3 units, four additional nodes (6,10,16,18) could benfit from double coverage. It is important to note that all demands would still be within 4.7 units of a facility if the service distance was increased to 5.3 units. The decision-maker must evaluate the willingness to have some or all of these doubly covered points farther than 4.7 units from a facility should change occur. If change did occur in the future, namely a

Figure 5: Maximizing Coverage at a Service Distance of 4.7 Units

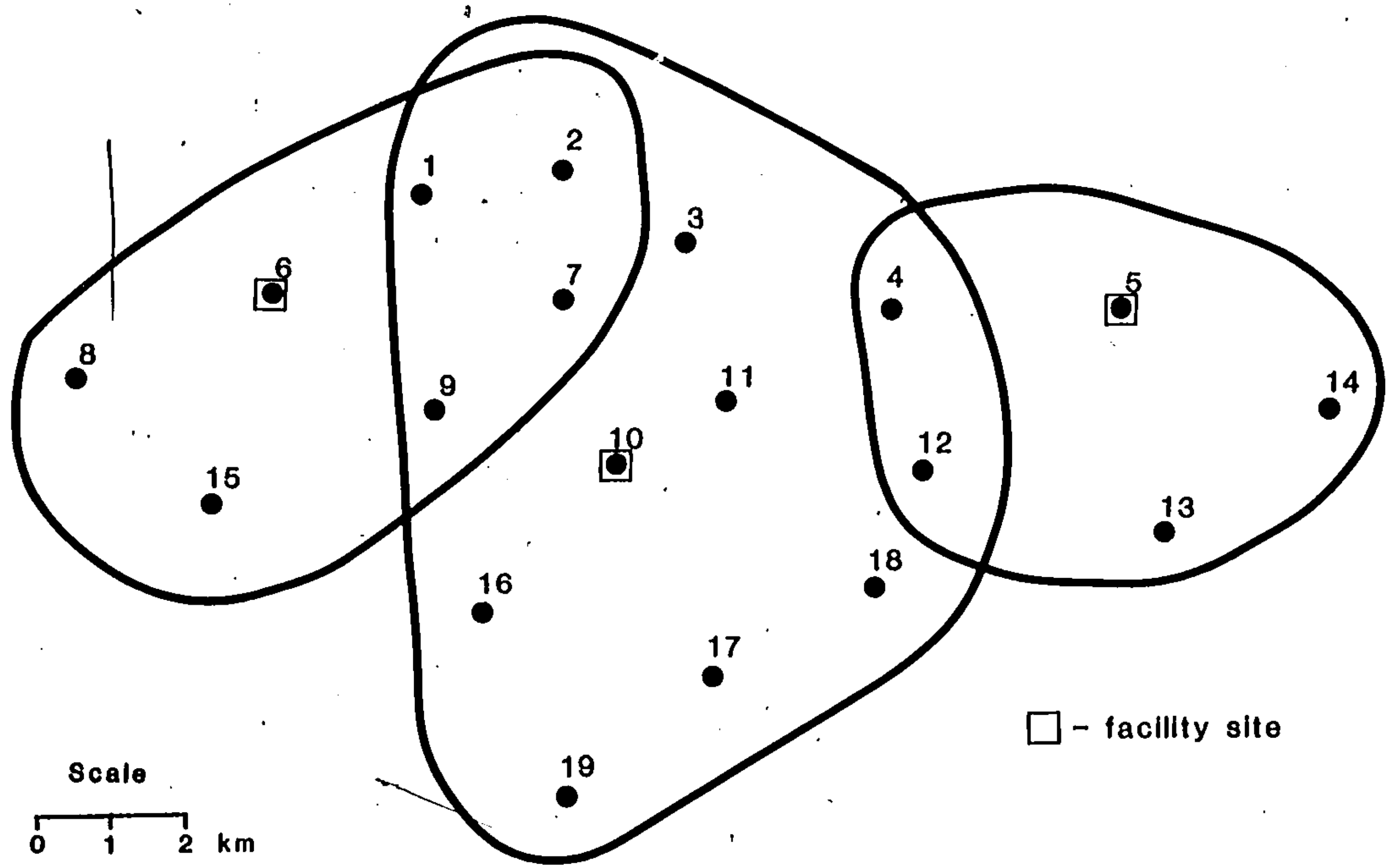
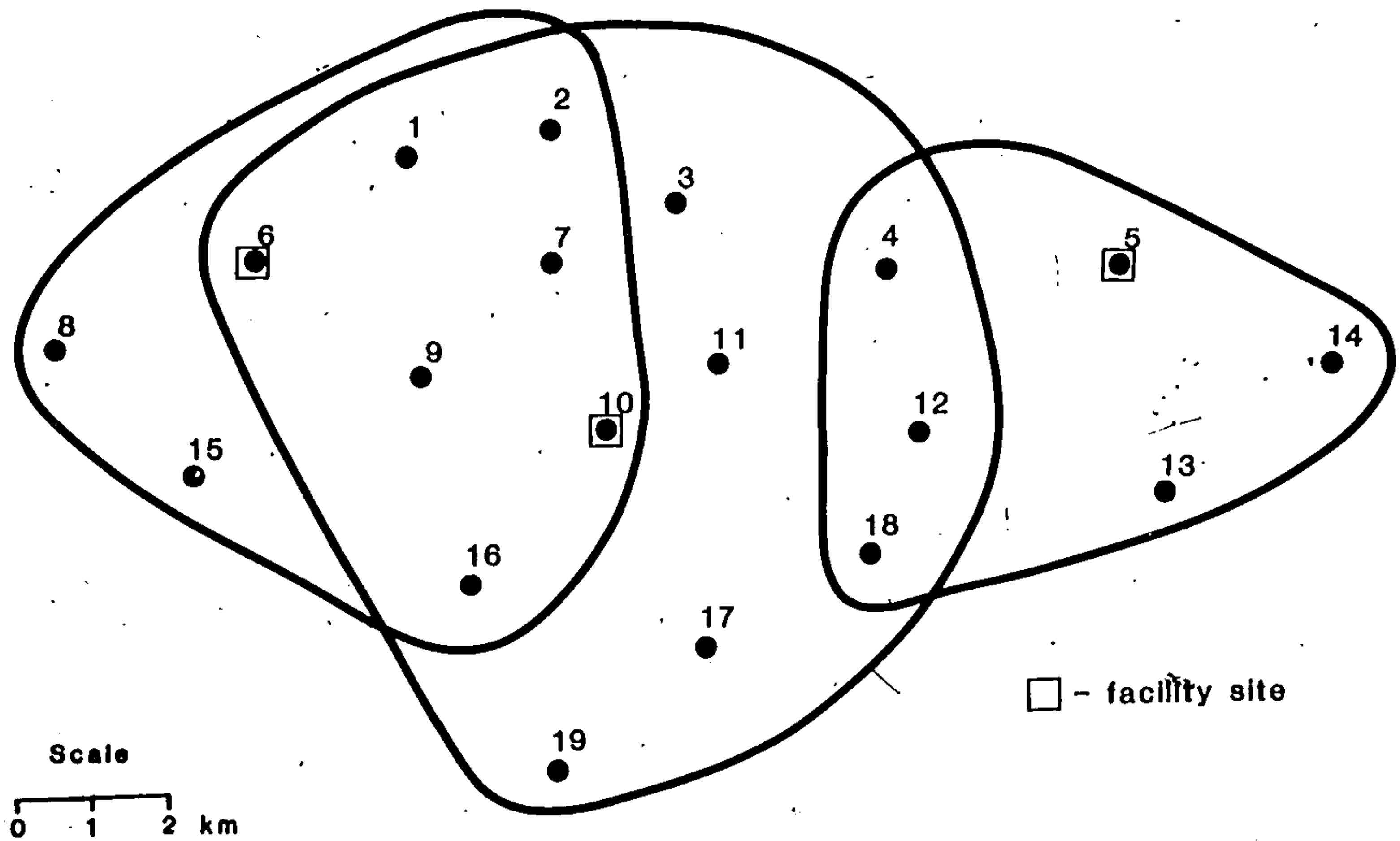


Figure 6: Maximizing Coverage at a Service Distance of 5.3 Units



reduction in facilities, it might be possible that some demands would remain serviced by serial flexibility.

4.4.2 Range of Coverage for a Number of Facilities

Applying the L.S.C.P. for a spectrum of service distances can provide insight into the set of potential servers and offer a supply side strategy. Of particular interest is the proportion of the entire range of distances over which a given number of facilities is able to provide coverage to all demand points. If increasing or decreasing the service distance by a small quantity results in a need to change the number of facilities for coverage, then that number of facilities could be considered to be serially inflexible. By comparison, if a specific number of facilities is able to maintain coverage for a greater measure of service distances, then serial flexibility might be deemed to exist.

The ability of a particular minimal number of facilities to provide demand coverage can be expressed as the portion of the total range of service distances that it occupies. This portion might be identified by measuring the difference between the highest and the lowest limits of the service distance that each number of facilities is able to ensure coverage. The difference could then be compared to the total range of service distances considered for the entire set of runs. The result would reveal the percentage of the total range of service distances that could be satisfied by any given number of facilities. The decision-maker could then rank the number of facilities based upon these percentages.

In this context, serial flexibility can be induced by choosing the number of facilities that ensures coverage for the greatest range of service distances. The result would be an arrangement that could accommodate variations with time in the specified service distance.

4.5 Combining Strategies

A final perspective on the flexibility offered in the L.S.C.P. stresses the value of collectively considering at least two of the strategies outlined in this chapter. While each one suggests different types and measures of flexible decision-making possibilities, the combining of two or more of these strategies may often prove even more useful.

Comparing the options that result from different strategies that are applied to the same problem may reveal trade-offs that would have otherwise gone unnoticed. These trade-offs can introduce to the decision-maker new questions regarding the performance of the system "...if strategy X suggests nodes A,B,C ... how might this compare with the selection of nodes D,E,F,G in strategy X and Y combined? By merging different strategies and their solutions it may be possible to create entirely new and more appealing alternatives.

4.6 Summary

This chapter explored some of the practical options open to the planner who looks beyond the standard solutions provided by the L.S.C.P. and instead considers alternative answers.

The theoretical discussions on parallel and serial flexibility offered in Chapter 3 might now be viewed in light of these alternatives. The following figure sets the strategies according to the standpoint of the decision-makers and the type of flexibility that might be offered.

Standpoint	Flexibility: Parallel	Flexibility: Serial
Demand	Minimize Distance	Maximize Double Coverage
Supply	Popularity of Potential Servers	Range of Service Distance

Figure 7: Operational Strategies for Flexibility

Chapter V

ILLUSTRATING FLEXIBILITY IN THE L.S.C.P.

5.1 Demand Side and Parallel Flexibility

If the budget of a city was reduced, forcing administrators to close two of the existing fire stations, planners might use the L.S.C.P. to assist them. In this example, if the number of stations was to be reduced from six to four the method would identify a standard arrangement of four facilities which would be able to provide coverage at the smallest service distance. The request of administrators to identify a pattern of four fire stations would be satisfied. However, if the two stations that did not appear in the standard arrangement identified by the L.S.C.P. were newly built facilities, then administrators and politicians might be interested in other options that would include these stations (Appendix A).

In an effort to offer parallel flexibility the planner might seek all the L.S.C.P. arrangements for four facilities that included the two new ones. To do so, the planner would need to consider larger service distances. The planner might then choose from those combinations the one which offered the smallest average service distance. Decision-makers would then need to decide if the benefits gained by keeping the new stations outweighed the increase in the service distance over that found in the standard solution for four facilities.

5.2 Supply_Side_and_Parallel_Flexibility

The administrators of a local school board are seeking an arrangement of three new schools. Since only the supply of facilities is specified, the planner might induce parallel flexibility by considering all possible arrangements of three.

In this situation the planner might initially consider the standard solution. However, if the minimization of the service distance is unimportant to administrators, the planner could use solutions from a full range of service distances to identify alternatives.

If a potential school site was identified in many of the solutions but not in the standard one for three facilities, flexibility might be gained by interchanging an unpopular site identified in the standard solution for three facilities with one identified in many of the other solutions (Appendix B). By including in the set of three, one or more of those sites that are popular in many of the other solutions, the system might be better able to handle changes in the school population without having to open or close a school.

Alternatively, change in this case, might be if the student population in the southern section of the city increased to the point that an additional school was required. Under such circumstances the standard solution for four schools could easily be used, since three of the four are already in operation.

5.3 Demand_Side_and_Serial_Flexibility

In the planning of emergency medical services it is important to locate facilities so that the population can be served in the shortest distance or time. There may also be situations in which the number of demand areas that a facility can cover is of interest.

A sample case would be if the Ministry of Health wanted to improve the level of ambulance care by building two ambulance depots in a city that previously had none. The L.S.C.P. would provide two sites from a set of potential ones in a standard solution. The population could be serviced by the depots and no area of demand would be farther than a specified service distance from a station.

The standard solution may provide some areas with a choice of being served by more than one depot. This would only occur by chance since double coverage is not an objective of the L.S.C.P. To satisfy the request of Ministry officials for double coverage the planner might examine arrangements of two that are possible when the service distance is increased beyond that of the standard answer. Increasing the service distance might reveal combinations of stations that provide many of the demands with a choice of being served by more than one facility (Appendix C).

Emergency medical services may be required to provide service to different areas at the same time. Double coverage would allow for improved service by sharing the demand areas of facilities and providing back-up service to each other.

Serial flexibility might be gained by providing double coverage. If the Ministry decided in the future to reduce the number of depots from two to a single one, adequate levels of service might be maintained. The planner could determine which depot should be closed and which remain operating by identifying the arrangement that served the most demands. It is likely, however, that some demands would not be served within the specified service distance following the reduction to a single depot. This is because the L.S.C.P. minimizes the number of facilities making the double coverage of some demand points not possible. Decision-makers would need to decide if increasing service distance beyond that of the standard arrangement for two facilities would be beneficial.

5.4 Supply_Side_and_Serial_Flexibility

In the situation that administrators are not set on a particular number of facilities, the planner has the freedom to select different alternatives. For example, if city administrators wanted a number of municipally operated day care centres to be located throughout the city, the planner could first consider all standard solutions. The nature of the L.S.C.P. generally reveals that as the number of facilities decreases the range of maximal distance that can provide coverage increases. It may, therefore, interest the planner to know that increasing the number of day care centres from three to four might only reduce the service distance marginally (Appendix D). At the other extreme, it may not be until the service distance is significantly large that two facilities are able to provide coverage to the city. In this example the planner might recomend that two centres be built. These facilities would be able to ensure coverage over the greatest range of service distance and demand that may occur in the future.

5.5 Combining_Parallel_and_Serial_Strategies

It may be possible for the planner to induce parallel and serial flexibility by merging two of the strategies already discussed. Consider again the case in which city administrators are forced by budget constraints to reduce the number of fire stations from six to four. If the standard solution does not offer the two new stations that are to be kept as part of the arrangement, the planner might seek other combinations of four stations that include them. Substituting new combinations with those in the standard solution is made possible by parallel flexibility. The planner could then go on to identify the combination which offered the smallest average service distance as one strategy.

If administrators were interested in long-term options, the planner might induce serial flexibility before recommending a particular arrangement. This could be achieved by identifying from the possible combinations of four the one which offered the most demand points with double coverage.

Having determined the average service distance and the number of demands with double coverage, for all possible alternatives, the planner might recommend to administration a combination of the objectives (Appendix E). The planner might suggest a slightly higher average service distance to enable a greater number of demands to have double coverage.

This case combines parallel and serial strategies from the demand side. The final arrangement identifies covering sets that are quite likely to represent real interests of decision-makers. The combined strategy illustrated addresses the requirements that:

1. The total number of facilities must be equal to four;

2. The two new facilities must be included in the arrangement;

3. The average service distance be minimized; and

4. The number of demands provided with double coverage be maximized.

Many other combinations of objectives exist and are likely to lead to their own unique arrangements. The willingness of the decision-maker to consider alternate solutions is vital if many of the potential advantages resulting from combined strategies are to be realized.

Chapter VI

CONCLUSIONS

6.1 Parallel Flexibility

In order to operationalize parallel flexibility a planner must have the freedom to decide which potential facility sites will become actual facility sites. Therefore, the L.S.C.P. solution for a specified service distance or number of facilities must allow for some degree of substitution among the set of eligible sites.

The planner may seek parallel flexibility in a case that the standard solution for a particular service distance does not include a specific facility that decision-makers may want included. A facility may be attractive because it is newly built or offers specialized services. For whatever reason it is desired, if the standard solution does not offer it, then an alternative answer may be sought by inducing parallel flexibility.

Increasing the service distance will create alternative answers. The direct trade-off for including a desired facility in an arrangement would be the increase in the service distance and/or the average service distance. In many instances the increase is only marginal and, therefore, is outweighed by the benefit of using a desired facility.

Parallel flexibility may be desirable in a problem that rests on the number of facilities to be provided. When decision-makers have specified the supply of facilities to be provided the planner might consider the full range of solutions that are possible. This could assist the planner to identify the sites that are the most popular choices among all different numbers of facilities. Parallel flexibility might be induced by substituting one or more of the popular sites for those that are less popular.

The penalty associated with substitution is that some citizens would be farther from a facility than if the standard solution was chosen. The benefit, however, is that arrangements containing popular servers are more likely to continue to serve in a system if the service distance or number of facilities required should change.

6.2 Serial Flexibility

Long-term strategies may be of considerable value to planners and decision-makers of public facility systems. The construction of a new facility is an expensive undertaking and it is intended to serve the community for many years. Therefore, strategies which might be able accommodate change are often desirable.

One strategy offers serial flexibility by maximizing the number of citizens served by at least two facilities. In many cases it may be possible to provide double coverage to many citizens if alternative solutions of the L.S.C.P. are examined.

If a reduced budget requires that a facility be closed, the planner might suggest closing the facility which can have its users served within the service distance by another facility. Some citizens may have a slightly larger service distance but it is likely that the reduced number of facilities will still be able to adequately serve the community.

If decision-makers are open to recommendations on the number of facilities that ought to be provided, the planner might induce serial flexibility. The range of service distance over which a given number of facilities is able to serve the community is also a measure of the stability of the arrangement. If a particular number of facilities is able to ensure coverage over a large service distance, it will most likely continue to provide coverage if the service distance should need to be changed in the future.

6.3 Summary

Planners and decision-makers of public facilities seek strategies that allow them to accommodate change in budgets, population demands for service, and the caliber of service. At first glance it appears that the deterministic nature of the L.S.C.P. allows it to offer only inflexible answers, and therefore, be of restricted use in planning situations.

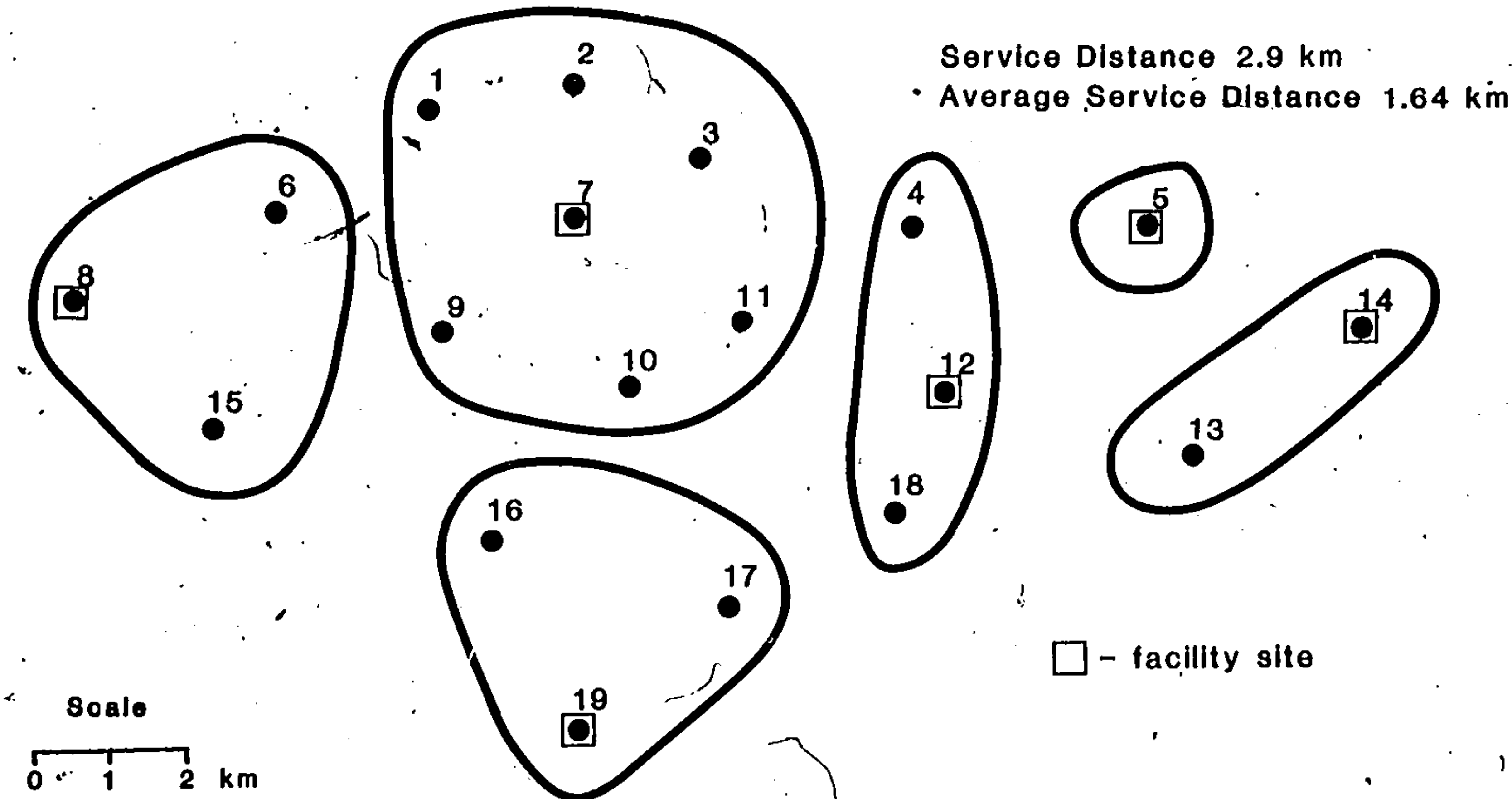
However, the strategies that may be employed when alternative answers are considered offer much to the decision-making process.

It has been possible to use the L.S.C.P. to develop strategies that focus on the number of facilities to be provided or the service distance between users and facilities or a combination of both. This thesis has demonstrated how the method can offer strategies that induce parallel or serial flexibility or both. With these enhancements the L.S.C.P. might now be considered an even more valuable tool with which planners and decision-makers can develop flexible strategies for the location of facilities.

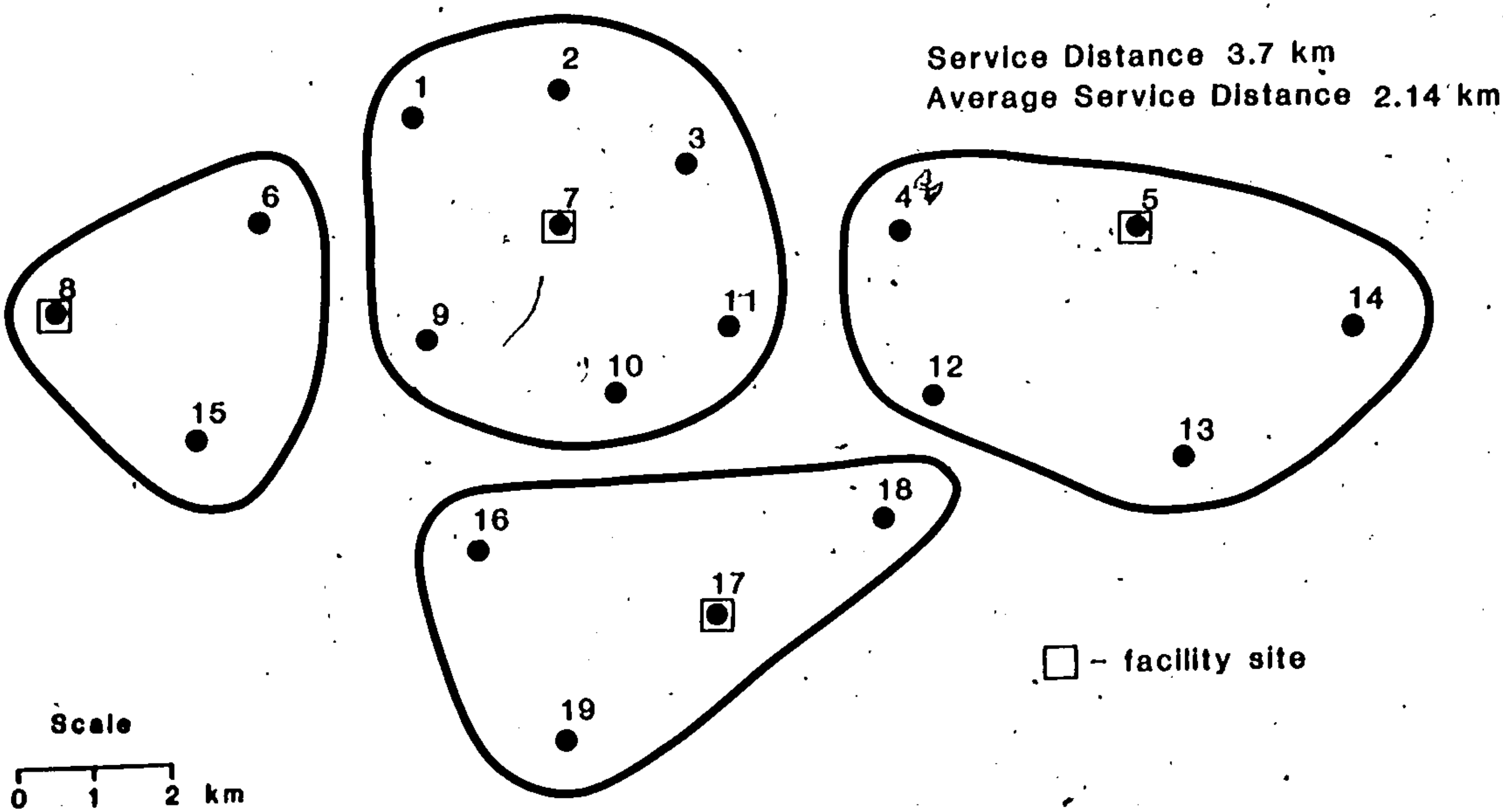
Appendix A

MINIMIZING_DISTANCE_FOR_A_FIRE_STATION_PROBLEM

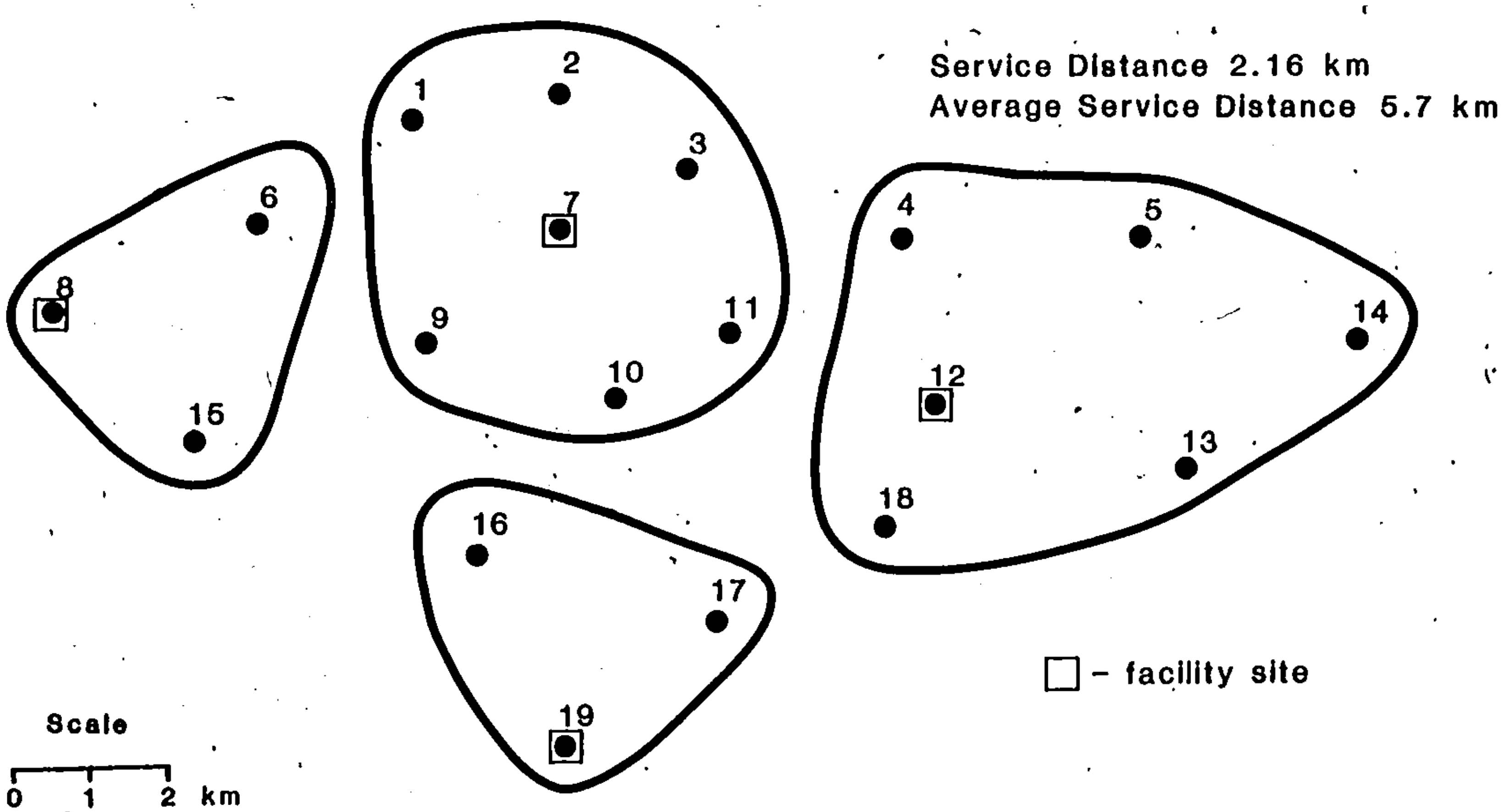
Existing Pattern of Six Fire Stations and the Demands they Cover
(Demands assigned to their nearest station)



The Standard Arrangement Identified for Four Fire Stations
(Demands assigned to their nearest station)



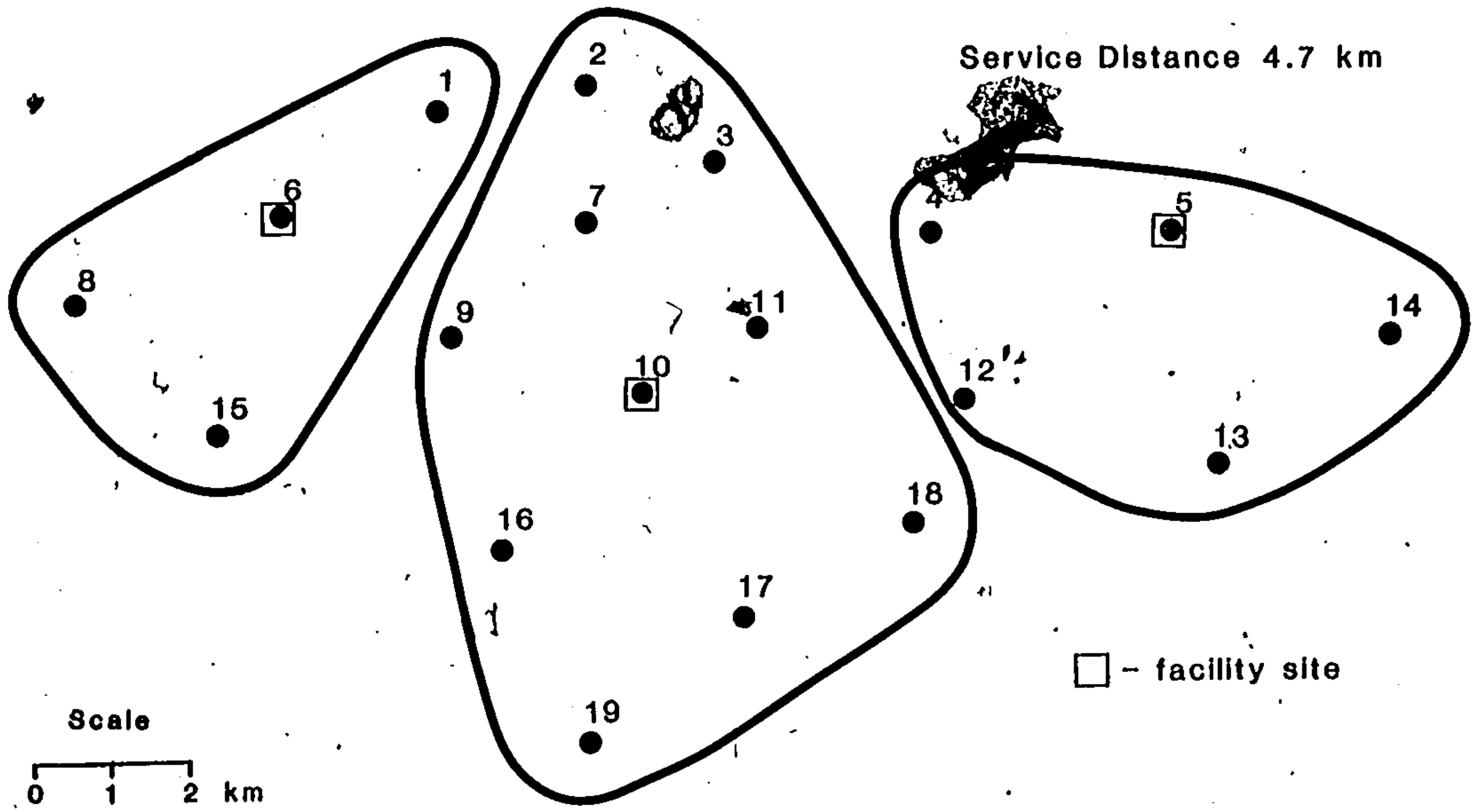
An Alternate Arrangement for Four Fire Stations –
Retaining the Two Newest 12 and 19
(Demands assigned to their nearest station)



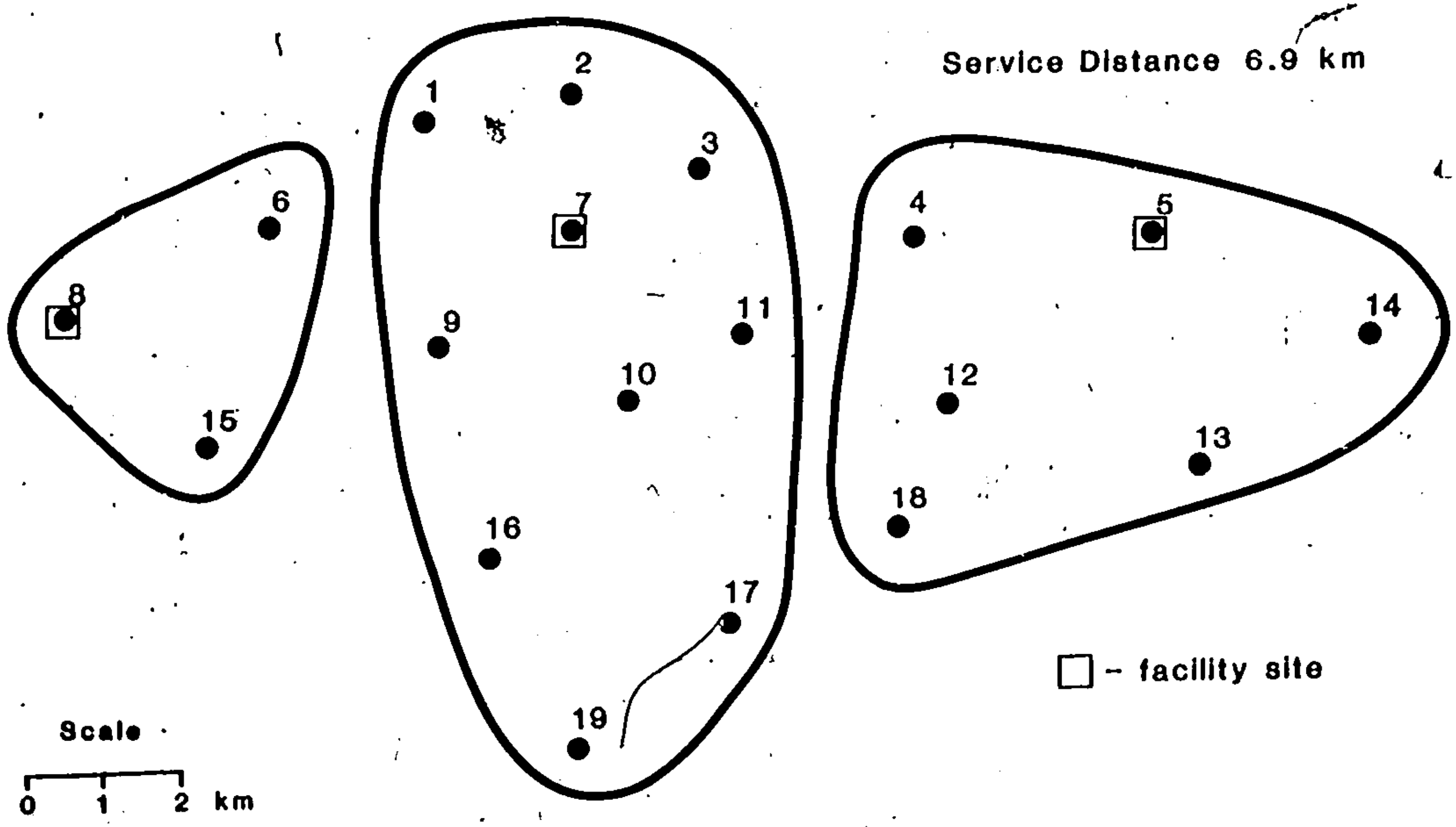
Appendix B

POPULAR_SITES_FOR_THE_LOCATION_OF_SCHOOLS

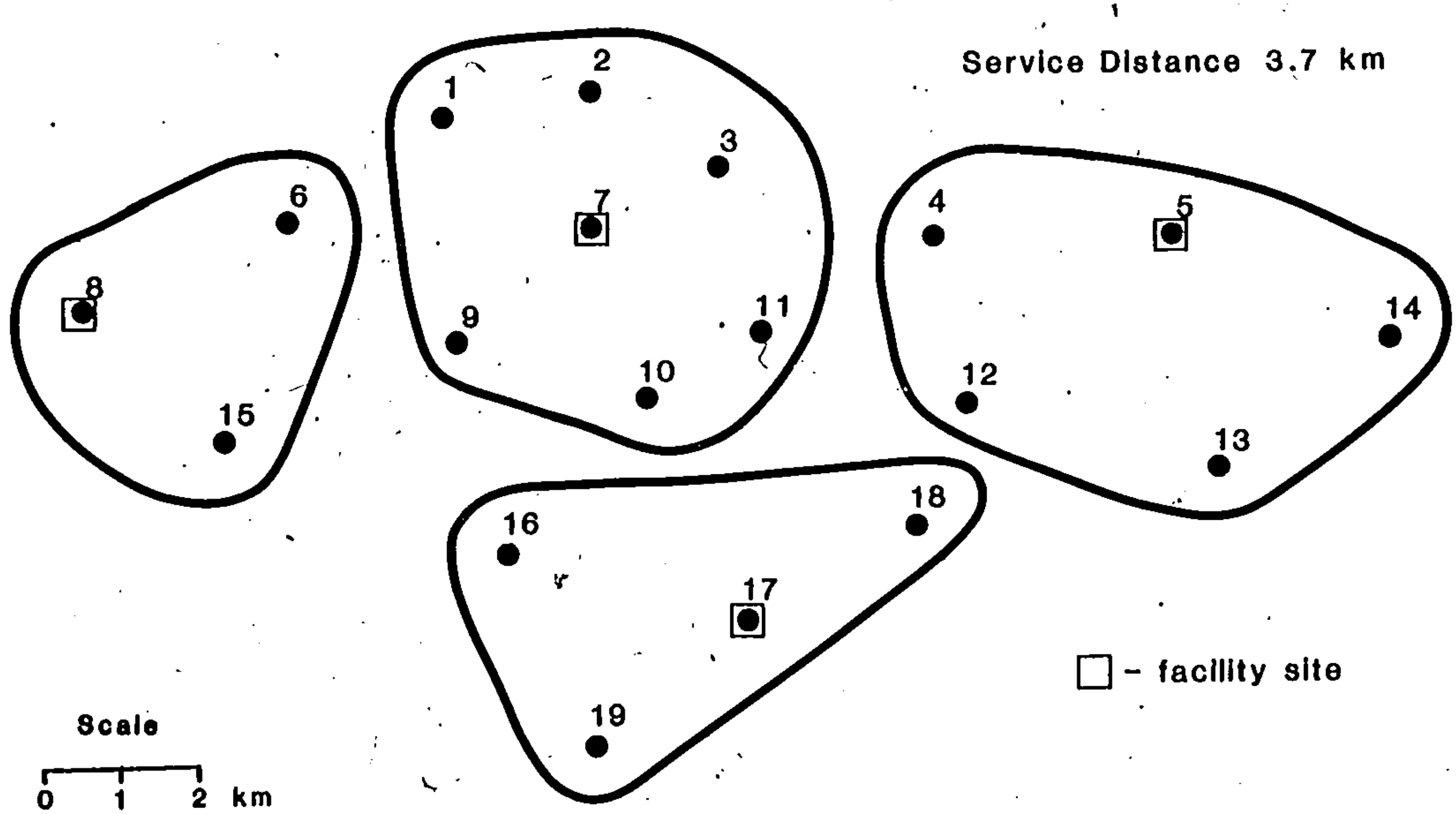
The Standard Arrangement Identified for Three Schools
(Demands assigned to their nearest school)



An Alternate Arrangement for Three Schools
(Demands assigned to their nearest school)



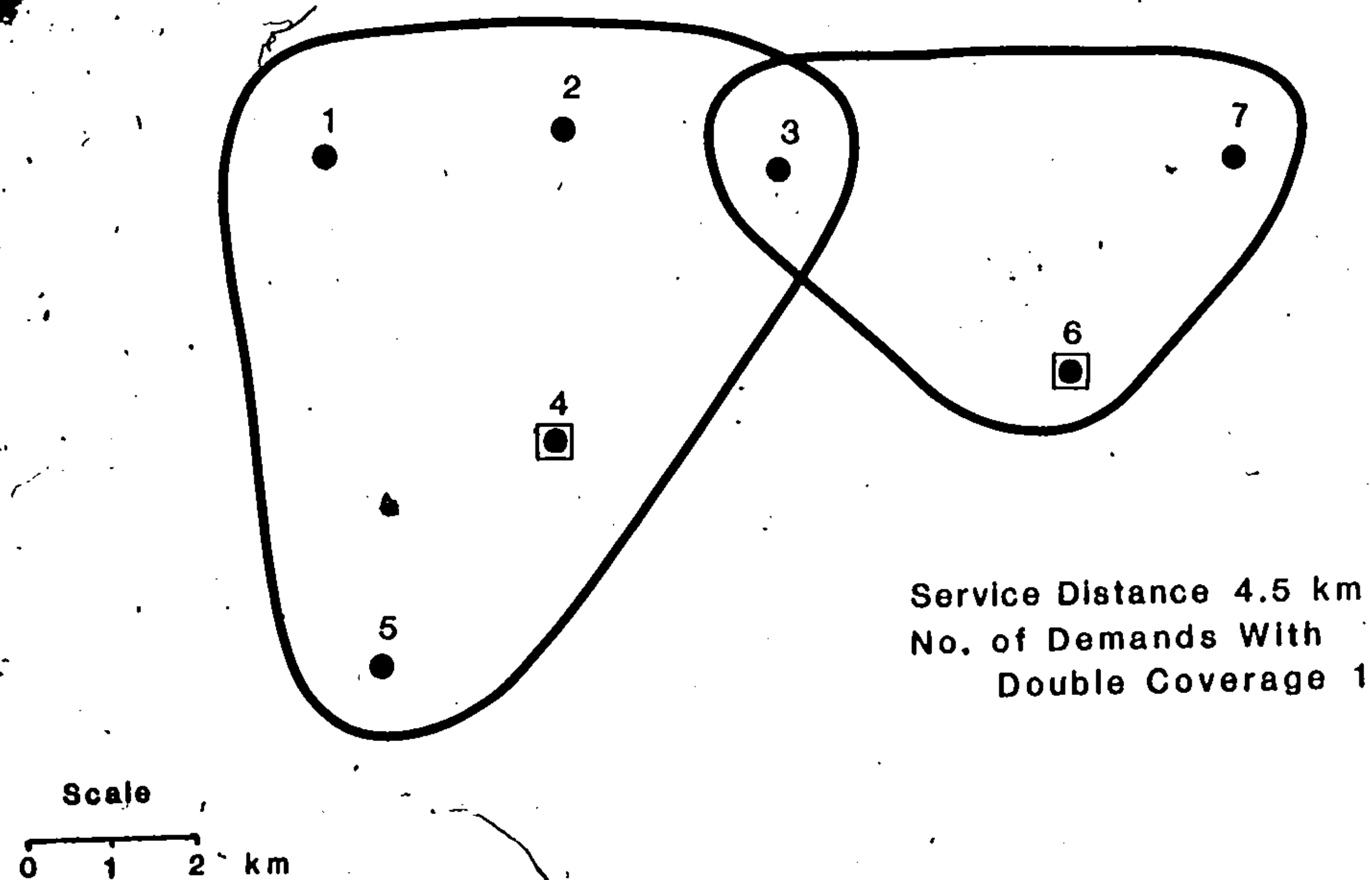
The Standard Arrangement for Four Schools
(Demands assigned to their nearest school)



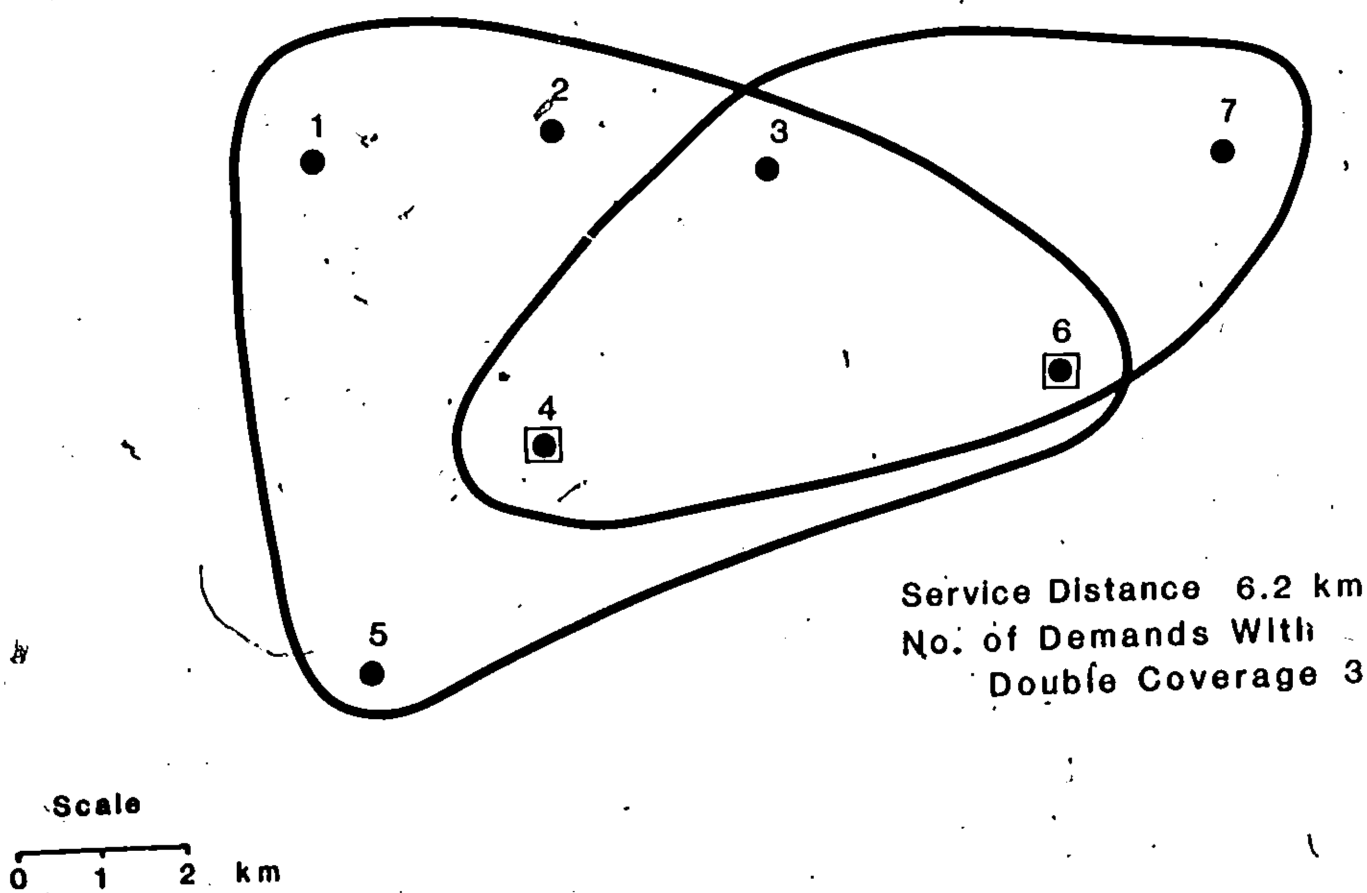
Appendix C

MAXIMIZING COMMUNITY COVERAGE OF AMBULANCE DEPOTS

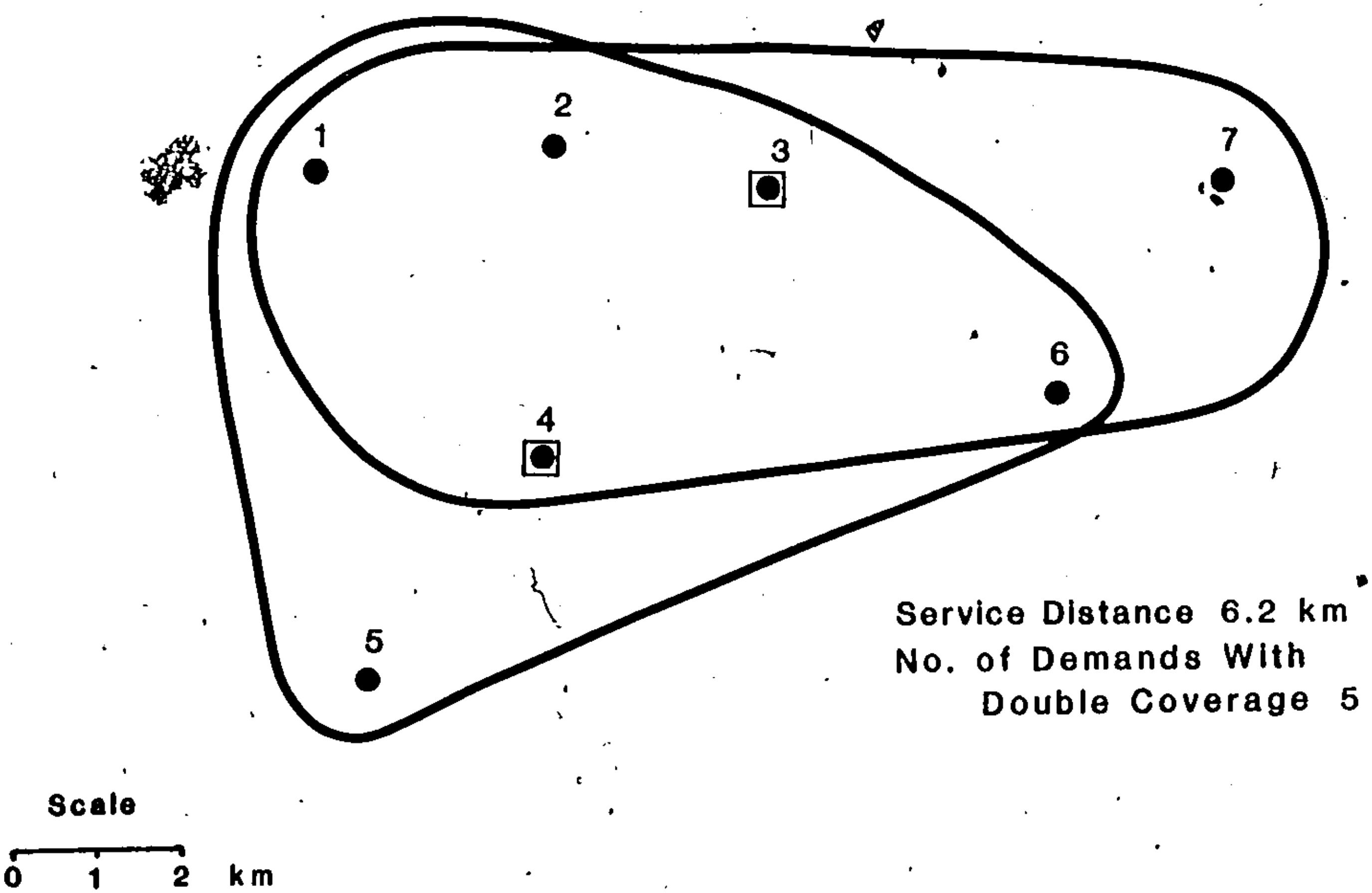
The Standard Arrangement for Two Ambulance Depots



An Alternate Arrangement for Two Ambulance Depots

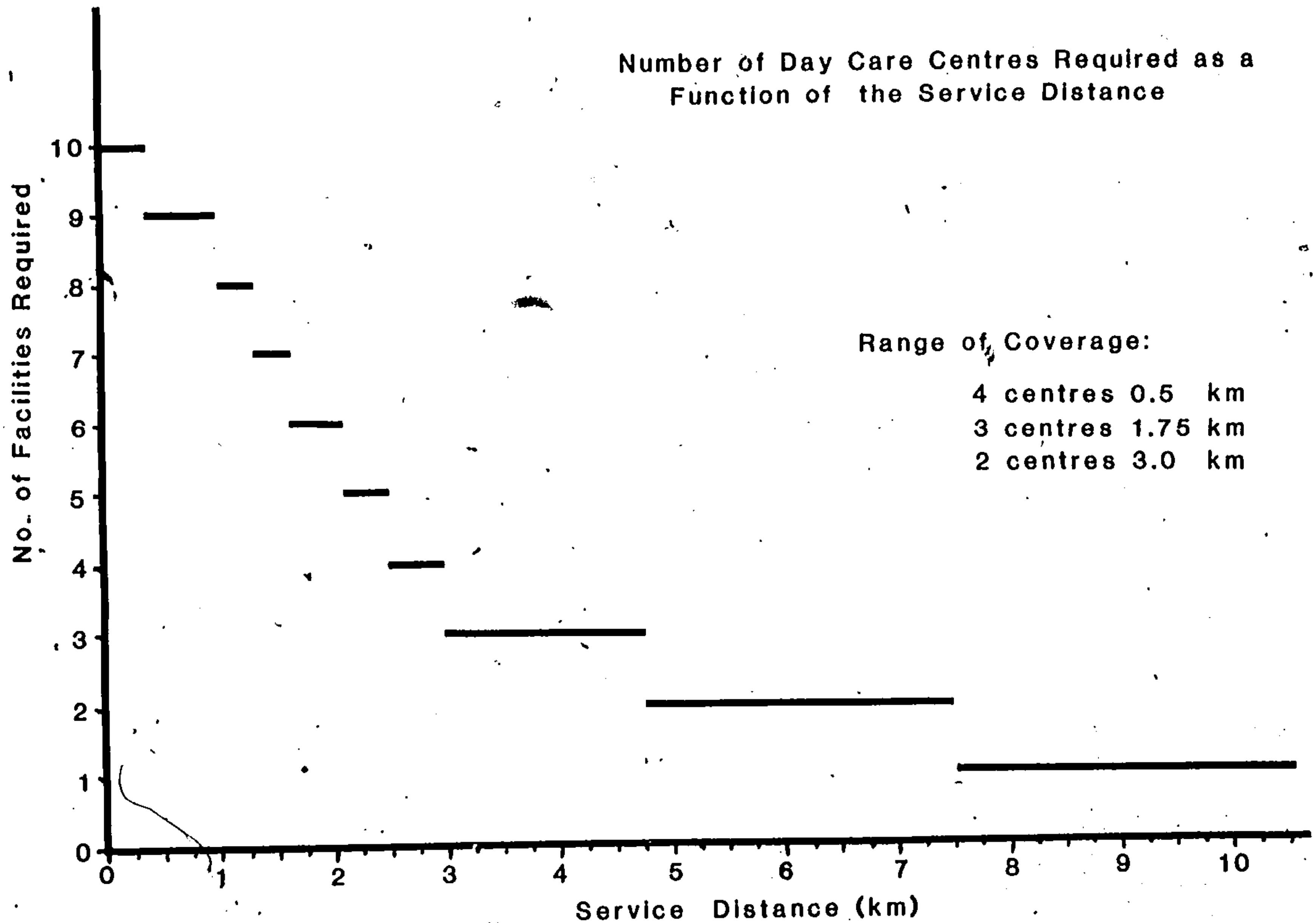


A Second Alternate Arrangement for Two Ambulance Depots



Appendix D

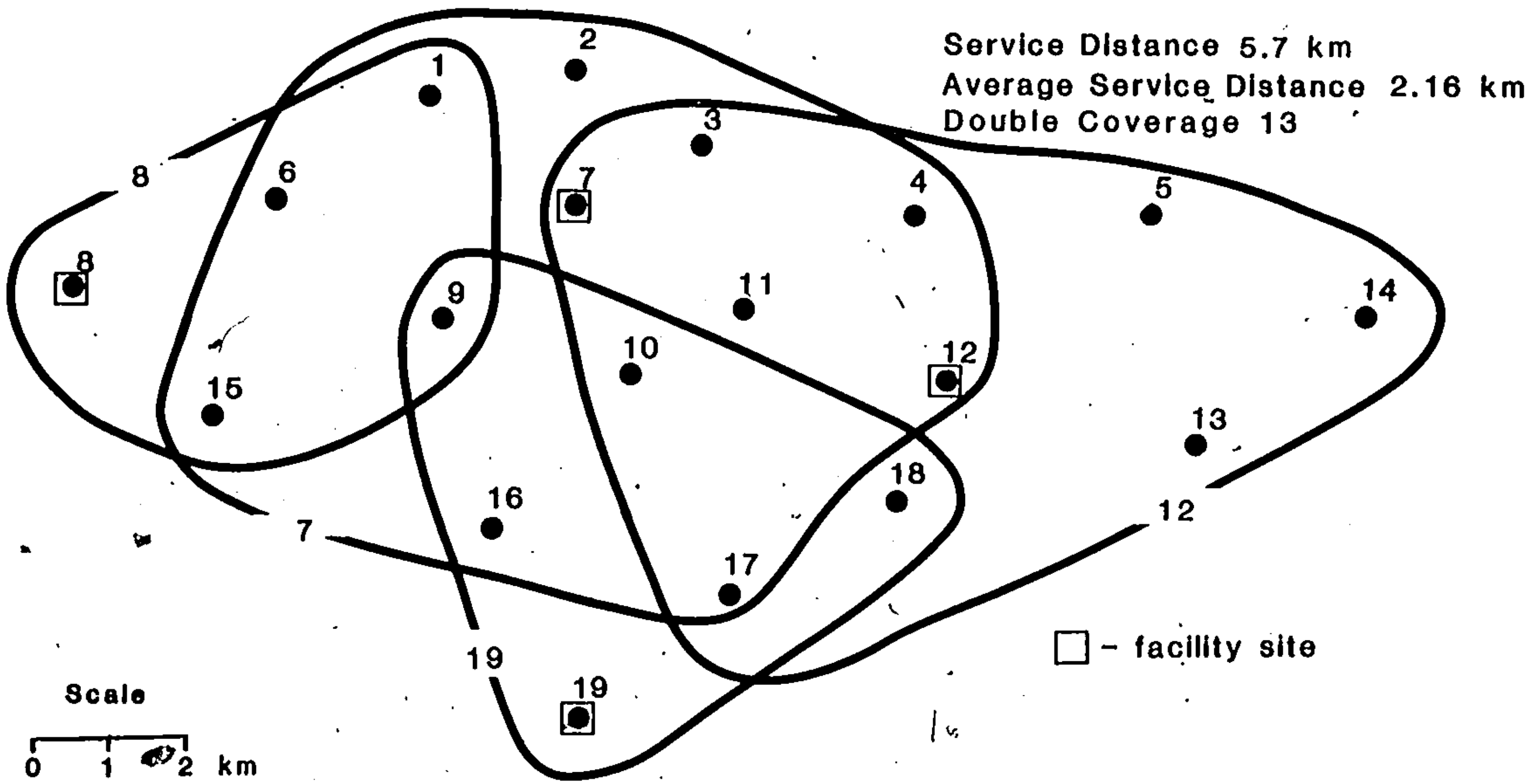
SERVICE DISTANCE COVERAGE IN A DAY CARE PROBLEM


Number of Day Care Centres Required as a Function of the Service Distance
Range of Coverage:
4 centres 0.5 km
3 centres 1.75 km
2 centres 3.0 km
No. of Facilities Required
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
Service Distance (km)

Appendix E

A_MULTI-OBJECTIVE_FIRE_STATION_PROBLEM

An Alternate Arrangement for Four Fire Stations - Retaining the Two Newest 12 and 19



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VITA AUCTORIS

Michael Kenneth Cooke was born on August 22, 1960, in Sarnia, Ontario. He attended elementary schools in Sarnia, London, and Windsor, Ontario and graduated with honours from Assumption College High School, Windsor, in 1979. He studied chemistry at the University of Windsor in 1979-1980 and graduated with an Honours Bachelor of Arts degree in Urban Studies in 1984. During his graduate studies he held a number of appointments with the Essex County Planning Department in Essex, Ontario. In 1987 the author graduated with a Master of Arts degree in Geography from the University of Windsor.