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Multi-criteria multi-facility location in Niwai block, Rajasthan

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Facility location;
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Local area planning

Abstract Rural regions often suffer disproportionately when compared to urban areas in the access to basic healthcare and educational opportunities. The provision of these facilities to the populace has been identified as one of the means of stimulating development in a region.

A problem-structuring method with multi-criteria decision analysis was used for the selection of different facilities based on the needs of the rural area under consideration. A facility location model was created and algorithms were developed in order to provide a solution for locating facilities in 45 villages of Niwai block in Tonk district, Rajasthan.

Sixteen different facilities were chosen for consideration, each falling into one of five broad groups: healthcare, education, connectivity, agriculture and drinking water. Alternative scenarios for locating facilities were generated and explored, providing a base for the micro-level planning process at the block level in a district.

Introduction

The study is concerned with developing a multi-criteria model to aid the micro-level planning process for the location of multiple facilities within a block in a district. The decision makers involved in this process may encounter difficulties when attempting to assimilate the intricacies of such a problem, and the planning process often fails to consider the location of more than one type of facility at any given time. The model presented here aims to enable the simultaneous consideration of an assortment of facilities.

In this context, facilities are considered as entities that provide some kind of service to a population. Some facilities may be confined to a building (such as schools or hospitals) or may have a fixed location (such as roads), whereas others may move around in order to meet the demands of the population (such as bus services or community health workers). Relatively few studies have been conducted on the theory of locating different types of facilities; this work seeks to explore the benefits (or otherwise) of such an integrated approach.

One can identify three main issues that need to be addressed while dealing with this problem:

- Identifying the relative needs and priorities
- Phasing of the facilities over time
- Identifying the exact locations and their operations

First, are the relative needs and priorities of the villages satisfied? For instance, if a village has neither a supply of

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fresh water nor a health clinic, then it may be that the population of the village desires both these facilities; however, clean water supply may be considered a higher priority as it would reduce the calls on such a clinic. Concentrating on the location of only one type of facility could result in the more basic needs of the villagers being overlooked. If an adequate method to address all the basic needs of the village can be developed, it would offer at least one advantage over merely considering the location of a single type of facility.

The second of these issues is how the facilities can be phased over a period of time. Budget and time constraints prevent all the required facilities from being located immediately. Indeed, it may not even be desirable for all the facilities to be located as quickly as possible; in some instances, demands would have to be generated before a facility is efficiently engaged. Similarly, if facilities are constructed at a rate that far exceeds the natural development of a region, then long-term sustainability may not be achievable.

The third issue relates to the exact location of the facilities and how they are to be operated. In order for a facility to be most effective, it is important that it is both available and accessible to the villages that it is intended to service. A facility is deemed available if it meets some predetermined criteria, such as being located within a fixed distance from the village. A facility is accessible if the population of the village has some means of making use of the facility. A facility might not be accessible if it is too expensive or if the opening hours of the facility coincide with the working hours of the population.

In the following section, we provide the objectives of the study. Then we present a very brief review of the literature on multi-criteria multi-facility locations. The methodology for locating and phasing of the facilities using Microsoft Excel and reasoning maps is then described. Finally, we present a case study on Niwai block in Tonk district in Rajasthan, and discuss different alternative scenarios and their associated costs and consequences.

Objectives of the study

The objectives of this study are:

- To provide a methodology that analyses the needs of the villages within a sub-district and generate possible scenarios for the location of facilities, which can be used as the base for the micro-level planning process in the sub-district;
- To estimate the budget required for constructing the new facilities proposed in each of the scenarios;
- To provide a user-friendly model that implements the methodology for generating the scenarios and the associated estimated costs; the model should be easily extendable and should allow for further analysis with different data;
- To demonstrate how the model can be used to deliver a detailed plan of action for locating multiple facilities in a sub-district over a pre-determined period.

Literature review

Two areas of research are relevant to the multi-criteria decision analysis (MCDA) and facility location models. This brief review aims to introduce the techniques that are employed in this study, and to justify the application of these particular techniques.

The first section concerns the MCDA, which is necessary to analyse the needs of the population with respect to multiple criteria. Particular attention is paid to the Analytic Hierarchy Process (AHP) (Saaty, 1977, 2008) and reasoning maps (Montibeller, Belton, Ackermann, & Ensslin, 2008). These two approaches are compared and the advantages and limitations of each model are presented. The problems related to the theory of facility location are discussed, and an overview of the different types of models and the possible solutions is presented.

Multi-criteria decision analysis

When faced with a decision regarding multiple criteria, it can be difficult for a decision maker (DM) to identify the most favourable course of action. The MCDA aims to provide decision makers a means of exploring the values of the different criteria and to choose an appropriate course of action. The characteristics of multi-criteria problems can be readily found in literature (Brugha, 2004 and Montibeller, 2005 among others). They include conflicting criteria; unknown values of the DM; multiple stakeholders, possibly with differing views; the vast amounts of information required in order to consider all the options; and the absence of a clear and desirable outcome.

These complexities mean that there is no single approach that is appropriate for all problem instances, as each problem would be unique. There is an extensive collection of decision-making aids that take very different approaches to tackling multi-criteria problems. It is not possible to represent all of these techniques here; instead, two methods that are relevant to this study are briefly discussed. The analytic hierarchy process (AHP) is a multi-criteria decision-making tool that aims to overcome the complexities of multi-criteria decision making by using pairwise comparisons (Saaty, 1977, 2008). Given the disadvantages of applying the AHP, an alternative integrated approach which uses reasoning maps, proposed by Montibeller et al. (2008) is presented, and the potential for applying this method is discussed.

Analytic hierarchy process

The analytic hierarchy process has been used in a variety of applications including facility location problems that involve multiple criteria (Badri, 1999; Chuang, 2001; Oddershede et al., 2007; Yang & Lee, 1997), which suggest that it is a valid technique to tackle the current problem. However, the AHP was found to be among the least used of 30 scientific methods that were considered in a survey (Munro & Mingers, 2002). The AHP has also received some criticism and has been the subject of debate, which led to the reconsideration of the suitability of the process for the current study.

Reasoning maps
Reasoning maps are multi-criteria decision-making aids that were developed to provide an integrated approach to problem structuring and multi-criteria evaluation (Montibeller et al., 2008). Two main phases of decision making that reasoning maps aim to support have been identified. The first of these is a *divergent* phase, where the values of the DM are explored and the complexities of the views are elicited and depicted in a causal (cognitive) map. The second is a *convergent* phase, where the causal map is evaluated and analysed in order to assist the DM in considering the options and reaching a conclusion.

Causal (or cognitive) maps are among a recognised number of *problem-structuring* methods (Rosenhead, & Mingers, 2001) that aim to capture the perceptions and values of a DM regarding a complex problem, thereby providing a richer understanding of both the problem and the available options.

The AHP and the reasoning maps provide two different approaches to analysing multi-criteria problems. The AHP is in some respects easier to understand; however, it is restrictive in the way in which the DM is required to interpret the problem, and it requires comparisons to be made between options that may be very difficult to compare. For example, even a qualitative answer to the question, 'How much more important is a veterinary service than a telephone connection with respect to improving education?' is fairly meaningless. The output of the process is a single vector that reflects how important each alternative is with respect to the overall goal, and has the advantage of being a straightforward result; however, it does not provide any further information about the problem or any indication of the accuracy of the solution.

Conversely, reasoning maps provide details about the effects of all the alternatives on each of the criteria based on a user-defined scale. Rather than obtaining a single solution, the DM is able to reflect on the effect of a finite number of alternatives. One of the attractions of reasoning maps is the integration of problem-structuring as well as evaluation techniques with the structure of the map and the qualitative scale specific to the DM. This is in contrast to the fixed hierarchical structure and scale in the AHP. By spending time on exploring the structure of the problem, it is anticipated that the result will be a deeper understanding of the issues involved in the problem. This has the potential to encourage sound evaluations and gives confidence in the final decision.

Facility location problems

The theory of facility location is concerned with developing models to find the optimal locations for facilities given certain objectives, constraints, and variables (Drezner & Hamacher, 2002; Smith, Laporte, & Harper, 2009). Facility location models are specific to their application; the objectives, constraints, and variables vary according to the facilities that are being considered and their purpose. There are two main steps in facility location models: creating a model and then solving the model.

In this review, we discuss four types of models and their solutions:

a) Discrete network models
b) Public sector models
c) Hierarchical models
d) Multi-objective models

Discrete network models
In discrete problems, there is a known set of candidate locations where facilities can be placed. In the problem relevant to our study, these locations are the villages in the area of interest. An underlying network is assumed to exist, connecting the villages in the form of roads (where they exist) or the main routes taken between villages. These types of models may also allow facilities to be placed along the network. Current, Daskin, and Schilling (2002) give two classifications of discrete models based on how they deal with distances: maximum distance models and total (or average) distance models.

Maximum distance models focus on locating facilities within a pre-determined distance of the population that they are intended to serve. The maximal covering location problem (Church & ReVelle, 1974) is an example of such a model. Appendix I provides an example of the formulation of a maximal covering location problem.

The second class of models focuses on minimising the total or average distances that the population has to travel in order to reach their nearest facility. One such model is the *p*-median model, which seeks to minimise the demand-weighted total distance between nodes (of demand) and the location of facilities (Hakimi, 1964). This model has also been applied to location allocation problems in rural areas in developing countries (Rahman & Smith, 1999).

Public sector models
A public sector model is not necessarily one where the facilities are under the control of the public sector but one that is not designed with competition in mind. Instead, such models are designed to co-operate and work with whatever facilities already exist (Marianov & Serra, 2002). The main difference between public sector models and other competitive models is in the objective function.

Typically, facility location models aim to provide the most *efficient* solutions, such as locating the facilities in order to meet the maximum amount of demand possible. The maximal covering location model and the *p*-median model both have objective functions that focus on efficiency. However, public sector objectives may be concerned with *equitable* solutions, such as decreasing the disparities within a region, and these result in very different models. The *p*-centre model (see Appendix II) concentrates on producing an equitable solution with an objective function that minimises the maximum distance between a demand node and the location of the facility to which it is assigned (Hakimi, 1964).

Hierarchical models
One assumption of the models discussed so far is that all the facilities are identical. However, this study is concerned with the location of different groups of facilities. Although relatively little research has been conducted in this area, there are a number of studies on locating a hierarchy of facilities. Smith, Harper, Potts, and Thyle (2007) have developed a range of models for locating a hierarchy of

health facilities in the rural areas of developing countries. Such a hierarchy may include village health workers, health clinics, and hospitals.

Marianov and Serra (2002) highlight the variation that may exist in the organisational structure of different types of hierarchies. Hierarchies of health facilities, for example, are hierarchical in the services that each facility provides, and their administration is structured accordingly; there may be some overlap in the services provided and in referral up through the hierarchy. Other groups of facilities may provide completely separate services. Primary schools, secondary schools, and universities can all be classed as educational facilities; yet, all of these provide services to different sectors of the population.

Multi-objective models

Models that have more than one objective function are referred to as multi-objective models. Such models may apply when there are several stakeholders with different objectives, or one group of stakeholders holding several conflicting objectives. Although problems with multiple objectives readily appear in 'real life' problems, models involving multiple objectives are not so common in the literature. This could be due to the complexities of solving such models.

Solution methods

Exact solution methods are only suitable for small problem instances; the majority of the models are classified as NP-hard (non-deterministic polynomial-time hard) (Current et al., 2002), and various heuristics are employed to generate solutions in these instances. Heuristic methods may not find the optimal solution, but these are designed to find a 'good' solution using a reasonable amount of computational time. Examples of such heuristics include greedy heuristics, genetic algorithms, and Lagrangean relaxation (Current et al., 2002). When selecting a heuristic, a trade-off is usually made between the quality of the solution and the computational complexity of the method.

Methodology

We provide an overview of the structure and the philosophy of the methodology. The model was created in Microsoft Excel using Visual Basic for Applications (VBA) without relying on external software; the result is that the model is self-contained and can easily be used for further analysis. The methodology includes the following aspects:

i) Dealing with one vs. many facilities simultaneously
ii) Considering relative needs and priorities (through the AHP/reasoning maps)
iii) Phasing the facilities over a period of time
iv) Locating the facilities
v) Considering the costs and consequences

Framework for the method

Over the years, planning decisions in India have been decentralised, moving from the central to the local governments, and the need to find region-specific solutions has been recognised (Datta & Bandyopadhyay, 1993). The aim of this methodology is to produce a model that can act as a decision support system by generating different scenarios for locating facilities in a rural area over a particular period, given a limited budget. The facilities and criteria to be considered in the model can be chosen according to the needs of the particular region. The model is designed to be a decision-making aid, and the need for human interaction to explore the scenarios and to arrive at a final decision cannot be ignored. To this end, it has been necessary to incorporate 'hard' analytical techniques—such as facility location models—with 'softer' participatory methods—such as reasoning maps.

Before any analysis can be carried out, some data is needed in order to set up the problem. It is necessary to obtain information about the area of interest; this area is required to be a rural area consisting of villages. For each village, its name, the size of its current population, its geographical location, and the facilities that already exist must be entered into the model. The geographical location of the villages must be in the form of (x, y) co-ordinates that may be obtained from a map of the area and they must represent the approximate 'centre' of the village. These co-ordinates may be based on any scale, so long as the scale is known.

A survey of the population of these villages is also important in order to identify the amenities that are lacking. The facilities are grouped into different categories, with different types of facilities in each group. For example, 'medical facilities' would be one group, with 'primary sub-centre', 'primary health centre', and 'hospital' as possible types in this group. (See Fig. 1 for a structure of the methodology.)

Health and education are widely regarded as essential to development, and it is anticipated that these will be among the facilities to be considered. The Millennium Development Goals that have been adopted by the member states of the United Nations support this view: out of the eight goals, four directly relate to either health or education (United Nations, 2007b).[1] Additional groups of facilities that support and/or complement medical and educational facilities are chosen in order to meet the criteria.

Analysing the needs of the village

Once the facilities to be considered are chosen, along with the criteria by which they are to be judged, there follows a consultation with the villagers in order to build up a reasoning map that reflects their opinions regarding the different facilities with respect to the criteria. This map is then analysed in order to identify the facilities that are of the highest priority to the local community. The output of this stage is a categorisation of the facilities into one of three groups: high, medium, and low priority.

[1] The Millennium Development Goals may be summarised as follows: eradicate extreme poverty and hunger; achieve universal primary education; promote gender equality and empower women; reduce child mortality; improve maternal health; combat HIV/AIDS, malaria, and other diseases; ensure environmental sustainability; develop a global partnership for development.

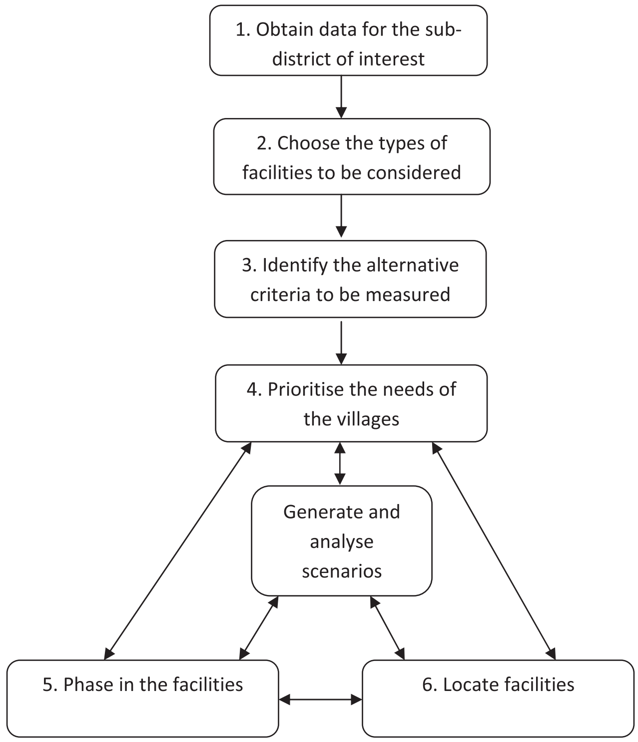

Figure 1 Structure of the methodology.

The views and needs of the population of the region are represented using reasoning maps with some minor amendments and room for flexibility. As an example of how the strength of perceived influence for each link may be determined, consider an attribute concept 'investment in tap water', that has been identified as influencing a consequence concept 'reduce the number of water-borne diseases'. These two concepts have associated variables, namely, 'the amount of money invested in providing tap water' and 'the number of water-borne diseases in the population per year', respectively. If the user-defined qualitative scale is 'negligible', 'weak', 'moderate', and 'strong', then, in order to determine the perceived strength of this influence, Montibeller et al. (2008) suggest that a question such as 'If the amount of money invested in providing tap water goes from negligible to strong, what effect does this have on the number of water-borne diseases in the population per year?' should be asked. The answer to the question should be one of the qualitative assessments (for example, 'strong'). It is possible for the user to build a mental representation of the reasoning map using the model; however, it is strongly recommended that the map be first drawn on paper in order to finalise the structure. The model calculates the total effects of investing in each of the facilities individually, and based on these results, conclusions may be made regarding the relative priority of each of the facilities. It is necessary to place each of the facilities into one of three priority groups, namely, high, medium, or low.

Operating and phasing the facilities

This part of the methodology requires the user to consider each of the groups of facilities (high, medium, and low priority) in turn, and to identify the most desirable order in which these facilities can be phased.

This order, however, may not coincide with the perceived order of importance of the facilities within each group, as practical issues may take precedence. For example, if a road and a telephone connection are both considered to be in the same priority group, with the road having stronger effects on the final value concepts, the user may decide that the telephone connection should be introduced first; if the road is built first, then it may have to be dug up again in order to lay the telephone cables. The output of this phase will be the ordering of the facilities to be located first through last within their respective priority groups.

Locating the facilities

The facility location model is used to generate the scenarios, and it takes elements of both the maximal covering location model and the *p*-centre model (shown in Appendices I and II, respectively). The optimisation process will then take place with respect to the objective function corresponding to the facility that is the highest priority, and all the way through to the objective of the facility that is the lowest priority, or until the constraints can no longer be satisfied.

Generating the scenarios

We now describe the algorithms that have been created to generate the scenarios for locating the facilities. We assume that facilities can be located only in the villages and not along the arcs of the network. The first algorithm is responsible for generating an initial scenario, which it achieves by solving the facility location model without constraints. The next two algorithms use an existing scenario in order to generate further scenarios with budget and distance constraints. The fourth algorithm takes any scenario that has been generated and distributes the budget over a given time period.

The other steps used in the model include generating the initial scenario, imposing budget- and distance-related constraints, and finally, distributing the budget.

Case study: Niwai block

The state of Rajasthan in India is divided into 32 administrative districts, and these districts are themselves divided into blocks. Tonk district is one of the less developed blocks in the state, and receives financial aid from the Backward Regions Grant Fund. Of the seven blocks within the Tonk district, Niwai block has been chosen as the subject of this case study. The details about the existing facilities and populations of the villages within this block were obtained from the latest Census of India, which was conducted in 2001. Though the data is ten-years-old, it is sufficient for demonstrating the application of the methodology. The geographical locations of the villages were obtained from the Government of Rajasthan's Geographical Information System.

Niwai block comprises 191 inhabited villages, of which 45 were chosen for this case study. While every effort was made to reduce the number of assumptions, it was not possible to eliminate all uncertainties. Some assumptions were unavoidable due to the time constraint imposed on this study. More accurate estimates for some of the figures could have been obtained if there had been more time.

Criteria

The three criteria on which the facilities were judged were, the improvements that the facilities provided to health, education, and the economic conditions in the region. These were chosen in order to reflect the three aspects of development whose indicators are used to develop the Human Development Index (HDI). It has been observed that benefits in all these three areas can help break the cycle of poverty afflicting many rural communities of developing countries (United Nations, 2007a).

Facilities

The choice of facilities selected for consideration in this study was based on the census data and on the results of multiple visits to the block. This was considered to be of sufficient interest when exploring a multi-criteria approach without introducing undue complexity. (Table 1 details the facilities considered in this study.) Each of these groups is discussed below.

Educational facilities

Of the four main stages of school education in India, the first three were included in this case study, namely, primary school (ages 6—11 years), upper primary or middle school (ages 11—14 years), and secondary school (ages 14—16 years). Additionally, the placement of adult literacy centres were also considered, as adult literacy rates in the rural areas of Tonk district were placed at only 47.8% in 2002 (Government of Rajasthan, 2002). The 2001 census states that there are 40 primary schools, 12 middle schools, four secondary schools, and four adult literacy centres in the 45 villages considered in this study.

Drinking water

Unsafe drinking water can lead to many diseases such as diarrhoea, enteric fever, and viral hepatitis, which are all potentially fatal if not properly treated; young children are particularly vulnerable to these diseases. Studies have shown that within Rajasthan, awareness related to the prevention of these diseases is poor (Government of Rajasthan, 2002). For instance, during the visit to Niwai block, it was noticed that the well being used as a source of drinking water was also being used by people to wash themselves, which could cause cross contamination of water. Of the 45 villages, only two had access to tap water, although other sources of water were available in every village.

Providing a convenient water source can have other positive benefits. If it is necessary to travel any distance to fetch safe drinking water, this responsibility is often assigned to young girls (Bapat et al., 2007). Noticeably fewer girls are enrolled in schools in Tonk district compared to boys (Government of Rajasthan, 2002). Therefore, the provision of tap water to a village may have a positive effect on the number of girls attending school.

Medical facilities

Life expectancy is often used as an indicator of the state of health of a population. In 2001, the estimated life expectancy in Tonk district was 59.2 (Government of Rajasthan, 2002). Good health has already been identified as an essential component for development, and therefore, medical facilities were chosen for this study. The 2001 Census of India listed 19 different types of health facilities. It is not possible to consider the placement of all of these facilities; instead, three basic facilities were chosen: primary health sub-centre, primary health centre, and health centre. These represent a hierarchy, with referrals taking place up the hierarchy.

Two additional facilities were chosen to complement the basic amenities: community health workers, and maternal and child welfare centres. Community health workers are members of the local community who are trained in the very basic health skills. While the medical knowledge they possess may not be very advanced, they have the advantage of offering better access to medical facilities by being available outside of the working hours of health centres. Smith et al. (2007) developed a range of models for locating a hierarchy of medical facilities in similar rural areas of

Table 1 The 16 facilities considered in the case study.

Facility group 1	Facility group 2	Facility group 3	Facility group 4	Facility group 5
Education	Drinking water	Medical	Connective	Agricultural
Type(s)	Type(s)	Type(s)	Type(s)	Type(s)
Primary school	Tap water	Community health workers	Bus service	Agricultural credit societies
Middle school		Maternity and child welfare centre	Telephone connections	Veterinary service
Secondary school		Primary health sub centre	Paved approach roads	Electricity of agricultural use
Adult literacy class/centres		Primary health care		
		Health centre		

India, and community health workers were deemed important by the authors, as the ability to recognise and treat basic illnesses was often lacking in such areas. Concern for maternal and child welfare is demonstrated in two of the Millennium Development Goals, namely 'reduce child mortality' and 'improve maternal health'.

Connective facilities

Connective facilities are defined by their ability to connect villages within a region. Paved approach roads, telephone connections, and bus services were the connective facilities selected for this study. Good connectivity within a region provides an 'inclusive' dimension to development that is important for the sustainability of facilities (Government of India, 2002). The Government of India launched a scheme under the Ministry of Rural Development in 2000, the primary objective of which was to provide paved road connections to unconnected habitations in rural areas. An assessment conducted by independent agencies examined the impact of this initiative and concluded that the provision of such roads had positive impacts on agriculture, employment opportunities, health, and education (Mohapatra & Chandrasekhar, 2007).

Bus services complement paved roads and improve access to nearby amenities. Similarly, telephone connections are a means of connecting villages, and can be used to gain information and to access facilities. For instance, a health centre may deploy medical staff to villages in an emergency. In 2001, 12 of the villages had paved approach roads, and there were 59 telephone connections in the 45 villages, although 50 of these were in the two larger villages. As for bus services, the census data recorded eight villages as having a bus service, while 'no information' was recorded about the others; in the latter case, it was assumed that no bus service existed.

Agricultural facilities

Agriculture and animal husbandry are the two predominant sources of livelihood in Rajasthan (Government of Rajasthan, 2002), and the agricultural facilities chosen for this study aimed to support both these occupations. During the visit to Niwai, the villagers identified veterinary services (or 'animal hospitals') as a facility that was lacking. No information was available in the latest census regarding such amenities, and it was assumed that none existed within the region of interest. The other two facilities chosen pertaining to agriculture were electricity and credit societies; of the 45 villages, 32 had electricity available for agricultural use, and there were five credit societies in 2001.

Constructing the reasoning map

The map that was created is shown in Fig. 2; it reflects the views expressed by the villagers based on the primary data collected and personal interviews conducted with the villagers of Niwai block, and uses additional information gathered from the National Human Development Report 2001 (Government of India, 2002) and the Rajasthan Human Development Report 2002 (Government of Rajasthan, 2002).

Initially, a scale of four qualitative assessments ('negligible', 'weak', 'moderate', and 'strong') was chosen; however, it was found that the total effects were not sufficiently distinguishable, as there were many moderate influences. Two more assessments—'very weak' and 'very strong'—were added to provide additional variation. However, this variation came at a price, as it was more difficult to build an accurate representation of the villagers' views using a greater number of assessments. The first step in this process would be to validate the current map, and to add further complexities to it if necessary.

Initially, the map was created using only the views of the villagers. However, it was felt that supplementing these views using additional information was necessary. This was particularly apparent in the area of health, as most of the views expressed were related to economic conditions and education; the subject of good nutrition was not initially indicated by the villagers.

Prioritising the facilities

Table 2 shows the total effects of each of the alternatives on the three criteria (the final values). The alternatives were defined as a 'very strong' investment in each of the facilities individually, thus providing the same number of alternatives and facilities. Using the information in Table 2, it was necessary to group the facilities into high, medium, or low priority.

The classification of each of the alternatives began with the following non-dominated solutions:

- Health centre: Since 'improvements in health' was deemed the most important of the three criteria, and providing a health centre was deemed to have a 'very strong' total effect on this criteria, health centres were classified as a high priority facility.
- Primary school: Similarly, providing a primary school had a 'very strong' total effect on 'improvements in education', and was also classified as high priority.
- Approach roads: Although 'improvements in economic conditions' could be viewed as the least important of the criteria, paved approach roads were also considered high priority. This was not only because of the 'very strong' effect on the criteria but also due to the 'moderate' effect on the other two criteria, implying an all round positive benefit.
- Adult literacy classes/centre: This facility was classified as a medium priority facility, as the total effect on 'improvements in education' ('strong') was less than the total effect of primary schools. Moreover, the total effect on 'improvements in health' ('weak'), which was the most important criteria, was less than the total effect of health centres and paved approach roads.

Next, the remaining alternatives were classified, beginning with those that had the greatest effect on health.

- Maternal and child welfare centre, primary health centre and tap water: These three facilities have all had either a 'strong' or 'very strong' effect on

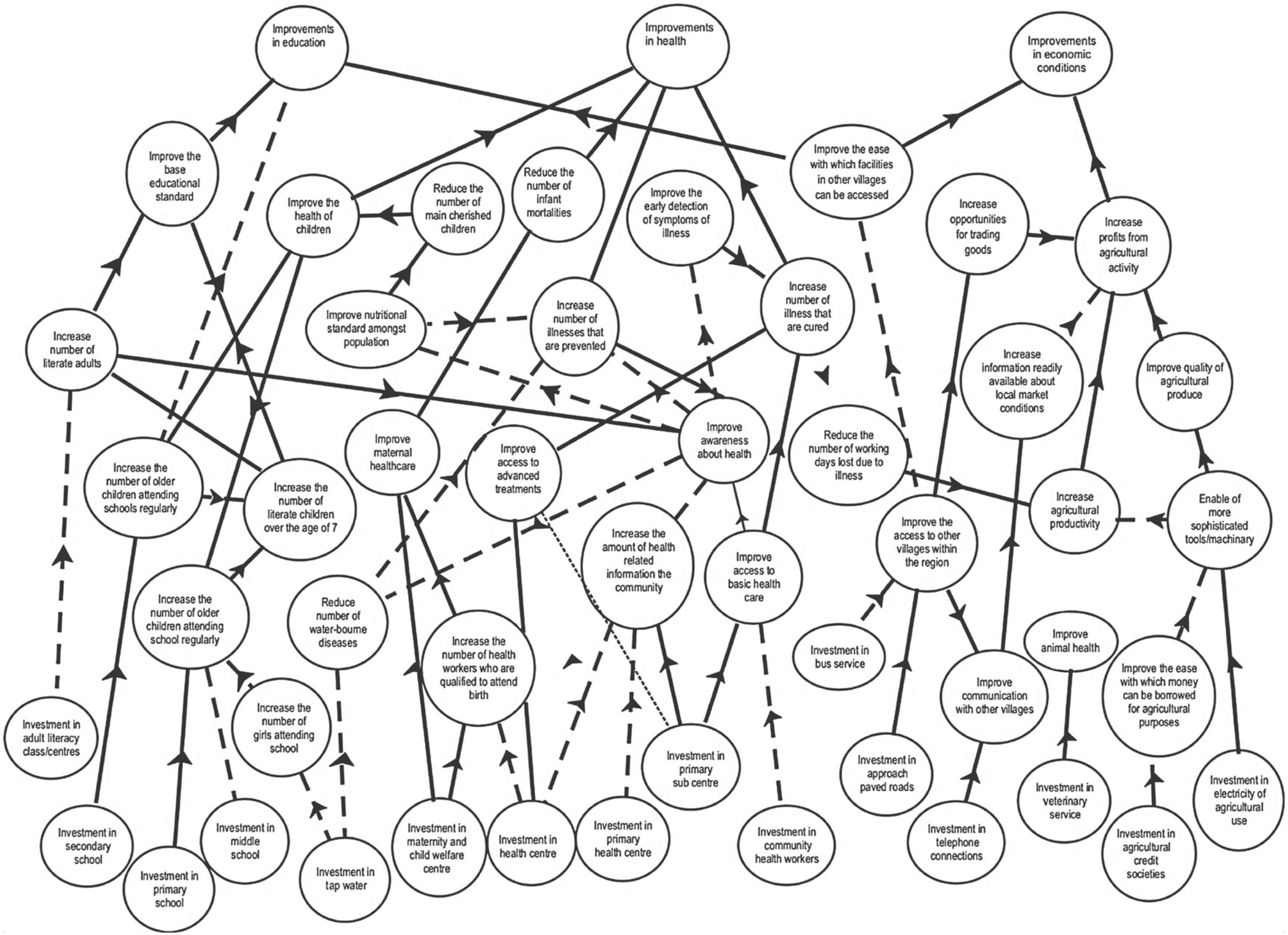

Figure 2 The completed reasoning map (all influences are positive).

Table 2 Outcome of the reasoning map process (non-dominated alternatives are highlighted).

Alternative	Effect on improvements in health	Effect on improvements in education	Effect on improvements in economic conditions
Investment in primary school	Negligible	Very strong	Negligible
Investment in middle school	Negligible	Strong	Negligible
Investment in secondary school	Negligible	Moderate	Negligible
Investment in adult literacy class/centres	Weak	Strong	Weak
Investment in tap water	Strong	Weak	Moderate
Investment in community health workers	Moderate	Weak	Moderate
Investment in maternal and child welfare centre	Very strong	Negligible	Negligible
Investment in primary health sub centre	Moderate	Moderate	Moderate
Investment in primary health centre	Strong	Moderate	Moderate
Investment in health centre	Very strong	Moderate	Moderate
Investment in bus service	Moderate	Moderate	Strong
Investment in telephone connections	Negligible	Negligible	Strong
Investment in paved approach roads	Moderate	Moderate	Very strong
Investment in agricultural credit societies	Negligible	Negligible	Strong
Investment in veterinary service	Negligible	Negligible	Moderate
Investment in electricity of agricultural use	Negligible	Negligible	Strong

'improvements in health', and therefore, were classified as high priority facilities.

- Primary health sub centre: This was deemed to have only a 'moderate' effect on 'improvements in health'; however, since it was a part of the hierarchy of health facilities, it was also classified as high priority.
- Community health workers, bus services, middle and secondary school: These were all classified as medium priority.
- Telephone connections, veterinary service, agricultural credit society, electricity for agricultural use: These four facilities were all classified as low priority, since they had 'negligible' effects on health and education.

Setting the constraints

To begin the process of generating various scenarios, it was necessary to first choose the order in which the facilities were to be phased for each of the priority groups. In the case of the medical and educational facilities, the costs were based on information obtained from the local government offices. Reliable estimates for the cost of providing each of the remaining facilities were harder to obtain in the time available for this study, and there was a higher degree of uncertainty about these values. The average cost for paved approach roads was particularly difficult to ascertain, as it would depend on the terrain of the area and the exact length of the road required to connect the village to the overall road network. The value used in the end was based on figures obtained from a government scheme that provides roads in rural areas.

The maximum capacities and distance criteria chosen for the medical and educational facilities were based on the national government policy; however, national requirements for the other facilities did not exist, and therefore, estimates had to be made. The population of Rajasthan grew by 28.33% between 1991 and 2001, which works out to approximately 2.5% per year (Government of Rajasthan, 2002); this was used as the growth rate in the model. A period of ten years was chosen over which to locate the facilities.

Discussion of results

The model first generated a scenario aimed at satisfying all the demands for all the facilities at the end of the ten-year period, given the distance constraints and maximum capacities. The number of facilities required in this case is shown in Table 3, along with the number of existing facilities and the estimated costs involved. Before further scenarios were generated, this solution was first examined to verify its suitability by plotting the locations of the villages and each of the facilities in turn.

Two observations arose from this examination, the first of which is related to the location of primary health centres. Initially, the distance criteria for primary health centres was given as six km; that is, a village can only be considered to be covered by a primary health centre if it is within six km of such a facility. The result was that five primary health centres were required in order to cover all the villages. However, if the distance constraint of primary health centres was increased to seven km, it was found that only three such facilities were required.

There were two health centres in the region already. If either of these facilities had been located closer to the centre of the map, the need for the third health centre could have been eliminated. Both the villages that already had health centres, had relatively large population; this provides an example of how placing facilities at nodes where there is most demand can result in solutions that are not optimal in terms of maximal coverage. However, no changes were made to the solution, as relocating the facilities was politically very difficult, and therefore, could not be considered an option.

Table 3 Initial results.

	Number of existing facilities	Number of additional facilities to locate	Estimated cost (in INR 10,000)
Primary health sub centre	2	20	920
Primary health centre	0	3	1650
Paved approach roads	12	33	6600
Maternity and child welfare centre	0	8	320
Primary school	40	2	200
Health centre	2	1	900
Tap water	1	47	470
Bus service	8	38	190
Communitv health workers	4	53	159
Middle school	12	9	900
Secondary school	4	1	100
Adult literacy class/centres	4	7	7
Telephone connections	59	79	3950
Electricity of agricultural use	32	36	2340
Agricultural credit societies	5	1	5
Veterinary Service	0	6	3000
			21,711

Reducing the budget

The effect of reducing the amount of money that was to be invested was explored by imposing budget constraints on the initial scenario. The budget was reduced in increments of 5% of the total initial cost each time, and a new scenario was generated. In order to realise the effect of reducing the budget, three indices were created to represent the effect that the number of facilities that existed in a given scenario had on the three criteria. (The indices should be viewed as being indicative only.)

Increasing equity

In the initial scenario, the maximum distance of any village from every one of its nearest facilities was 32.4 km. Constraints were progressively imposed on this scenario in an attempt to decrease this figure; the model was able to produce a solution that reduced this maximum distance to 23.4 km. No further reductions appeared possible, which may be explained by the lack of sophistication in the algorithm.

The inclusion of a problem-structuring method in the decision-making process was seen as an advantage of the method, as it had the potential to provide a richer understanding of the problem. Other positive features included the fact that all the assessments that were made were qualitative and the scale that was used could be defined to best suit the decision makers.

Conclusion

A methodology has been presented and implemented in Microsoft Excel that, with human interaction, is able to generate scenarios for locating facilities within a district over a given period of time. The model allows for any number of alternative scenarios to be generated by changing the attributes of the facilities, such as, how much they cost and their capacity. These scenarios can also be explored by reducing the budget or by imposing a constraint on the maximum distance of any village from all the facilities.

The advantages of the methodology were found to be as follows:

a) is easier to implement
b) considers local participation
c) is less time-consuming and has the least computational needs
d) includes qualitative measures
e) is a relatively less expensive method

The application of this methodology was demonstrated in a case study where the details of 45 villages were obtained, and a suggested plan for locating facilities over a ten-year period was provided. The potential for applying the methodology was illustrated and, to this end, the objectives of the study have been fulfilled. The methodology of multi-criteria multi-facility location and its associated software will improve the local area management and planning systems and the decision-making processes.

Appendix I

Maximal covering location problem

This model aims to satisfy the most amount of demand for one type of facility as possible by locating a fixed number of facilities. The following definitions are required:

I = the set of demand nodes, indexed by i
J = the set of possible facility locations, indexed by j
d_{ij} = the distance between node i and site j

D_c = the maximum distance that a facility can be from a demand node if it is to cover the node
$N_i = \{j|d_{ij} \leq D_c\}$ = the set of all locations that can cover node i
h_i = demand at node i
p = the number of facilities to locate

The decision variables are:

$$X_j = \begin{cases} 1 & \text{if we locate at site j} \\ 0 & \text{otherwise} \end{cases}$$

$$Z_i = \begin{cases} 1 & \text{if demand node i is covered} \\ 0 & \text{otherwise} \end{cases}$$

The objective function is:

$$\text{Maximise} \sum_{i \in I} h_i Z_i \quad (I.1)$$

Subject to the following constraints:

$$\sum_{j \in N_i} x_j - z_i \geq 0 \ \forall i \in I \quad (I.2)$$

$$\sum_{j \in J} x_j = p \quad (I.3)$$

$$x_j \in \{0,1\} \forall j \in J \quad (I.4)$$

$$z_i \in \{0,1\} \forall i \in I \quad (I.5)$$

Appendix II

p-centre problem

The p-centre problem minimises the maximum distance that a demand node is from its closet facility given that a pre-determined number of facilities are to be located. The following definitions are required:

I = the set of demand nodes indexed by i
J = the set of possible facility locations, indexed by j
d_{ij} = the distance between demand node i and site j
h_i = demand that exists at node i
p = the number of facilities to locate
W = the maximum distance between a demand node and the facility to which it is assigned

$$X_j = \begin{cases} 1 & \text{if we locate at site j} \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if demand node i is assigned to a facility at node j} \\ 0 & \text{otherwise} \end{cases}$$

The objective function is:

$$\text{Minimise } W \quad (II.1)$$

subject to:

$$\sum_{j \in J} x_j = p \quad (II.2)$$

$$\sum_{j \in J} y_{ij} = 1 \forall i \in I \quad (II.3)$$

$$y_{ij} - x_j \leq 0 \forall i \in I, j \in J \quad (II.4)$$

$$\sum_{j \in J}^{W-} h_i d_{ij} y_{ij} \geq 0 \forall i \in I \quad (II.5)$$

$$x_j \in \{0,1\} \forall j \in J \quad (II.6)$$

$$y_{ij} \in \{0,1\} \forall i \in I,\ j \in J \quad (II.7)$$

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