Locating Police Service Points in Rural Areas of South Africa

by

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Executive Summary

A total count of 2,178,700 crimes was committed in South Africa during the year 2012 (Crime Stats SA, 2012). 15,940 murders were committed, resulting in a murder rate of 31.8 per 100,000 inhabitants, and ranking South Africa at the 12th highest murder rate in the world (Crime Stats SA, 2012). These alarming crime rates need to be reduced. Consequently, the need for safety and security is growing among South Africans. This is especially true for the communities living in the rural areas of South Africa: nine of the ten district municipalities with the highest murder rates are in rural areas (South African Press Association, 2011).

The South African Police Service (SAPS) has recognised the need to improve policing services in combatting crime. However, the SAPS is currently not visible or accessible in the rural areas, so that people have to travel long distances to access basic policing services. These rural areas are situated in municipal districts that are underdeveloped, known as Integrated Sustainable Rural Development (ISRD) nodes.

The SAPS needs to locate police service points to meet the growing need of the communities living in the ISRD nodes. This project may assist the SAPS to create a safe and secure environment for the people living in the Central Karoo district by determining the number of, and optimally locating, police service points. This is achieved through the development and implementation of two mathematical models: the set covering problem (SCP) and the maximal covering location problem (MCLP) models.

The SCP model determined the minimum number of police service points needed to cover the entire population, while the MCLP model located a limited number of police service points that would cover as much of the population as possible. SAPS's resources are limited, so only a limited number of police stations can be located in the Central Karoo. The MCLP model was therefore used to identify the optimal locations for the SAPS police facilities.

Thirteen ideal locations were identified that between them would ensure that 92.9% of the entire Central Karoo population were no more than 20km away from the nearest police station. This solution could assist the SAPS in their quest to combat crime and provide increased security and protection for the people living in the Central Karoo.

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Chapter 1

1. Introduction

1.1 Introduction & background

According to a news report of the South African Press Association (SAPA), the South African Institute of Race Relations (SAIRR) revealed that violence against people was more prevalent in the rural areas than in the urban areas of South Africa. In fact, of the ten district municipalities with the highest murder rates, nine were in rural areas (South African Press Association, 2011).

The South African Police Service (SAPS) has recognised the need to improve policing services in combatting crime in the rural areas. However, the SAPS is currently not visible or accessible in the rural areas, forcing people to travel long distances to access basic policing services. These rural areas are situated in municipal districts that are underdeveloped, known as Integrated Sustainable Rural Development (ISRD) nodes.

The aim of this project is to improve the accessibility of policing services in the Central Karoo ISRD node. This will be done by identifying optimal locations to locate police service points in the district. The Central Karoo District Municipality is situated in the Western Cape region.

Figure 1: Western Cape Region (Adapted from (Western Cape, 2013))

Beaufort West, Laingsburg, Murraysburg, and Prince Albert are the four major towns situated in the Central Karoo district.

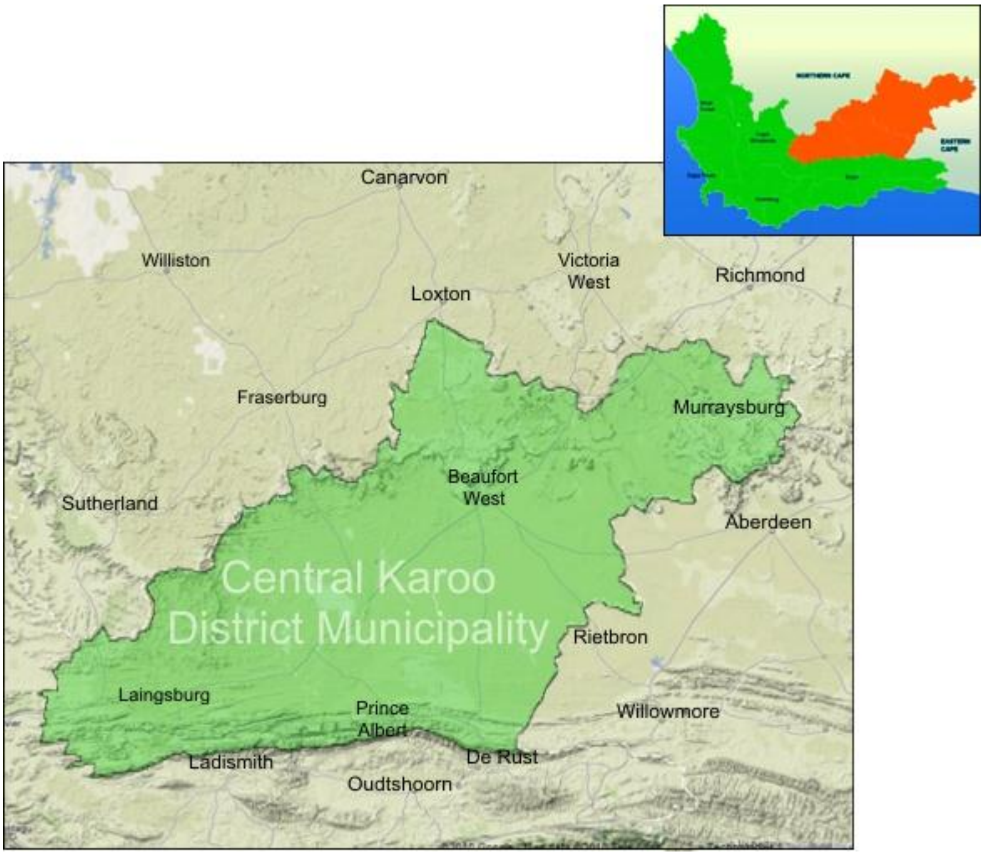

Figure 2: Central Karoo District Municipality (Adapted from (Western Cape Government, 2013))

1.2 Problem statement

South African citizens living in the ISRD nodes are forced to travel long distances to make use of policing services at the nearest SAPS service point. Due to the long distances and the inconvenience of visiting the nearest police service point, the majority of crimes in these areas are not reported.

According to Rabie (Rabie, 2011), challenges experienced within the ISRD nodes include:

- Underdeveloped infrastructure: poor or no road infrastructure, lack of public transport and telecommunications.
- Natural geographic challenges such as mountains and rivers.
- Lack of physical and human resources at the existing service points.
- Existing service points being open only during specified times.

- Large nodes of scattered communities, with most of the population living more than 24km from the nearest service point.
- Existing police stations are not located optimally for the current population distribution.

Rabie (2011, p. 54) concluded that:

> [i]n a 4km radius from the service points, with a minimum of 1 hour walking distance to the nearest service point, 56% of the stations in the ISRD nodes only served 0% to 30% of the population.

Five police stations, three satellite police stations, and one fixed contact point are located in the Central Karoo district, and are required to service the entire population of 71,016 people (Statistics South Africa, 2011). The population is scattered across this large 38,854km^2 district (The Local Government Handbook, 2013) with insufficient access to police services.

According to Crime Statistics of South Africa (Crime Stats SA, 2012), the total number of crimes committed in the Central Karoo district increased from 4,659 in 2006 to 6,185 in 2012 – an increase of 32.75% in just six years.

1.2.1 Why is this problem worth solving?

As stated in the Annual Performance Plan, the vision of the SAPS is to "create a safe and secure environment for all people living in South Africa" (South African Police Service, 2011). However, due to the circumstances mentioned above, citizens living in some of the rural areas of South Africa do not have access to the services of the SAPS. All South Africans must be protected and crime needs to be managed and mitigated. Every person living in the ISRD nodes is entitled to safety and security. This project will assist the SAPS to create a safe and secure environment for the people of the Central Karoo by allocating service points in such a way that the majority of citizens will be accommodated.

1.3 Project aim

The aim of this project is to determine the number of, and optimally locate, SAPS service points that will provide convenient access to people living in the Central Karoo.

1.4 Research design

This project aims to formulate mathematical models that will determine the optimal locations for police service points in the Central Karoo district. Mathematical modelling is a scientific approach to understanding the problem context and to providing decision support (Winston & Venkataramanan, 2003). Thus mathematical models will be used to understand the problem and to develop a suitable solution for the SAPS. The models formulated can also be applied to the remaining ISRD nodes with minimal adjustments.

1.5 Project scope

The content of this project is encapsulated in the following five chapters:

Chapter 1 – Introduction: The introductory chapter describes the background and the context of the problem, as well as the research design.

Chapter 2 – Literature Review: A detailed literature review is conducted to identify existing mathematical location models applicable to this problem, and to give an overview of the South African Police Service.

Chapter 3 – Model Formulation: This chapter formulates mathematical models to determine the optimal locations for police service points in the Central Karoo district. The costs associated with locating the facilities have not been determined; but because the SAPS is not concerned with the costs at this stage, costs are excluded from this project.

Chapter 4 – Data Analysis: Population data obtained from STATS SA are analysed and used as input for the models for the Central Karoo. The Geographic Information System (GIS) software is used extensively throughout this project to plot population data. The model results and sensitivity analyses are discussed in order to test the validity of the models.

Chapter 5 – Conclusions and Recommendations: The last chapter concludes the report and makes recommendations to the SAPS. The implementation of the project is not included in this report.

1.6 Deliverables

The following deliverables are envisioned for this project:

- A comprehensive literature review that will provide relevant models and techniques that can be used to improve police accessibility in rural areas
- A detailed analysis of existing police service points, demonstrating the extent to which the existing infrastructure correlates with the access norms set by the SAPS
- Alternative optimal locations for additional service points, based on the results obtained from location models

1.7 Project approach

1.7.1 Step-by-Step plan

1. Conduct the literature review.
2. Gather and evaluate data on the population densities and distributions of the Central Karoo district.
3. Use the GIS software to plot the gathered data.
4. Formulate and implement the relevant mathematical location models.
5. Study the geographic features of the rural areas, and assess the various challenges.
6. Analyse the generated solutions and construct a sensitivity analysis.
7. Present results to the stakeholders (SAPS and Mrs Botha) and receive feedback.
8. Change methodologies and/or assumptions according to the stakeholders.

Chapter 2

2. Literature Review

2.1 An overview of the South African Police Service

2.1.1 Mission & Vision of the South African Police Service

The Vision of the South African Police Service is *to create a safe and secure environment for all people in South Africa.*

The Constitution of the Republic of South Africa, 1996 (Act 108 of 1996) states that the SAPS has a responsibility to:

- *prevent, combat and investigate any crime that threaten the safety or security of any community;*
- *maintain public order;*
- *protect and secure the inhabitants of the Republic and their property;*
- *uphold and enforce the law;*
- *create a safe and secure environment for all people in South Africa;*
- *ensure criminals are brought to justice; and*
- *participate in efforts to address the causes of crime.*

The SAPS, therefore, has a responsibility to provide serviceability through accessibility throughout the country for all South Africans. Locating police service points in strategic positions will assist the SAPS in achieving the required expectations.

2.1.2 Service points

There are four types of service points categorized by the SAPS (Rabie, 2011). These four are:

- Police Station
- Satellite Police Station
- Fixed Contact Point
- Mobile Contact Point

All four service points provide visible policing services.

Police stations are generally referred to as the 'mother station' as they are responsible for the entire station area they are located in (Rabie, 2011). The number of staff employed in a police station is different for each station and dependant on factors such as the amount of crime in the area, population, and environmental factors.

Police stations render all the necessary services, namely:

- Reporting of complaints
- Administrative enquiries
- Custody management
- Complaints attendance and emergency response
- Crime prevention
- Court duties
- Firearms, liquor and second hand goods
- Property and exhibit management
- Investigation of crime
- Attending to crime scenes

Satellite police stations and fixed and mobile contact points are simply extensions of police stations in order to improve the accessibility of SAPS services.

Satellite police stations are established to render a 24-hour service with 17 employees and one vehicle. A satellite police station renders the following services:

- Reporting of complaints
- Administrative enquiries
- Complaints attendance and emergency response

Fixed and mobile contact points allocate eight employees to render the following 24-hour services:

- Reporting of complaints
- Administrative enquiries

Fixed contact points are located in specific areas to offer their specific duties. Mobile contact points are vehicles that follow predetermined routes and plans to render their services in the relevant station areas.

2.2 An overview of the ISRD nodes

2.2.1 Rural areas

Large regions of South Africa are judged as rural areas, in fact, according to World Bank Indicators (2012), 39.3% of the entire South African population live in rural areas (World Bank Indicators, 2012). It is assumed that rural areas are larger in size than urban areas because rural areas stretch across the countryside and undeveloped spaces of South Africa; whereas urban areas are all the cities of South Africa. Therefore, about 40% of the population is spread across large portions of South African soil.

Rural areas in South Africa can experience the following problems:

- Poor road quality and infrastructure
- No safe drinking water
- No running water
- No electricity
- Lack of proper education
- Lack of health and safety governmental services
- Unemployment or low paying jobs which lead to poverty

South Africans rely on road transportation as the only means of transportation especially in rural, undeveloped areas where no passenger trains exist. Hence, poor road quality increases the difficulty of travel and time travelled to reach a destination. On top of the poor road infrastructure, police stations are incorrectly located relevant to the population distribution. This leads to crimes being reported very late, or due to the inconvenience, people may neglect reporting the crime altogether. The response of the SAPS will also be much slower than in an urbanised area due to the travelling difficulties.

The SAPS police stations need access to electricity to operate. This is a limitation to locating the service facilities in the rural areas. No safe drinking or running water increases the complexity of locating police stations in the undeveloped areas.

2.2.2 Service areas: ISRD Nodes

Integrated Sustainable Rural Development (ISRD) nodes are the municipal districts in South Africa that are underdeveloped and have high levels of poverty. The national government wants to focus on developing these areas and on reducing the unemployment rate and poverty. Due to high levels of poverty and poor infrastructure, these areas currently do not receive adequate security and safety services from the SAPS.

The following table represents the 15 district municipalities that are identified by the Department of Public Service and Administration (South Africa, 2009) as the ISRD nodes of South Africa:

District Municipality	Province
Alfred Nzo	Eastern Cape
Bushbuckridge	Mpumalanga
Central Karoo	Western Cape
Chris Hani	Eastern Cape
Kgalagadi	Northern Cape
Maluti-a-Phofung	Free State
Maruleng	Limpopo
Okhahlamba	KwaZulu-Natal
OR Tambo	Eastern Cape
Sekhukhune	Limpopo
Ugu	KwaZulu-Natal
Umkhanyakude	KwaZulu-Natal
Umzimkhulu	KwaZulu-Natal
Umzinyathi	KwaZulu-Natal
Zululand	KwaZulu-Natal

Table 1: ISRD Nodes

The province of KwaZulu-Natal has 11 districts, of which no fewer than six are identified as ISRD nodes. The Eastern Cape has seven districts, with three of them identified as ISRD nodes. Limpopo province has ISRD nodes, while Mpumalanga, the Free State, the Northern Cape, and the Western Cape each have only one ISRD node.

The pie chart below represents the number of stations in the ISRD nodes and the respective service areas they need to cover (Rabie, 2011). For example, 10 police stations are responsible for servicing an area of up to 100km² each.

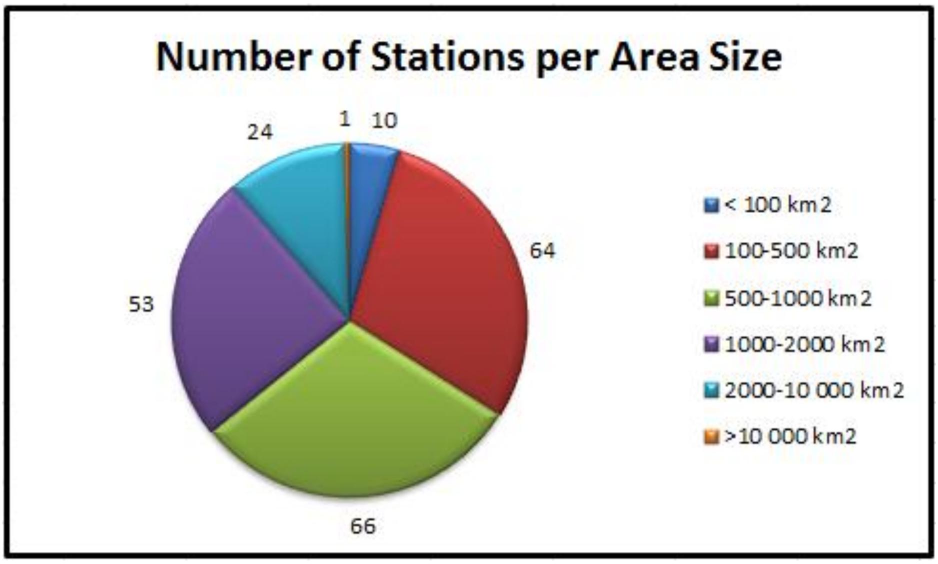

Diagram 1: Number of stations per area size (Adapted from Rabie, 2011)

Currently, 30% of the stations cover a service area of 500 to 1000 km² each; 24% cover a service area of 1000 to 2000 km² each; and 11% of all the stations cover 2000 to 10 000 km² of service area each. These statistics show that most of the stations (66% of all stations) have to cover far too much ground, making it difficult for these stations to be accessible.

The Central Karoo district covers an area of 38,854km² (The Local Government Handbook, 2013) in the Western Cape. Currently, five SAPS police stations are located within the district, covering a service area of 7,770km² each. This translates into a buffer radius of 111km for each station. The larger the size of the service area, the greater are the distances for people to travel to service points. Hence, the existing police stations in the Central Karoo are covering too much ground. This contributes to the inaccessibility of police stations in this area.

2.3 Mathematical location models

2.3.1 An overview of location models

There are four major location models that are used to identify the optimum location of services, stations, facilities such as warehouses, etc. These four models are: analytic models, continuous models, network models, and discrete models (Daskin, 2008).

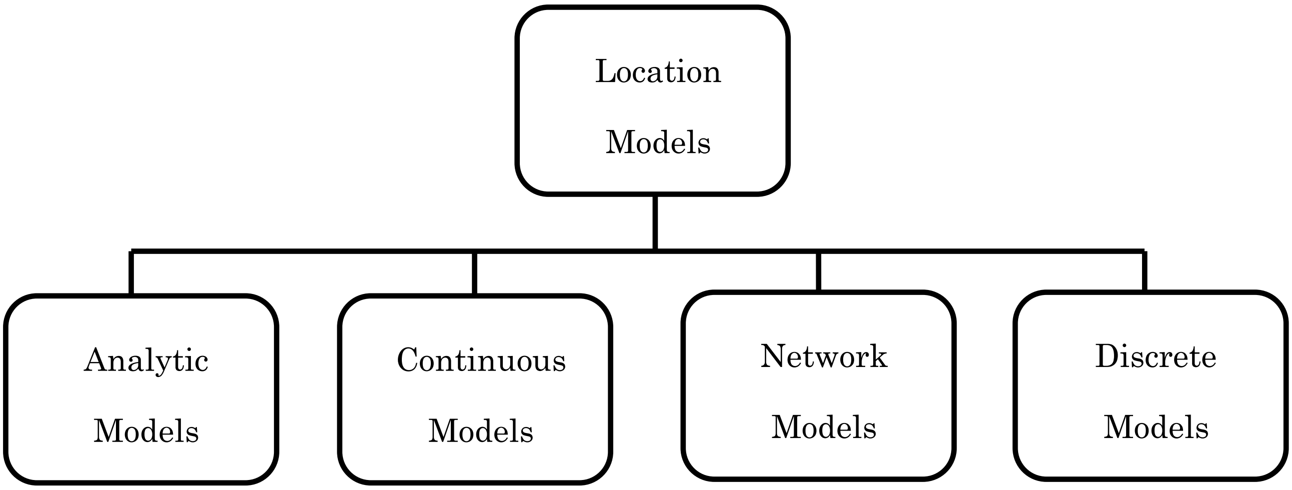

Figure 3: Location Models (Adapted from Daskin, 2008)

According to Daskin (2008), analytic models are the most basic, and they assume that demand is distributed in a specific way, such as uniformly, over a service area. The optimum locations identified by the model can be found anywhere in the service area. Analytic models will require calculus or other simple skills to solve the problems.

Continuous models are quite the opposite of analytic models, as they assume that the demands in a service area are discrete points, instead of a continuous distribution (Daskin, 2008). Continuous models are based around the location and intensity of demands in the service region, and use iterative numerical procedures, such as the Weiszfeld algorithm.

Network models are used in problems where demands are located on a network comprised of nodes and links; the demands, however, mostly arise on the nodes of the network tree. The facilities may be located anywhere on the network tree, and the model's objective is to minimize the furthest distance between any node and the closer facility (Daskin, 2008).

Discrete location models are further classified into three categories: covering-based models, median-based models, and other models (Daskin, 2008). Covering-based models are used to locate facilities within a service region in order to serve demands within a specific time or distance. These models are generally used for locating emergency stations, such as fire stations. Covering-based models are broken down further into three different models: set covering, maximal covering, and p-center models (Daskin, 2008).

2.3.2 Covering-Based models

The set covering and maximal covering models are the most popular covering-based location models. As Tompkins, White, Bozer and Tanchoco (2010) state in their book, the set covering model refers to “determining the minimum number of new facilities required to cover a set of existing facilities” (Tompkins et al. 2010, p.551) and the maximal covering location model “determines the locations of specified new facilities to maximise the number of existing facilities covered” (Tompkins et al. 2010, p.553). Simply stated, the set covering model minimizes the number of sites needed to cover all the demands; and the maximal covering location model maximises the number of covered demands with a certain number of sites. The p-center model minimises the coverage distance needed to cover all the demands with a certain number of sites (Tompkins et al., 2010).

It is recognised that the two categories of coverage facility location problems – the set covering problem (SCP) and the maximal covering location problem (MCLP) – are the most relevant to this project. The objective of these models is to locate new facilities that will accommodate demand in a service area.

This project needs to locate SAPS facilities in order to be accessible to the people living in the rural areas and thus to provide the necessary service coverage. The difference between the two models is the method they employ in solving the coverage of the demand area. The MCLP is implemented when the minimal number of facilities must be installed to cover as much demand as possible; whereas the SCP ensures that every single demand is met, locating as many facilities as are deemed necessary (Daskin, 2008). These two categories of location problems are therefore most applicable to this project, and are studied in greater detail.

2.3.2.1 The Set Covering Problem (SCP)

As already mentioned, the SCP locates facility locations where coverage (demand is met) is required. The SCP model will try to reach a specific level of coverage by minimizing the location cost (Farahani et al., 2011).

The set covering problem was formulated by Daskin and Dean (2004) as follows:

I = Set of demand nodes

J = Set of potential facility sites

$$a_{ij} = \begin{cases} 1 & \text{If demand node i can be covered by a facility at candidate site j} \\ 0 & \text{If not} \end{cases}$$

$$x_j = \begin{cases} 1 & \text{If candidate site j is selected} \\ 0 & \text{If not} \end{cases}$$

f_j = fixed cost of locating a facility at candidate site j

$$\text{Minimize } Z = \sum_{j \in J} f_j x_j \qquad (1)$$

s.t.

$$\sum_{j \in J} a_{ij} x_j = 1 \qquad \forall \quad i \in I \qquad (2)$$

$$x_j \in \{0, 1\} \qquad \forall \quad j \in J \qquad (3)$$

The objective function (1) minimises the total cost of locating at the selected facilities. Constraint (2) ensures that every demand node is covered by at least one of the selected sites. Constraint (3) is a standard operations research condition to ensure x_j is a binary variable (Daskin & Dean, 2004).

2.3.2.2 The Maximal Covering Location Problem (MCLP)

The MCLP was first formulated in the 1970s (Church & ReVelle, 1974).In many situations, the allocated facilities are not sufficient enough to cover the entire service area. The MCLP models were designed for such problems where a given number of facilities must be located to cover the maximum amount of demand (Farahani et al., 2011). In other words, the goal of the model is to maximize covered demands, while the constraints ensure that a demand node is covered if at least one potential facility is located to cover it.

2.3.2.2.1 A case study on determining optimal police patrol areas with maximal covering and backup covering location models

This paper was written by Curtin, Hayslett-McCall, and Qui in order to present a new method for locating police resources in the police patrol areas of Dallas to cover the demand (Curtin et al., 2007). They utilized a maximal covering problem and a backup covering formulation to determine the optimal solutions for the police. They also integrated Geographic Information Systems (GIS) with linear programming to determine optimal solutions. Curtin et al. wanted to efficiently distribute police resources, reduce their response times, and consequently save money through optimal deployments.

Curtin et al. (2007) used the following Police Patrol Area Covering (PPAC) model to generate optimal police patrol areas:

Maximize $Z = \sum_{i \in I} a_i y_i$ (1)

s.t.

$\sum_{j \in Ni} x_j \geq y_i \quad \forall \quad i \in I$ (2)

$\sum_{j \in J} x_j = P$ (3)

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

$y_j = \{0, 1\} \quad \forall \quad i \in I$ (5)

Where:

I, i = the set and index of known incident locations or calls for service

J, j = the set and index of potential locations for police patrol command centers

S = the acceptable service distance

d_{ij} = the shortest distance from the incident location i to police command center location j

x_j = 1 if a police patrol is located at potential site j, and 0 otherwise

y_i = 1 if an incident location at i is covered by at least one located police patrol area, and 0 otherwise

N_i = $\{j \text{ in } J \mid dij \leq S\}$

a_i = weight or priority of crime incidents at incident location i

P = the number of police patrol areas to be located

The objective function (1) is to maximize the number of weighted incidents covered. They are covered if they are within the acceptable service distance S. Constraint (2) enforces the fact that the site is covered when one or more patrol cars are located at the site. Constraint (3) limits the number of patrol cars and (4) and (5) simply ensure the solutions are integer values.

The PPAC model assumes the distance between the demand and service is a good determination of the police performance and response time. However, Curtin et al. (2007) integrated the GIS, that is maintained by the police administration, into the solution in order to get a more accurate result. The GIS contained more detail information about the physical factors regarding the "distances" used in the calculation. For example, the GIS included street width, speed limit, traffic congestion, turn complications, and other factors that would influence the actual response times. They did note that road conditions may not influence the amount of crime in a region, but it certainly does affect the response times of the police.

Curtin et al. (2007) also noted that modelling the police patrols into random locations is unrealistic because the central tendency of these randomly chosen locations will always converge on a central location. They mapped out all the different sectors that are divided by boundaries and recorded all the crime incidents. The incidents were also assigned weights to distinguish the extreme crime incident locations such as murders and armed robberies.

Once they formulated a solution, they calculated the total distance to travel to a certain incident with the new facility locations and compared it to the distance that would need to be travelled with the current facilities. They found that the new solution reduced the travel time by 19%. Not only does this reduce the response time and distance travelled, but also reduces the travel costs and improves the police's service.

Curtin et al. (2007) then went further to consider an alternative strategy which utilises the multiple coverage concept in a Location Set Covering Problem (LCSP). This method also served as a backup coverage problem as they wanted to ensure the potential incidents are covered by multiple police facilities, as the police may want multiple patrol cars available within the service distance.

The model built for the backup coverage problem is almost the same as the PPAC model, the only difference is the constraint (5) is replaced with:

$$Y_i \in \{0, 1, \ldots, P-1, P\} \text{ for all } i \in I \qquad (6)$$

This constraint ensures the number of facilities that can cover the incidents to range from 0 to P instead of restricting them to 0 or 1. The objective function increases the more y_i increases, therefore backup coverage is achieved of the incidents.

Curtin et al. (2007) discovered however, that the solution to the maximal backup site located all the police facilities in the high incident region alone, sacrificing the rest of the service area. This information may be useful for the police to know, but does not provide a solution for the police who wish to cover the entire service region. However, the maximal covering solution did not allocate more than one facility for most of the incidents, so Curtin et al. (2007) suggested that a trade-off between the two different objectives may give the best alternative optimal solutions.

2.3.2.2.2 A case study on fire station site selection in rural areas

Sherry Massey (Massey, 2011) compiled the study and tried to find the optimal site in the Dickinson County, Kansas, area to place new fire stations to accommodate any unmet demands.

Massey (2011) implemented the Maximal Covering Location Problem model which meant a minimum amount of new stations were located to service the maximum amount of unmet demand. Massey (2011) classified the potential sites as discrete, address points and the potential building sites by a continuous plane in the model.

Mehrez and Stulman (Mehrez & Stulman, 1982) deduced that each facility has an effective service range or radius of R, which is then used to measure the service area that it will serve. The radius R was centred on the demand points and circular disks were drawn to represent the area covered by each fire station. Every disk would cover N demand points, which was maximised to find the ideal locations. All the address points that fell outside the service area were categorised as the unmet demand. They reasoned that address points that fell on the perimeters of two service disks were in the intersection point. A single facility could then be shifted to centre its service radius R on the intersection point and cover more N demand points. This resulted in fewer stations needing to be built and covering more demand points.

The existing fire stations were evaluated based on the service area they cover. The total demand points that would be covered by the new facilities were used to calculate the optimal solution.

Regarding the service areas, Massey (2011) considered the response area as a Euclidian buffer but concluded that the Euclidian buffers often over-estimated the service areas; especially in rural areas where there are few road networks. Matisziw and Murray (Matisziw & Murray, 2009) focused on non-circular service areas in order to address the over-estimation. They applied the planar maximal cover location problem in an urban environment that had continuous demand and irregular service areas based on the road networks.

2.3.2.2.3 A case study on covering-location models for emergency situations that require multiple response units

In this study, Batta and Mannur (Batta & Mannur, 1990) compared the set covering and maximal covering location problems which had to be valid for the following two kinds of applications:

i. The model should locate the fire trucks in ideal locations to be able to cover the various emergencies by being within the acceptable distance in the service area.
ii. Currently, the demand volume is too much to cover in the service area, so the model needed to place ambulances optimally to accommodate the demand.

Batta and Mannur (1990) made the assumption that a demand is only covered if the response unit is within the acceptable distance or travel time to the demand.

Studying the set covering location model, Batta and Mannur (1990) made the following propositions:

1. Each node (demand) will need at most L units to cover it.
2. In order to cover all demands at node i it will be able to cover demands with l_i units, at node i.

Batta and Mannur (1990) continued to construct their model, transformed it into a binary integer program and made use of a branch-and-bound algorithm. The branching rule they adopted simply meant they analysed the branches with the greatest feasibility by measuring the number of covered nodes.

The maximal covering location model had the objective of maximizing the weighted coverage of demand by locating M units in the service area. The model they built was also a binary integer program and they followed the same procedure as the set covering location model.

Batta and Mannur (1990) concluded that M equalled to 60 percent of the optimal number of units calculated in the set covering problem. The amount of units located in the maximal covering problem was far less and still provided substantial coverage. The set covering model required every demand to be covered and so created infeasibility with regards to the amount of units that would need to be installed.

2.3.3 Selection of location model

The problem of locating police service points for the SAPS in the Central Karoo is a discrete problem because the demand nodes and potential police station locations are discrete data points. A mathematical tool that locates police stations to cover all the demand nodes, and that also locates a fixed number of police stations to cover as much demand as possible, is required to solve this problem. Thus covering-based mathematical models will be implemented to find the optimal solution.

It is known that the set covering problem (SCP) and the maximal covering location problem (MCLP) are the most popular covering-based strategies that are implemented in facility locating problems. The SCP will be implemented to specify the number of service points needed to cover every single demand; while the MCLP will be utilised to locate a limited number of service points in strategic positions to cover as much demand as possible.

It is recognised that the SCP model assumes no limit in allocating police stations. This may result in the model locating many service points in the large region of the Central Karoo, which would not be economically feasible for the SAPS.

Chapter 3

3. Model formulation

In this chapter the set covering and maximal covering location models will be formulated to provide valuable information for the SAPS in locating police service points.

3.1 Set Covering Problem (SCP)

Enumeration Areas (EA) are the smallest area statistics that can be obtained from Stats SA in order to describe accurately the census data of South Africa, and to ensure an acceptable level of confidentiality (Statistics South Africa, 2006). The x and y co-ordinates of the EA nodes within the Central Karoo district were used as the demand nodes for the model. Since police stations are located in communities where people live, the co-ordinates of the EA nodes were used as possible sites to locate the police service facilities. Potential sites have not been identified by the SAPS, and therefore the demand nodes will be used as candidate sites to generate an initial solution.

The allowable service distance of each police facility is considered to be variable, and has been changed accordingly to analyse the different scenarios. The distance between the potential sites and demand nodes was calculated using the rectilinear distance formula. The assumption is made that people do not walk or drive in straight lines to police stations; hence, the rectilinear distance equation more closely represents the distance covered by people travelling on foot or by road.

The SCP model determined the minimum number of facilities needed to cover every demand. The model was adapted from le Roux and Botha's work (le Roux & Botha, 2012), and was formulated in the following way:

Sets

I = Set of potential police station sites

J = Set of demand nodes

Decision variables

$$s_i = \begin{cases} 1 & \text{if police station is located at site } i \in I \\ 0 & \text{otherwise} \end{cases}$$

$$p_{ij} = \begin{cases} 1 & \text{if police station at site } i \in I \text{ can cover demand node } j \in J \\ 0 & \text{otherwise} \end{cases}$$

Parameters

a_i = the x co-ordinate of potential site $i \in I$

b_i = the y co-ordinate of potential site $i \in I$

x_j = the x co-ordinate of demand node $j \in J$

y_j = the y co-ordinate of demand node $j \in J$

h_{ij} = the calculated rectilinear distance between police station site $i \in I$ and demand node $j \in J$

K = the allowable service distance

SCP Model

Minimize $Z = \sum_{i \in I} s_i$ (1)

s.t.

$h_{ij} = |x_j - a_i| + |y_j - b_i|$ $\quad \forall \quad i \in I, j \in J$ (2)

if $h_{ij} \leq K$ then $p_{ij} = 1$

$h_{ij} > K$ then $p_{ij} = 0$ $\quad \forall \quad j \in J$ (3)

$\sum_{i \in I} p_{ij} s_i \geq 1$ $\quad \forall \quad j \in J$ (4)

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

The objective function (1) minimizes the number of police stations located at the possible sites. Constraint (2) calculates the rectilinear distance between the demand nodes and possible sites. Constraint (3) determines that if the distance between the site and the demand node is less than or equal to the allowable service distance, the demand node can be covered by that particular site. If the distance is greater than the allowable service distance, the demand node cannot be covered by the site. Constraint (4) guarantees that every demand node is covered by at least one site. Constraint (5) ensures that s_i is a binary variable.

3.1.1 SCP model alterations

The SCP model was altered to minimize the number of police stations located, rather than minimizing the cost of locating facilities. The cost associated with locating the facilities has not been determined and the SAPS is not concerned with costs at this stage. The outcome of the SCP model is to calculate the number of facilities needed to cover the entire population; thus cost is excluded from this project.

Constraints were also added to include the serviceability distance of the police stations, which could be changed accordingly.

3.2 Maximal Covering Location Problem (MCLP)

The MCLP model uses the same data, calculations, and assumptions made in the SCP. However, the population sizes of the EA nodes were assigned as weights to the demand nodes. The MCLP model locates the specified number of police service facilities in strategic positions to accommodate as much demand as possible. The model was formulated in the following way (le Roux & Botha, 2012):

Sets

I = Set of potential police station sites

J = Set of demand nodes

Decision variables

$$s_i = \begin{cases} 1 & \text{if police station is located at site } i \in I \\ 0 & \text{otherwise} \end{cases}$$

$$p_{ij} = \begin{cases} 1 & \text{if police station at site } i \in I \text{ can cover demand node } j \in J \\ 0 & \text{otherwise} \end{cases}$$

$$n_j = \begin{cases} 1 & \text{if demand node } j \in J \text{ is covered} \\ 0 & \text{otherwise} \end{cases}$$

Parameters

a_i = the x co-ordinate of potential site $i \in I$

b_i = the y co-ordinate of potential site $i \in I$

x_j = the x co-ordinate of demand node $j \in J$

y_j = the y co-ordinate of demand node $j \in J$

h_{ij} = the calculated rectilinear distance between police station site $i \in I$ and demand node $j \in J$

g_j = the size of population at demand node $j \in J$

K = the allowable service distance

T = the total number of police facilities to locate

MCLP Model

$$\text{Maximize } Z = \sum_{j \in J} g_j n_j \quad (1)$$

s.t.

$$h_{ij} = |x_j - a_i| + |y_j - b_i| \qquad \forall \quad i \in I, j \in J \quad (2)$$

$$\text{if } h_{ij} \leq K \text{ then } p_{ij} = 1$$
$$h_{ij} > K \text{ then } p_{ij} = 0 \qquad \forall \quad i \in I, j \in J \quad (3)$$

$$n_j - \sum_{i \in I} p_{ij} s_i \leq 0 \qquad \forall \quad j \in J \quad (4)$$

$$\sum_{i \in I} s_i = T \quad (5)$$

$$\sum_{i \in I} p_{ij} s_i \leq 1 \qquad \forall \quad j \in J \quad (6)$$

$$s_i \in \{0, 1\} \qquad \forall \quad i \in I \quad (7)$$

$$n_j \in \{0, 1\} \qquad \forall \quad j \in J \quad (8)$$

The objective function (1) maximizes the number of people covered in the demand nodes. Constraint (2) calculates the rectilinear distance between the demand nodes and possible sites. Constraint (3) determines that if the distance between the site and the demand node is less than or equal to the allowable service distance, the demand node can be covered by that particular site. If the distance is greater than the allowable service distance, the demand node cannot be covered by the site. Constraint (4) ensures that a demand node is not counted unless a site is located to cover it. Constraint (5) limits the number of possible sites to locate. Constraint (6) ensures that a demand node is covered by at most one site or none at all. Constraints (7) and (8) ensure that s_i and nj are binary variables.

3.2.1 MCLP model alterations

The MCLP model was altered to include the serviceability distance of the police stations, which could be changed accordingly. Constraint (6) was added to ensure that the police stations were located across the entire Central Karoo district. If constraint (6) were excluded from the constraints, the model would locate police stations on each of the highly populated demand nodes, resulting in many stations covering the same population. This is not feasible, as each demand node should only be covered by one police service point.

Chapter 4

4. Data analysis

This chapter discusses the data used as input for the covering location models, and analyses the results generated. The sensitivity analysis determines the functionality of the models.

4.1 Problem context

Five SAPS police stations are currently located in the densely-populated areas of the Central Karoo district. The stations cover a total of 54,040 people within a 4km coverage distance – 76% of the entire population. However, the remainder of the population is distributed across the large 38,854km^2 area of the district (The Local Government Handbook, 2013), as shown in Diagram B. 1 in Appendix B. This results in small communities having to travel long distances to the nearest police station. Thus new police stations need to be located to improve police service accessibility for the sparsely-populated regions.

The Central Karoo ISRD node has 246 EA demand nodes, each containing a population ranging from 0 to 1440 people. A standard personal computer was used to process the data and models and to make calculations, using Microsoft Excel 2010 and Lingo 14.0.

4.2 Set Covering Problem (SCP)

4.2.1 Pre-processing procedure

Sets

Two sets were defined for the SCP. Set I was defined as the set of possible police station sites, and set J was defined as the set of demand nodes. Sets I and J used the same x and y co-ordinates of the EA nodes' centroids, because every demand node was also the potential location for a new police station. Thus set I and set J each had 246 x and y co-ordinate data points.

The diagram below displays the x and y co-ordinate locations of the demand nodes, and possible police station sites, in decimal degrees (DD) in the Central Karoo ISRD node.

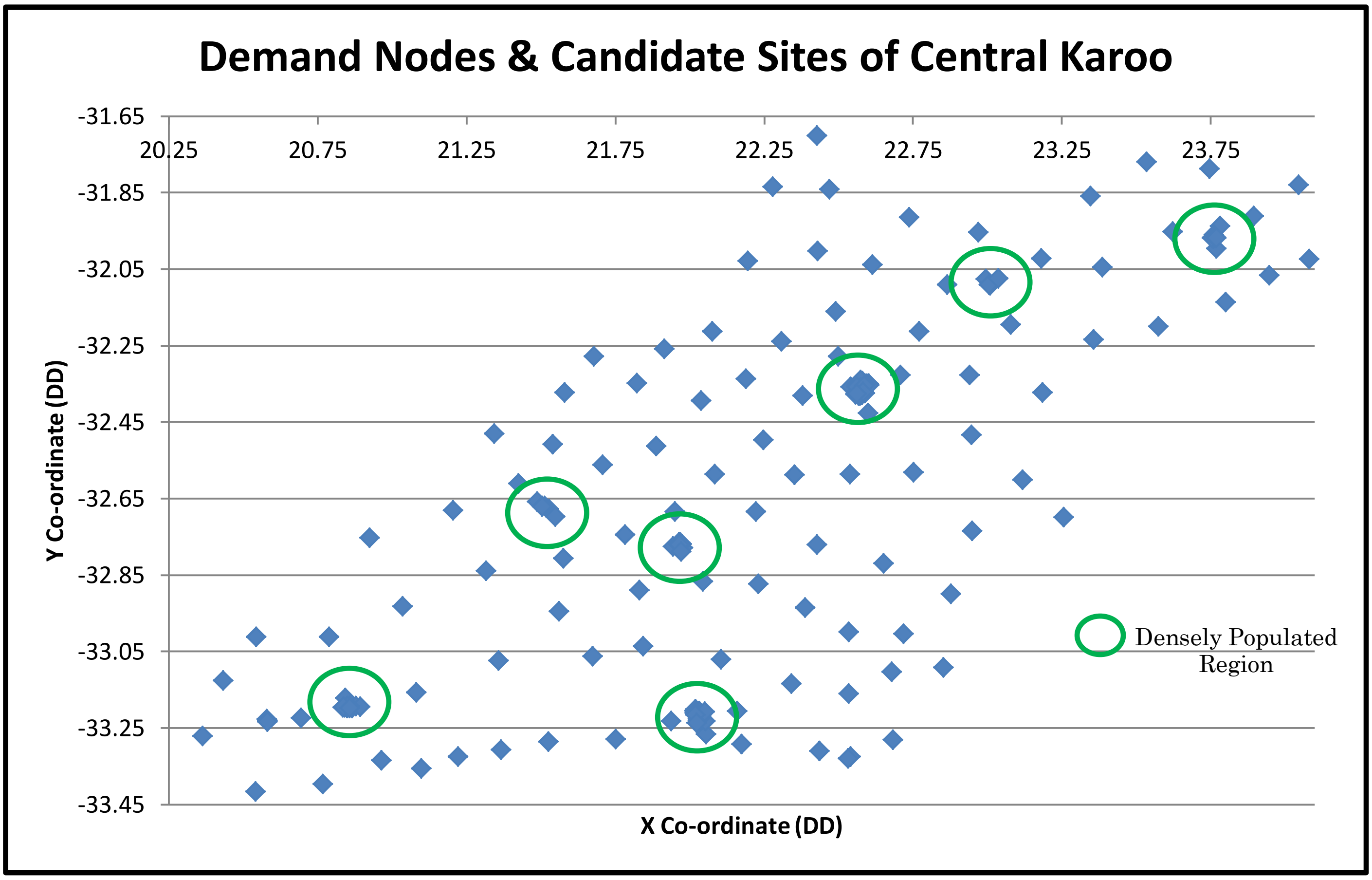

Diagram 2: Demand nodes & candidate sites of Central Karoo

Parameters

To solve the SCP, the distance h_{ij} between each candidate site i and demand node j was calculated in decimal degrees. Since there were 246 demand nodes, Lingo took extremely long to calculate the individual distances and solve the problem; so a program was constructed in Excel to calculate the rectilinear distances. A 246 by 246 matrix was generated in Excel that contained each individual distance between the demand nodes. Excel was then programmed to test whether the calculated distance h_{ij} was less than or equal to the required service distance. Excel then generated a 246 by 246 binary matrix to represent the p_{ij} values. The p_{ij} matrix was used in Lingo to solve the SCP. A detailed list of the x and y co-ordinates for the candidate sites and demand nodes is provided in Table B. 1 in Appendix B.

The allowable service distance between the police stations and each demand node was set at 4km, 8km, 20km, 30km, 40km, and 50km in order to provide decision support for the SAPS. The conversion factor for converting one decimal degree to kilometres is 111.325km/DD (The Classroom, 2013). This was used to convert the serviceability ranges from kilometres to decimal degrees.

4.2.2 Model results

The following table displays the results generated by the SCP model in calculating the number of sites needed to cover all the demand nodes within the respective coverage distances.

SCP Results	
Rectilinear Coverage Area (km)	**Number of Sites**
50	13
40	18
30	32
20	82
8	107
4	114

Table 2: Results generated by the SCP model

The SCP model indicates that, if the SAPS wanted to cover every demand node within 4km, they would have to locate 114 facilities. This is not feasible for economic reasons. Currently there are five police stations in the Central Karoo district, indicating that the 50km coverage area result would be more appropriate. Thirteen sites would be needed to cover the entire demand with a service coverage area of 50km. However, the locations of these sites would not be feasible, as they would not be situated within 4km of the largely populated demand nodes, as can be seen in Diagram E. 1 in Appendix E. Some sites would also be located quite close together, which would be impractical.

So the SCP model's results cannot be used to locate the police sites. The model is only useful in showing the number of sites needed to cover the demand nodes for the various service coverage areas.

4.3 Maximal Covering Location Problem (MCLP)

4.3.1 Pre-processing procedure

Sets

The same sets identified in the SCP model in 4.2.1 were used in the MCLP model. The x and y co-ordinates of the sets are shown in Table B. 1 in Appendix B, and displayed in Diagram 2.

Parameters

The calculation of the rectilinear distances (h_{ij}), the respective p_{ij} matrices, and the service coverage areas (K) used in the SCP model were applied in solving the MCLP model.

The parameter g_j represents the number of people living in each of the demand nodes, and was assigned as the demand of each demand node. The population of each demand node is shown in Table B. 1 in Appendix B, and mapped out in Diagram B. 1 in Appendix B.

The parameter T indicates the number of stations to locate. As explained in the Problem Context in section 4.1, the Central Karoo district contains both densely- and sparsely-populated regions. The MCLP model must therefore identify the optimal locations in both the densely-populated areas and the in the sparsely-populated regions. In order to analyse the two populated regions, six scenarios were created. These scenarios allocated different coverage areas for the police stations, and varied the number of stations to locate. This is clarified in the table below.

Scenario	Rectilinear Coverage Area (km)	Number of Stations To Locate
1	50	10
2	40	14, 12, 10
3	30	20, 18, 16, 14, 12, 10
4	20	20, 18, 16, 14, 12, 10
5	8	10, 9, 8, 7, 6, 5
6	4	5

Table 3: The various scenarios used in the MCLP model

Scenarios 1, 2, 3, 4

The SAPS needs to improve accessibility in the regions that are currently not receiving policing services in the Central Karoo. These are the areas where low-population communities are scattered across the large regions of the district; typically these EA demand nodes are more than 10km from each other. The MCLP model therefore needs to identify the optimal locations to cover as many scattered EA demand nodes as possible in the sparsely-populated regions. So scenarios 1, 2, 3 and 4 were created to assign large coverage areas to the police stations to accommodate the scattered demand nodes.

Scenario 1 was limited to 10 stations because they covered the entire Central Karoo district, while complying with constraint (6) (as explained in 3.2.1). Scenario 2 was limited to 14 stations for the same reasons.

Scenarios 3 and 4 were designed to locate up to 20 stations across the district. This allowed the MCLP model to identify the ideal locations for new police stations in the low-population areas.

Scenario 5

In order to analyse the ideal locations in the densely populated areas, a small coverage area of 8km was assigned to the police stations. This would result in the MCLP model locating police stations in the regions where the demand nodes are within 8km of each other. Since there are, at the most, seven densely-populated regions in the Central Karoo, as shown in Diagram 2, scenario 5 was designed to locate a maximum of 10 stations.

Scenario 6

Scenario 6 was designed to locate five police stations in the Central Karoo. The purpose of this scenario was to compare the MCLP model's result with the location of the existing SAPS police stations.

4.3.2 Model results

The following table displays the results generated by the MCLP model for each scenario, in locating the specified number of sites to maximize the demand covered.

MCLP Results			
Scenario	Number of Sites	Population Covered	%
1: 50km Coverage Area	10	70496	99.3
2: 40km Coverage Area	14	69960	98.5
	12	69334	97.6
	10	68434	96.4
3: 30km Coverage Area	20	69177	97.4
	18	68845	96.9
	16	68384	96.3
	14	67595	95.2
	12	66847	94.1
	10	65957	92.9
4: 20km Coverage Area	20	65717	92.5
	18	65300	92.0
	16	64846	91.3
	14	64340	90.6
	12	64004	90.1
	10	63111	88.9
5: 8km Coverage Area	10	59545	83.8
	9	59099	83.2
	8	58614	82.5
	7	58030	81.7
	6	56416	79.4
	5	54717	77.0
6: 4km Coverage Area	5	54040	76.1

Table 4: Results generated by the MCLP model

The locations of the stations are presented in Appendix F for each scenario.

As discussed in section 4.3.1, scenarios 1, 2, 3, and 4 were created to locate police stations in the scattered regions of the Central Karoo. The EA demand nodes are located far apart from each other, and the long distances make policing services inaccessible. Police stations were therefore assigned large coverage areas to service the scattered EA demand nodes. Each of the four scenarios generated different results that can be compared and used to identify the ideal locations in which to locate police stations in the scattered regions.

The results generated by scenario 5 indicate the ideal locations to cover the seven densely-populated areas of the Central Karoo, mapped in Diagram F. 11 in Appendix F. It is interesting to note that five stations cover 77% of the population within 8km, and locating only another three stations increases the total population covered to 82.5%. This translates to each police station covering approximately 2% more of the population. Locating the 9^{th} and 10^{th} sites, however, only covers a further 0.7% and 0.6% of the population respectively. As mapped in Diagram F. 10, the 9^{th} and 10^{th} sites are also located extremely close to other proposed sites, which is impractical.

Scenario 6 identified the ideal locations in which to locate five police stations. This result was compared with the locations of the five existing SAPS police stations in Diagram F. 13, in Appendix F.

From the results generated by the MCLP model, specifically scenario 5, it can be assumed that 80% of the population is densely-populated and that the rest of the population is scattered. A solution must therefore be derived to locate seven facilities that cover the densely-populated regions by implementing scenarios 5 and 6. The solution must also establish six additional possible locations that provide more accessibility in the scattered regions by utilising scenarios 1, 2, 3, and 4. For economic reasons, and because the SAPS have five police stations currently operating in the Central Karoo, the solution was limited to locating 13 sites. The solution would therefore need to identify 13 ideal locations in which to plant police stations.

4.4 The ideal locations

By implementing the results produced in sections 4.2 and 4.3 above, 13 ideal sites were identified at which to locate police stations in the Central Karoo district. The following diagram displays the location of the 13 ideal sites.

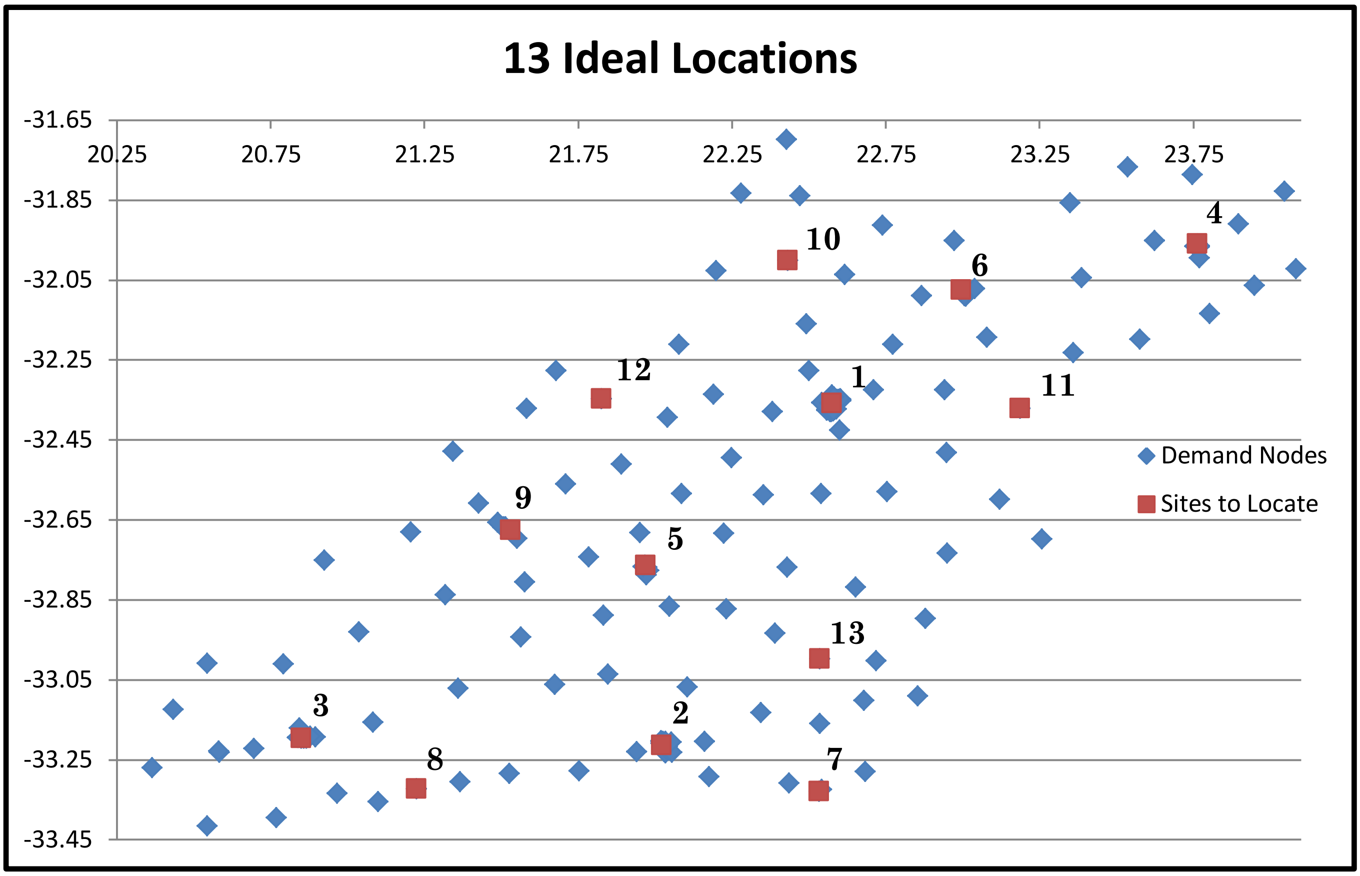

Diagram 3: Locations of 13 ideal sites

The following table lists the 13 sites in descending order of population covered within a 20km radius.

Site Number	Population Covered in 20km Radius	X Co-ordinate (DD)	Y Co-ordinate (DD)
1	34,951	22.574683	-32.359925
2	7,741	22.020975	-33.215641
3	6,296	20.849788	-33.197351
4	5,858	23.762437	-31.960564
5	3,071	21.969255	-32.765889
6	2,477	22.995484	-32.076422
7	1,300	22.532994	-33.330402
8	1,098	21.223214	-33.325099
9	1,087	21.529085	-32.677341
10	931	22.431139	-32.002305
11	468	23.186208	-32.372232
12	398	21.82462	-32.34889
13	270	22.535981	-32.998612
Total	**65,946**		

Table 5: Population covered by 13 sites within 20km radius

After observing Diagram 3 and Table 5, it is clear that the 13 sites are evenly distributed across the entire Central Karoo district, ensuring that 92.9% of the entire population are no more than 20km from the nearest police facility.

Sites 1 – 6 and site 9 are located to cover the seven densely-populated areas, as displayed in Diagram 2. These seven sites cover 61,481 people, or 86.6% of the entire population within a 20km radius. Sites 7 and 8 are located in the sparsely-populated areas, and yet they each cover more people than site 9 does.

Sites 10 – 13 service the sparsely-populated regions, covering a total of 2,067 people. These sites are important for servicing the communities that currently have to travel further than 20km to the nearest police station.

4.4.1 Sensitivity analysis

4.4.1.1 Proposed versus existing

The following diagram shows the locations of the existing SAPS police stations and the active contact points operating in the Central Karoo.

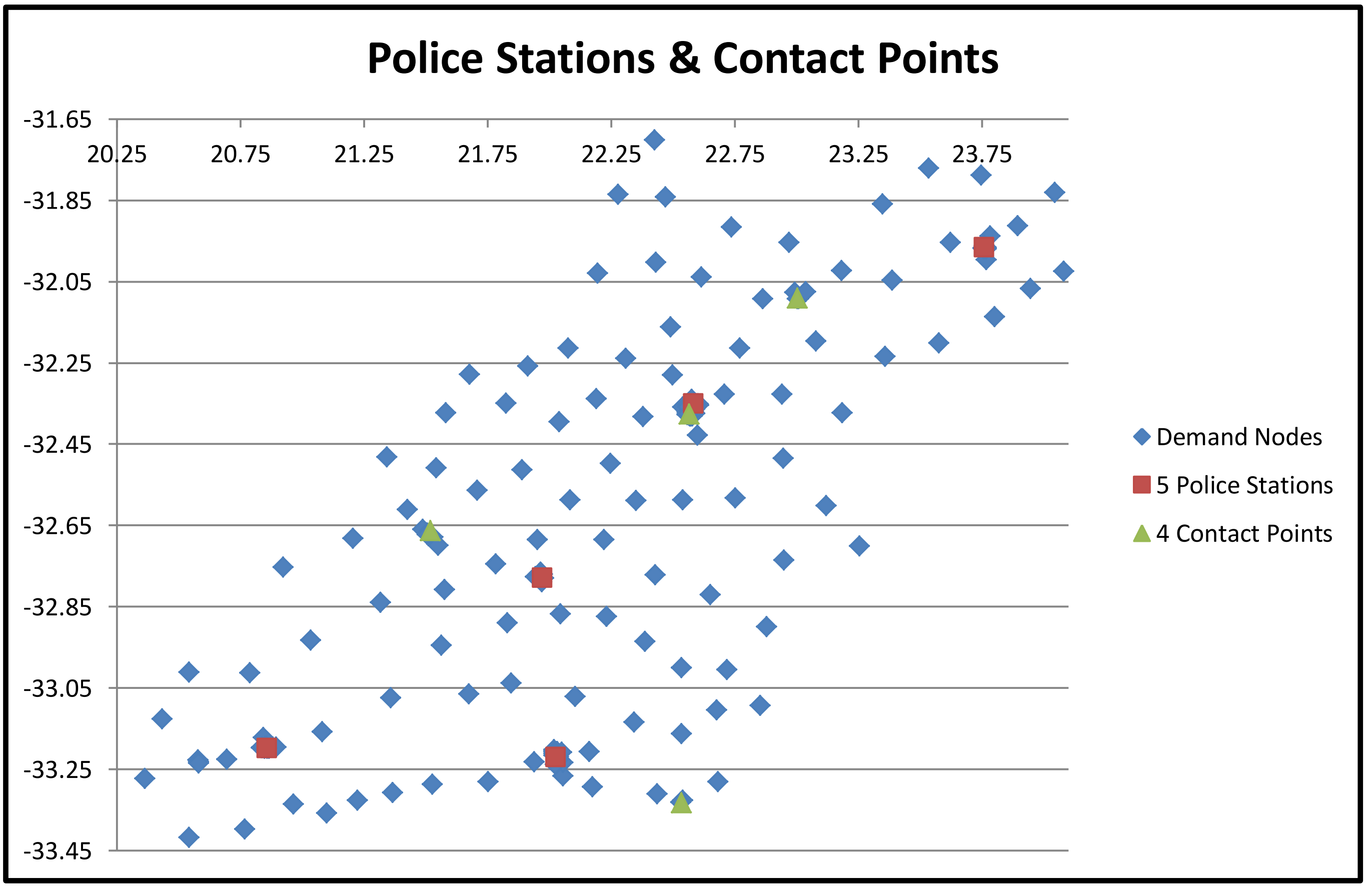

Diagram 4: Locations of the SAPS police stations and contact points

The SAPS currently has five police stations operating in the Central Karoo. These five stations are located in almost exactly the same locations as sites 1 to 5 as listed in Table 5. This confirms the fact that the existing SAPS police stations are placed in the correct locations to cover some of the densely-populated regions in the Central Karoo.

The SAPS also have four active contact points that are currently operating in the Central Karoo, three of which are satellite police stations, and the other a fixed contact point. The fixed contact point is located near an existing police station in site 1, as shown in Diagram 3. It is assumed that this fixed contact point is located there to help service the large population of 34,951 people.

The three satellite police stations are located in sites 6, 7, and 9. Again, this proves the SAPS have positioned the contact points in good locations. However, due to the size of the population within 20km of these sites, it is recommended that police stations be constructed in sites 6, 7, and 9 to render all the necessary policing services.

The SAPS is currently neglecting the communities near site 8, and should construct a new police station there to improve police accessibility.

Sites 10 – 13 are located in areas currently neglected by the SAPS. Satellite police stations are recommended for these sites to improve the accessibility of the SAPS.

4.4.1.2 Geographical feasibility

The following figure portrays the geographical terrain of the Central Karoo District, and presents the locations of the 13 ideal sites listed in Table 5. Figure 4 was adapted from Google Maps Imagery (Map data AfriGIS (Pty) Ltd, Google, 2013).

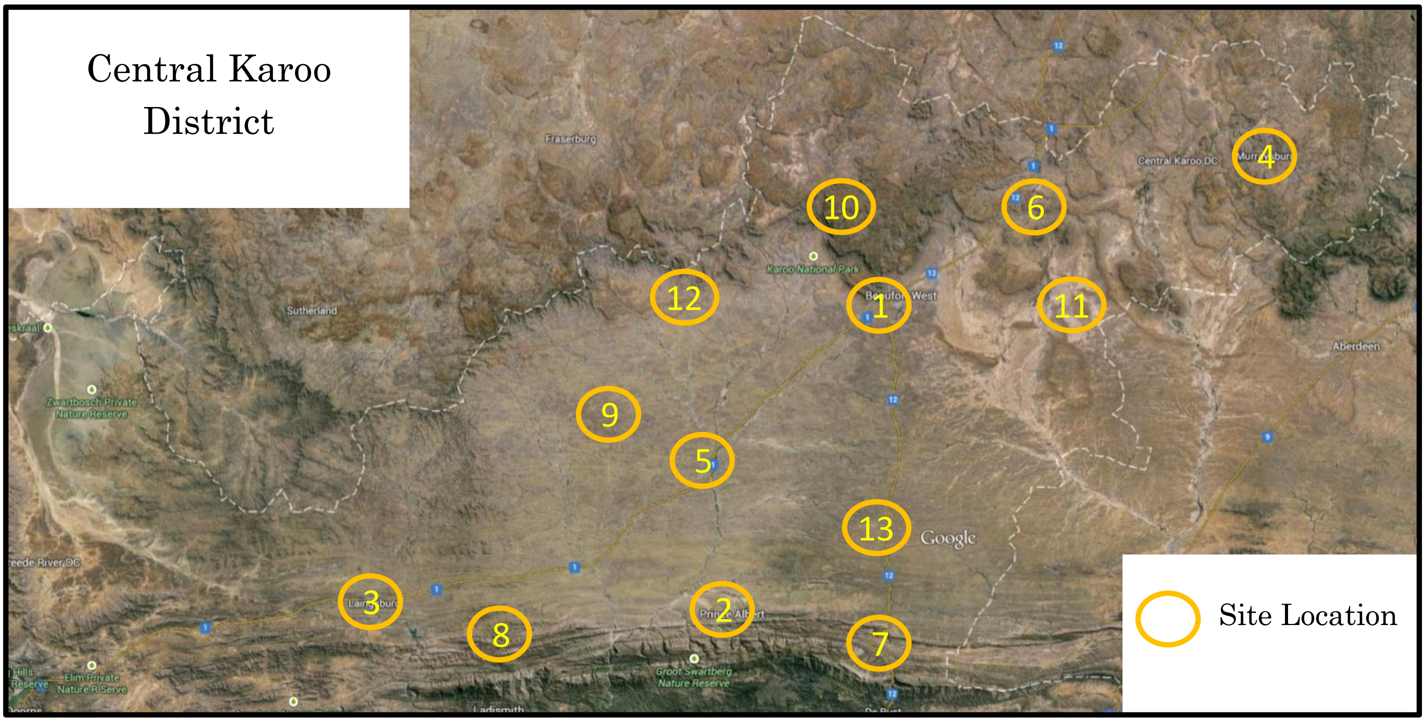

Figure 4: Geographic map & ideal site locations (Adapted from Google Maps Imagery, 2013)

Figure 5 below displays the major roads in the Central Karoo, and was adapted from RoomsForAfrica.com (RoomsForAfrica.com, 2013).

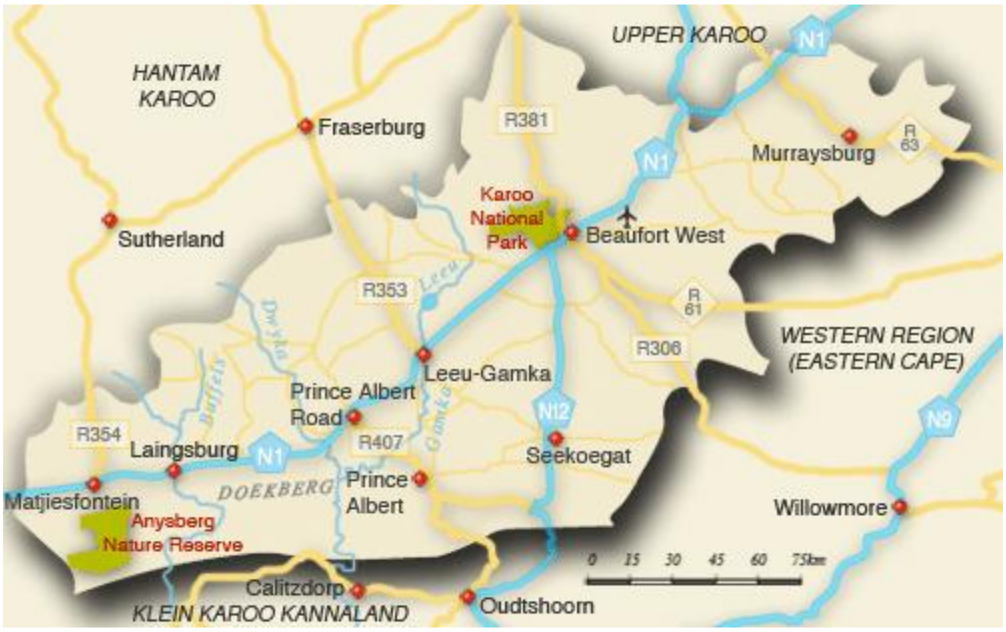

Figure 5: Major road network in Central Karoo (Adapted from RoomsForAfrica.com, 2013)

Table 6 below specifies the current geographic locations of the 13 ideal sites. The feasibility of the current locations was analysed, preferred locations were suggested, and the road network was investigated in relation to each location.

Site	Current Location	Feasibility	Suggested Location	Road
1	Beaufort West	Feasible	Beaufort West	N1 national route
2	Prince Albert	Feasible	Prince Albert	R407 regional route
3	Laingsburg	Feasible	Laingsburg	N1 national route
4	Murraysburg	Feasible	Murraysburg	R63 regional route
5	Leeu-Gamka	Feasible	Leeu-Gamka	N1 national route
6	Nelspoort	Feasible	Nelspoort	Near N1 national route
7	Grootrivier river	Infeasible	Klaarstroom	N12 national route
8	Groot Swartberge mountain range	Infeasible	Middelplaas	R323 regional route
9	Near Merweville	Feasible	Merweville	Unrecognized road
10	Rosedene	Feasible	Rosedene	R381 regional route
11	50km East of Beaufort West	Feasible	Current location	Unrecognized road
12	50km North West of Leeu-Gamka	Feasible	Current location	R353 regional route
13	Near Seekoegat	Feasible	Seekoegat	N12 national route

Table 6: Suggested geographic locations of the 13 ideal sites

Future work should determine the exact points in which to locate the police stations in the suggested locations.

Chapter 5

5. Conclusions and recommendations

5.1 Recommendations and future work

This project provided possible sites in which to locate SAPS facilities in the Central Karoo district. Future work should determine the exact points in which to locate the facilities in the suggested locations. The cost of locating the police stations in the various candidate sites should be taken into account, and may rearrange the order of which sites to build first.

The models that were developed could be adapted to investigate the remaining ISRD nodes. Each ISRD node is unique and would require individual analysis. The methods employed in this project could also be used to improve police accessibility in similar ISRD nodes.

5.2 Conclusion

The aim of this project was to determine the number of, and optimally locate, SAPS service points to provide convenient access to people living in the Central Karoo ISRD node.

Five SAPS police stations are currently located in the Central Karoo. These stations cover 76% of the population within 4km. However, the remainder of the population is distributed across the large 38,854km^2 area of the district (The Local Government Handbook, 2013). This results in small communities having to travel long distances to the nearest police station. The total number of crimes committed in the Central Karoo has increased by 32.8% in the last six years (Crime Stats SA, 2012). That is why new SAPS police stations need to be located to improve access to policing services.

This report has presented possible solutions to improve police service accessibility by using mathematical modelling techniques.

The SCP model was developed to determine the minimum number of police service points needed to cover the entire population. The model generated results that are useful in understanding the distribution of the population, but it was not feasible to locate the service points for economic reasons.

The SAPS's resources are limited and so only a limited number of police stations can be located in the Central Karoo. The MCLP model was implemented to locate limited numbers of police service points to cover as much of the population as possible. Various scenarios were used to analyse the effects of changing the coverage areas and the specified number of police service points. The results identified the optimal locations for covering the densely-populated and scarcely-populated regions in the Central Karoo district. Thirteen ideal sites were identified that would ensure that 92.9% of the entire population were no more than 20km from the nearest police station.

Security and protection from crime is vital for all human beings; and it is important that all South Africans receive the necessary policing services. This report could help the SAPS in their quest to combat crime by providing an optimal solution for locating police service point facilities in the Central Karoo ISRD node.

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Appendix A

Department of Industrial & Systems Engineering
Final Year Projects
Identification and Responsibility of Project Sponsors

All Final Year Projects are published by the University of Pretoria on *UPSpace* and thus freely available on the Internet. These publications portray the quality of education at the University and have the potential of exposing sensitive company information. It is important that both students and company representatives or sponsors are aware of such implications.

Key responsibilities of Project Sponsors:

A project sponsor is the key contact person within the company. This person should thus be able to provide the best guidance to the student on the project. The sponsor is also very likely to gain from the success of the project. The project sponsor has the following important responsibilities:

1. Confirm his/her role as project sponsor, duly authorised by the company. Multiple sponsors can be appointed, but this is not advised. The duly completed form will considered as acceptance of sponsor role.
2. Review and approve the Project Proposal, ensuring that it clearly defines the problem to be investigated by the student and that the project aim, scope, deliverables and approach is acceptable from the company's perspective.
3. Review the Final Project Report (delivered during the second semester), ensuring that information is accurate and that the solution addresses the problems and/or design requirements of the defined project.
4. Acknowledges the intended publication of the Project Report on UP Space.
5. Ensures that any sensitive, confidential information or intellectual property of the company is not disclosed in the Final Project Report.

Project Sponsor Details:

Company:	South African Police Service (SAPS)
Project Description:	Utilising mathematical modelling to locate SAPS facilities in rural areas of South Africa
Student Name:	Shaun Cramer
Student number:	10018825
Student Signature:	
Sponsor Name:	Brig Leon Rabie
Designation:	SAPS Organisational Design
E-mail:	rabiel@saps.gov.za
Tel No:	012 393 3016
Cell No:	082 770 4642
Fax No:	None
Sponsor Signature:	

Appendix B

Candidate Sites/ Demand Nodes			
#	X Co-ordinate	Y Co-ordinate	Population
1	20.869166	-33.194087	1111
2	20.860958	-33.192181	442
3	20.86667	-33.197756	1393
4	20.790213	-33.012377	81
5	20.965834	-33.335377	291
6	21.526706	-33.285981	125
7	20.849788	-33.197351	115
8	21.366547	-33.306768	156
9	21.099959	-33.356325	280
10	20.841407	-33.195938	673
11	20.836305	-33.196488	643
12	20.878399	-33.19308	37
13	20.843281	-33.17144	73
14	20.544114	-33.011113	125
15	20.579989	-33.226893	0
16	21.205868	-32.681207	87
17	20.894898	-33.194513	51
18	20.364178	-33.271628	144
19	20.542675	-33.416488	70
20	21.036436	-32.931236	29
21	20.767746	-33.396358	38
22	20.85763	-33.193135	220
23	20.925022	-32.75245	90
24	20.4335	-33.125857	42
25	21.223214	-33.325099	246
26	21.083009	-33.157094	125
27	20.850391	-33.193545	245
28	20.581912	-33.230233	27
29	20.582597	-33.23345	395
30	20.695271	-33.223878	50
31	20.838201	-33.19469	469
32	21.359477	-33.073444	188
33	21.317802	-32.838447	83
34	20.858319	-33.19741	146
35	21.978794	-32.778018	264
36	22.018775	-33.2056	986
37	21.966802	-32.764611	858
38	22.019244	-33.210514	7

39	22.021699	-33.210953	629
40	22.029379	-33.231034	180
41	21.965894	-32.767164	624
42	22.540986	-33.325218	2
43	22.719027	-33.004121	8
44	22.029108	-33.221236	217
45	21.944564	-32.776242	0
46	22.683886	-33.280472	219
47	21.969255	-32.765889	0
48	22.025594	-33.208929	505
49	21.970219	-32.770345	0
50	22.033395	-33.234149	124
51	22.020993	-33.205636	840
52	22.018859	-33.203717	786
53	21.939591	-33.231523	261
54	22.343157	-33.133833	67
55	22.045448	-32.867103	192
56	22.582615	-32.360959	974
57	22.535981	-32.998612	81
58	21.961297	-32.768157	30
59	22.388846	-32.934731	58
60	22.105487	-33.07039	221
61	22.580913	-32.364304	555
62	22.436446	-33.310462	485
63	22.020467	-33.200869	0
64	22.023384	-33.208525	451
65	22.056932	-33.26613	0
66	21.969169	-32.768226	137
67	22.024419	-33.20543	723
68	22.025745	-33.211635	484
69	22.033358	-33.206293	36
70	22.561486	-32.358516	0
71	22.054972	-33.232438	17
72	22.536295	-33.161032	12
73	22.532994	-33.330402	582
74	22.615828	-32.038646	37
75	22.738269	-31.914335	148
76	21.674313	-33.063157	246
77	21.783395	-32.744166	50
78	22.022249	-33.207408	632
79	21.973698	-32.769311	190
80	22.58449	-32.365519	158
81	21.752438	-33.279379	260

82	22.560212	-32.369836	810
83	22.569553	-32.365456	325
84	23.783414	-31.937281	0
85	21.343407	-32.480094	31
86	22.02937	-33.225841	155
87	22.039163	-33.219037	43
88	22.03499	-33.225763	81
89	21.831849	-32.889746	110
90	22.679281	-33.103679	56
91	22.854236	-33.09254	65
92	22.161347	-33.206199	50
93	22.558768	-32.377327	787
94	22.572639	-32.38059	672
95	22.174399	-33.29312	86
96	22.026649	-33.216272	154
97	22.052135	-33.207704	4
98	22.020975	-33.215641	0
99	22.49942	-32.27854	199
100	21.845552	-33.037102	69
101	21.562607	-32.944322	48
102	22.565881	-32.352531	648
103	22.190084	-32.337361	27
104	22.652839	-32.818916	179
105	22.571771	-32.370839	496
106	22.381383	-32.381125	50
107	22.024661	-33.236948	0
108	21.965953	-32.770278	504
109	22.231713	-32.873441	48
110	22.578988	-32.379937	92
111	22.580224	-32.372863	458
112	22.865848	-32.090795	89
113	21.914817	-32.257705	0
114	23.010511	-32.091693	1440
115	22.585884	-32.370113	0
116	22.565185	-32.356025	0
117	22.561625	-32.354083	621
118	22.995484	-32.076422	65
119	22.567422	-32.377873	0
120	21.889402	-32.512603	98
121	22.572403	-32.367373	693
122	21.67818	-32.277937	62
123	23.536015	-31.769617	273
124	22.971675	-31.953166	410

125	22.950487	-32.734289	127
126	22.560018	-32.360667	0
127	22.583286	-32.363551	193
128	22.580526	-32.367076	490
129	22.582727	-32.366871	456
130	21.58136	-32.372265	46
131	22.60262	-32.349331	61
132	22.584606	-32.354464	315
133	21.529085	-32.677341	0
134	22.541877	-32.358294	9
135	22.428758	-32.770306	106
136	22.279113	-31.835175	166
137	22.077951	-32.212924	32
138	22.539755	-32.58622	198
139	22.582534	-32.374717	522
140	22.471404	-31.84052	117
141	22.603488	-32.350574	397
142	23.358612	-32.233929	171
143	22.309636	-32.238884	0
144	23.757881	-31.965828	464
145	22.59482	-32.355934	507
146	23.802206	-32.135732	25
147	23.348139	-31.858723	342
148	22.563739	-32.35398	646
149	23.183392	-32.021637	0
150	22.57929	-32.358167	344
151	22.577351	-32.367608	624
152	22.575053	-32.370315	594
153	23.762437	-31.960564	26
154	23.769758	-31.995707	11
155	21.513911	-32.669237	240
156	22.580012	-32.34474	176
157	22.941235	-32.327086	89
158	22.24786	-32.496701	23
159	22.589297	-32.362334	582
160	23.623783	-31.952462	152
161	22.581295	-32.343476	58
162	22.581009	-32.369411	507
163	22.561851	-32.352161	642
164	22.567939	-32.373174	850
165	22.56396	-32.369107	0
166	22.039365	-32.394433	90
167	22.431139	-32.002305	94

168	22.491837	-32.160702	323
169	22.710048	-32.326685	446
170	23.186208	-32.372232	108
171	23.079554	-32.195165	179
172	22.427855	-31.700368	75
173	22.569087	-32.375908	499
174	22.572634	-32.377037	824
175	22.568276	-32.369358	869
176	22.573752	-32.374606	683
177	21.82462	-32.34889	102
178	22.570285	-32.378865	764
179	22.574601	-32.379279	798
180	22.75305	-32.58142	67
181	22.568628	-32.380099	699
182	22.564849	-32.376515	801
183	22.582418	-32.376458	307
184	22.589357	-32.374319	580
185	23.764652	-31.968228	756
186	22.580832	-32.353262	123
187	23.769357	-31.965989	862
188	21.541936	-32.507994	0
189	22.561858	-32.356042	657
190	23.947681	-32.065874	158
191	23.895873	-31.911477	414
192	22.590604	-32.350183	259
193	23.75937	-31.969113	769
194	22.574851	-32.373303	724
195	22.600083	-32.426679	159
196	22.879176	-32.898565	87
197	23.00555	-32.091052	191
198	23.387429	-32.045189	187
199	21.488524	-32.658168	52
200	22.572504	-32.350985	849
201	22.569498	-32.356269	380
202	22.565039	-32.357734	541
203	23.755214	-31.967775	1015
204	22.565582	-32.354614	567
205	22.558522	-32.375396	668
206	22.564117	-32.351897	651
207	23.120525	-32.600935	65
208	22.946941	-32.483342	100
209	22.597193	-32.350596	313
210	22.576065	-32.363156	461

211	22.583881	-32.346547	404
212	22.570513	-32.353459	686
213	22.22286	-32.684407	33
214	22.085549	-32.585884	40
215	22.575891	-32.339503	127
216	22.575537	-32.376281	666
217	22.566218	-32.368279	721
218	22.561961	-32.372412	465
219	21.506383	-32.669083	456
220	23.576193	-32.199929	233
221	22.197119	-32.028308	194
222	23.038153	-32.073799	3
223	22.604526	-32.35333	201
224	22.592823	-32.352195	130
225	22.352741	-32.588593	48
226	22.574683	-32.359925	185
227	22.569084	-32.360447	5
228	22.562341	-32.35724	671
229	24.046531	-31.829345	19
230	23.74749	-31.787414	196
231	24.083596	-32.023406	214
232	21.505942	-32.670771	843
233	22.77216	-32.212265	100
234	22.587353	-32.355276	394
235	23.256913	-32.699136	81
236	21.425826	-32.610136	73
237	21.708299	-32.56259	36
238	21.550153	-32.697936	23
239	22.583855	-32.370397	538
240	21.575918	-32.806975	37
241	21.951316	-32.68337	42
242	21.971508	-32.788808	120
243	23.765829	-31.9645	130
244	22.561959	-32.375836	616
245	23.768639	-31.968541	484
246	23.770031	-31.967979	554

Table B. 1: Candidate sites/ demand node locations & population

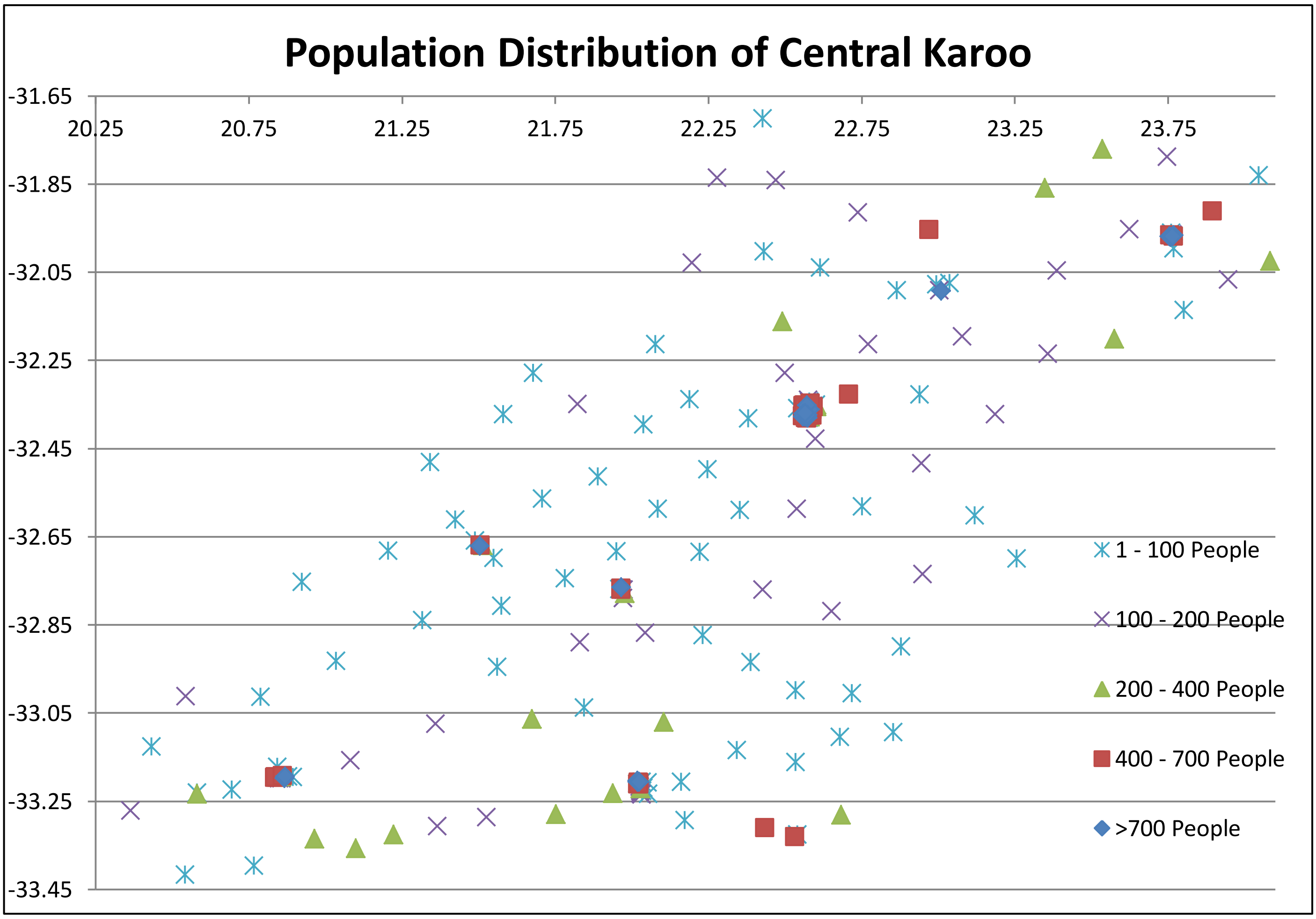

Diagram B. 1: Population distribution of Central Karoo

Appendix C

Set Covering Problem model (SCP): LINGO model

```
Model:
!The model must determine the minimum number of police service points
needed to cover all the demand nodes;

Title Set Covering Problem Model (SCP);

Sets:
sites/1..246/:s;
nodes/1..246/;
locate(sites,nodes):p;
Endsets

Data:
p = ! 246 x 246 binary matrix exported from Excel - A new matrix was
generated for each coverage distance specified;
Enddata

[Objective]       Min = @sum(sites(i):s(i));

@for(nodes(j):@sum(locate(i,j):p(i,j)*s(i))>=1);
@for(sites(i):@bin(s(i)));
End
```

Appendix D

Maximal Covering Location Problem model (MCLP): LINGO model

```
Model:
!The model must maximize the demand nodes covered with limited police
service points;

Title Maximal Covering Location Problem Model (MCLP);

Sets:
sites/1..246/:s;
nodes/1..246/:n,g;
locate(sites,nodes):p;
Endsets

Data:
g = ! Population data exported from Excel - As listed in Table B.1 in
Appendix B;
p = ! 246 x 246 binary matrix exported from Excel - A new matrix was
generated for each coverage distance specified;
Enddata


[Objective]        Max = @sum(nodes(j):g(j)*n(j));

@for(nodes(j):n(j) - @sum(locate(i,j):p(i,j)*s(i))<=0);
@sum(sites(i):s(i)) = !Specify Number;;
@for(nodes(j):@sum(locate(i,j):p(i,j)*s(i))<=1);
@for(sites(i):@bin(s(i)));
@for(nodes(j):@bin(n(j)));
End
```

Appendix E

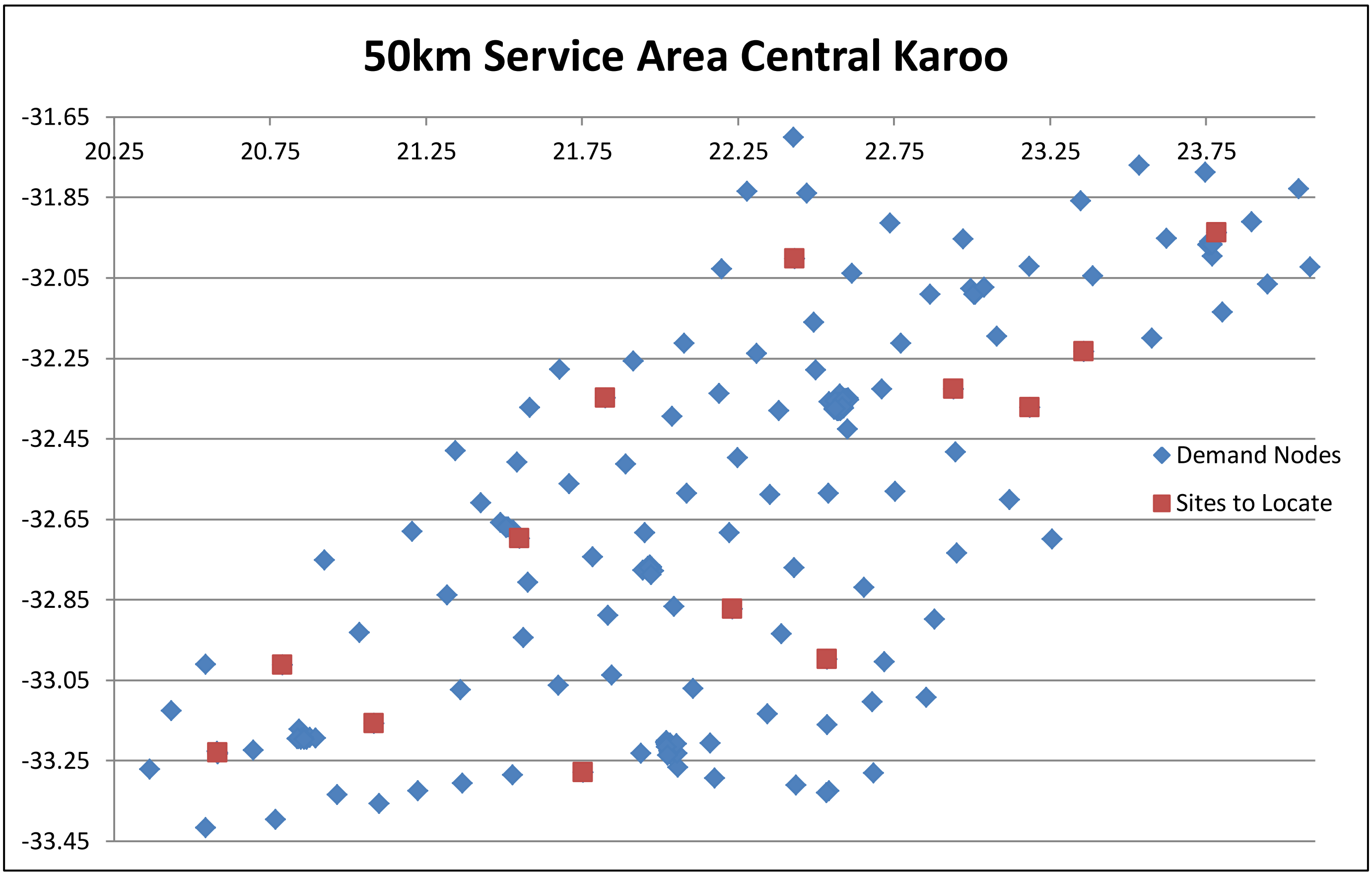

Diagram E. 1: SCP model results for 50km coverage area

Appendix F

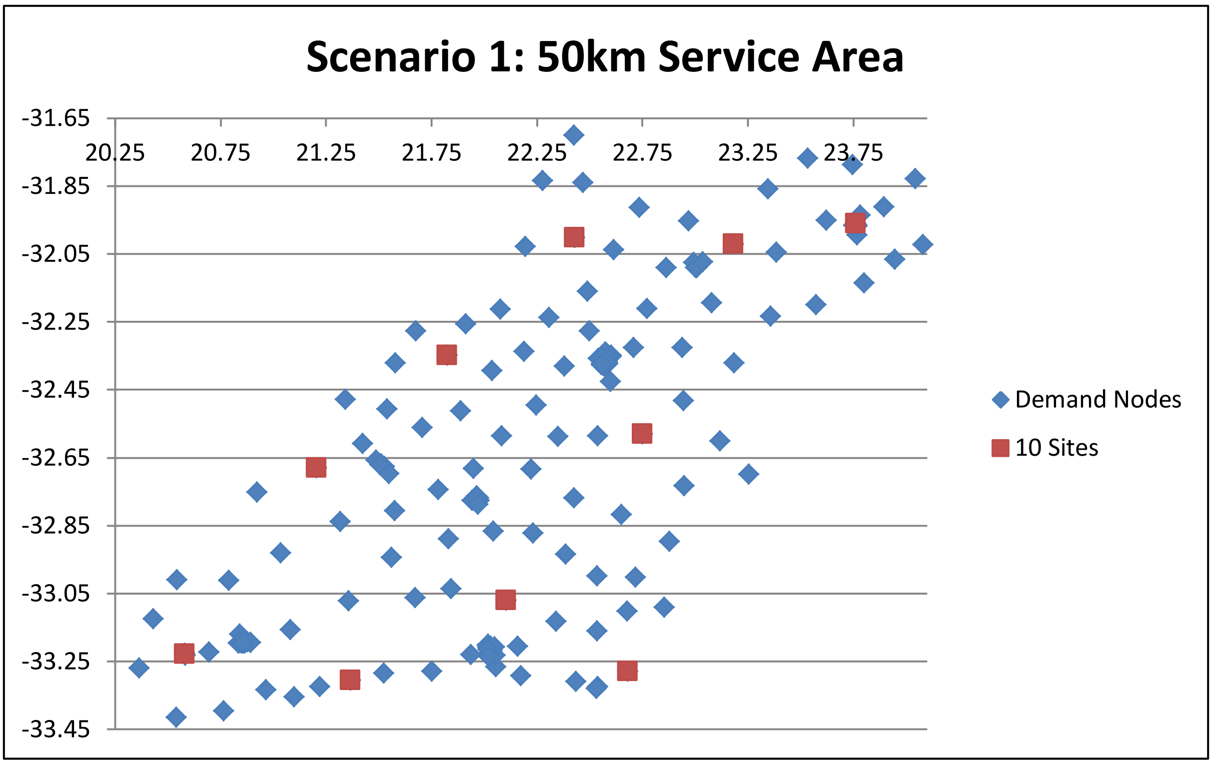

Diagram F. 2: MCLP model results for scenario 1

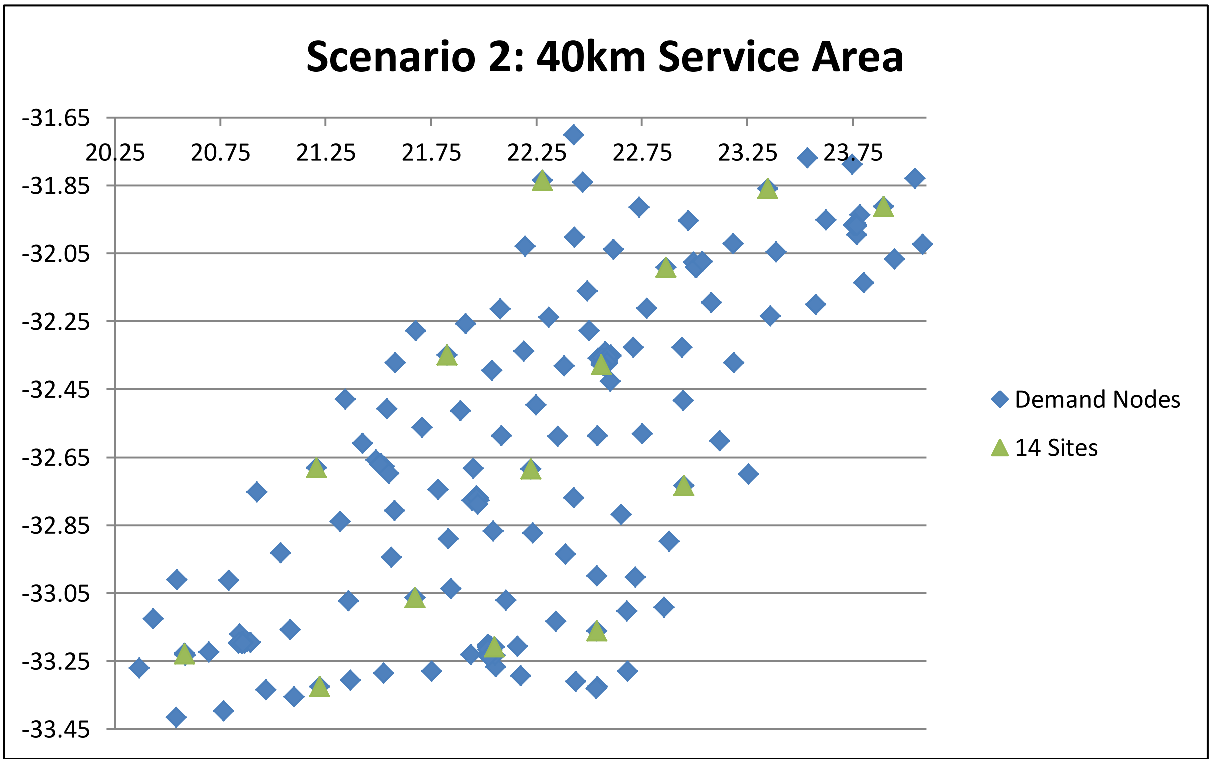

Diagram F. 1: MCLP model results for scenario 2 – 14 sites

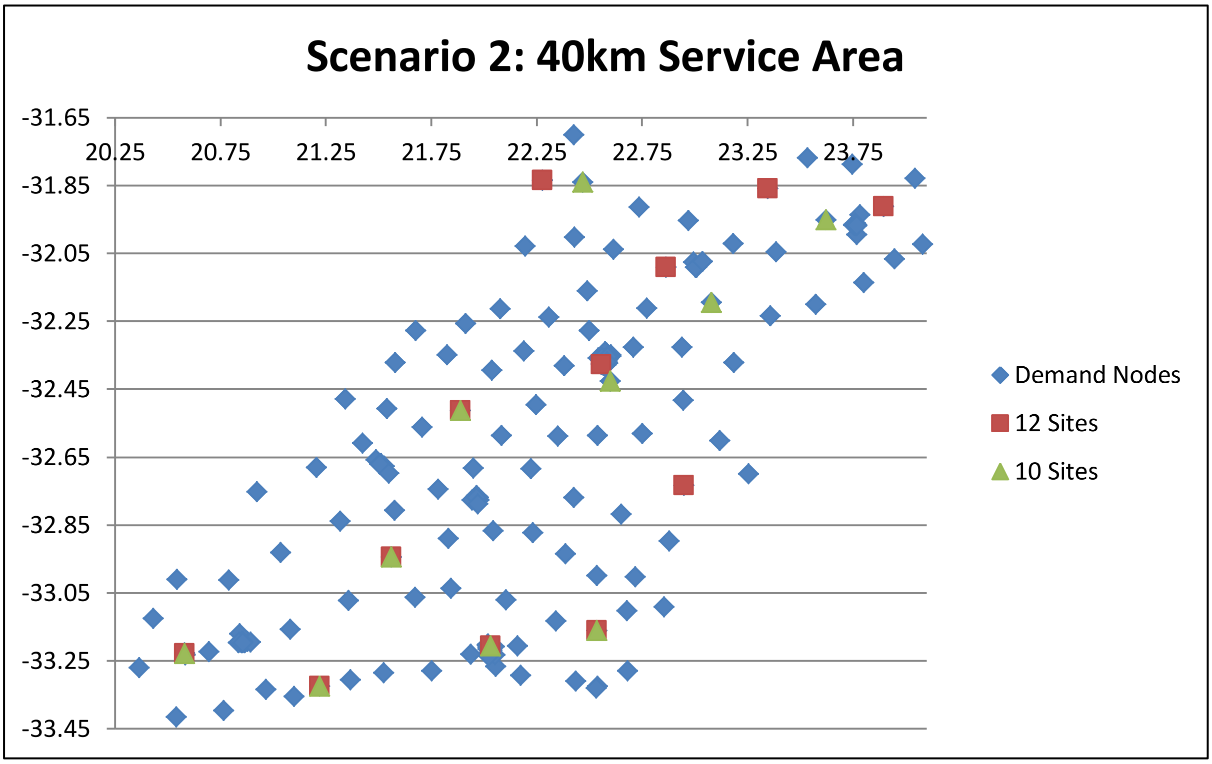

Diagram F. 3: MCLP model results for scenario 2 – 12 & 10 sites

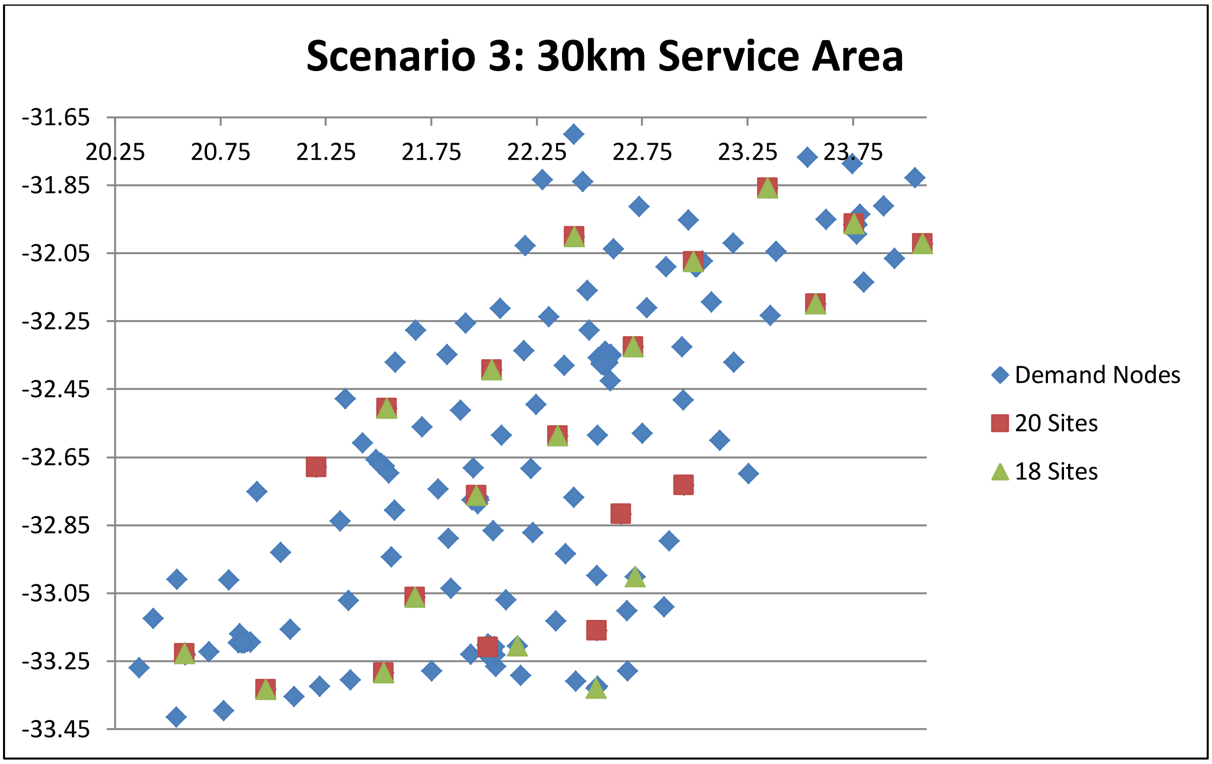

Diagram F. 4: MCLP model results for scenario 3 – 20 & 18 sites

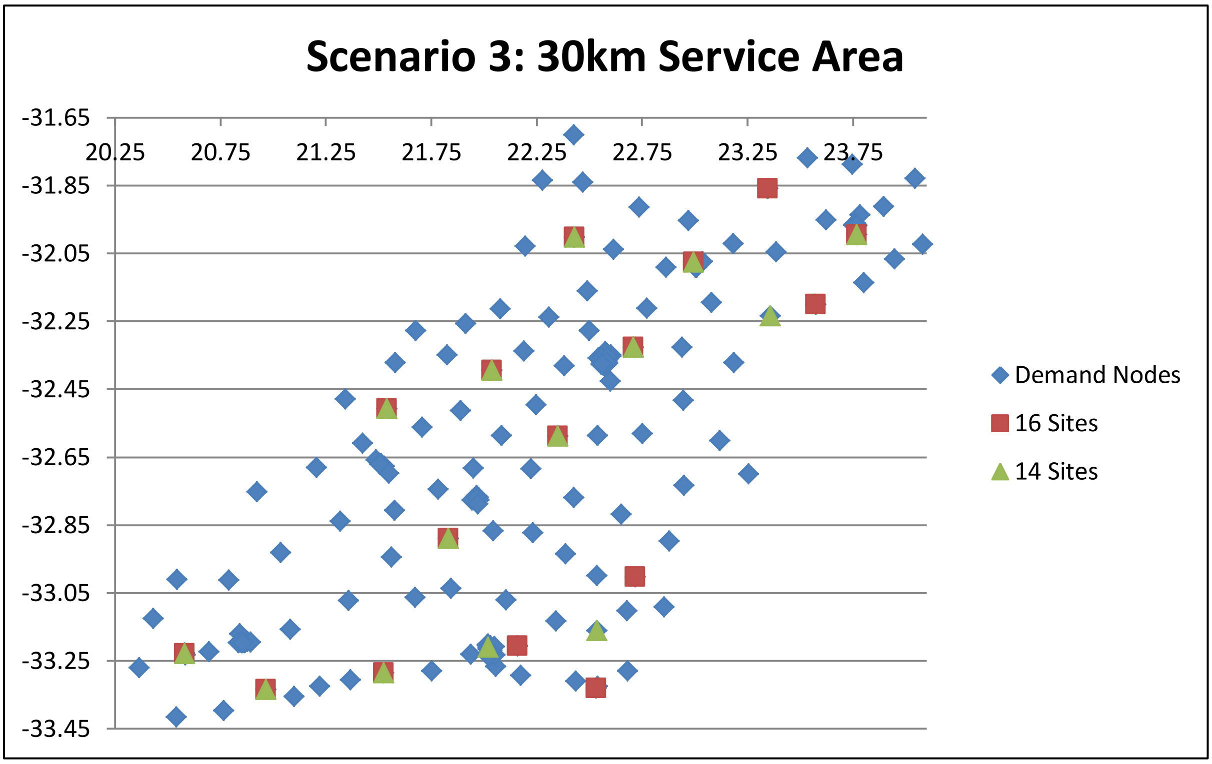

Diagram F. 5: MCLP model results for scenario 3 – 16 & 14 sites

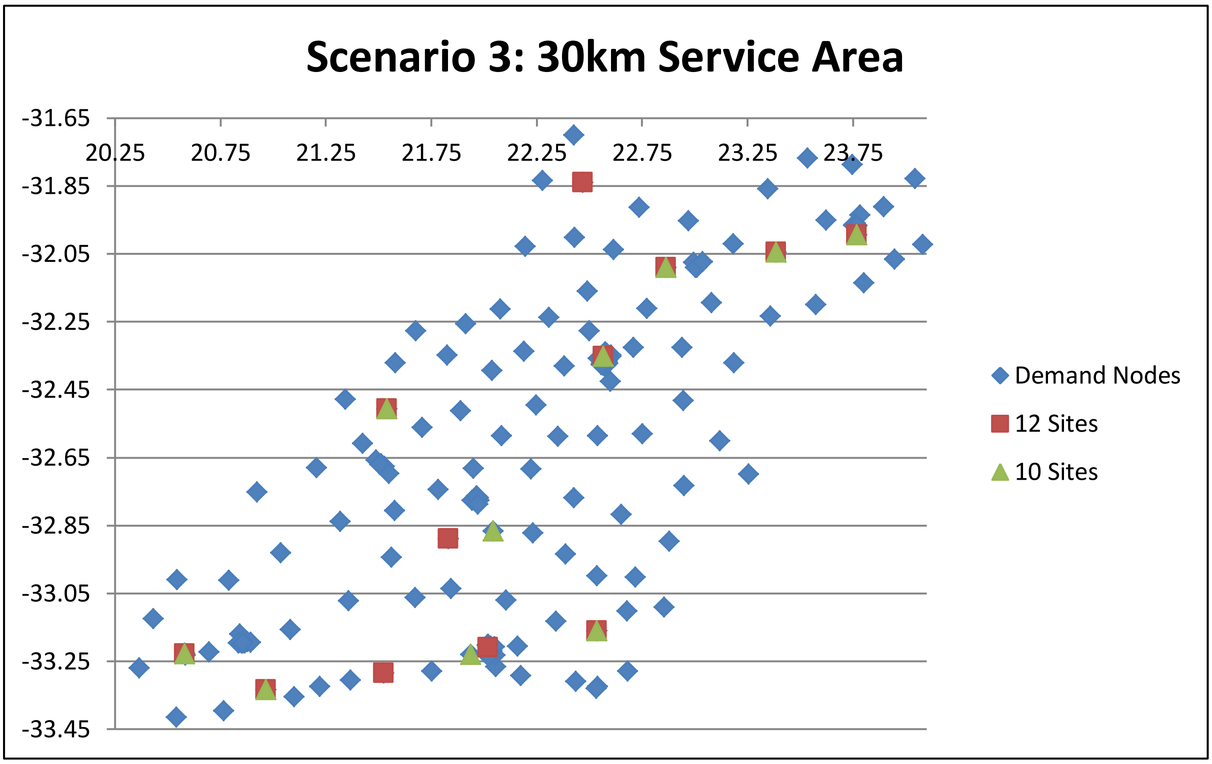

Diagram F. 6: MCLP model results for scenario 3 – 12 & 10 sites

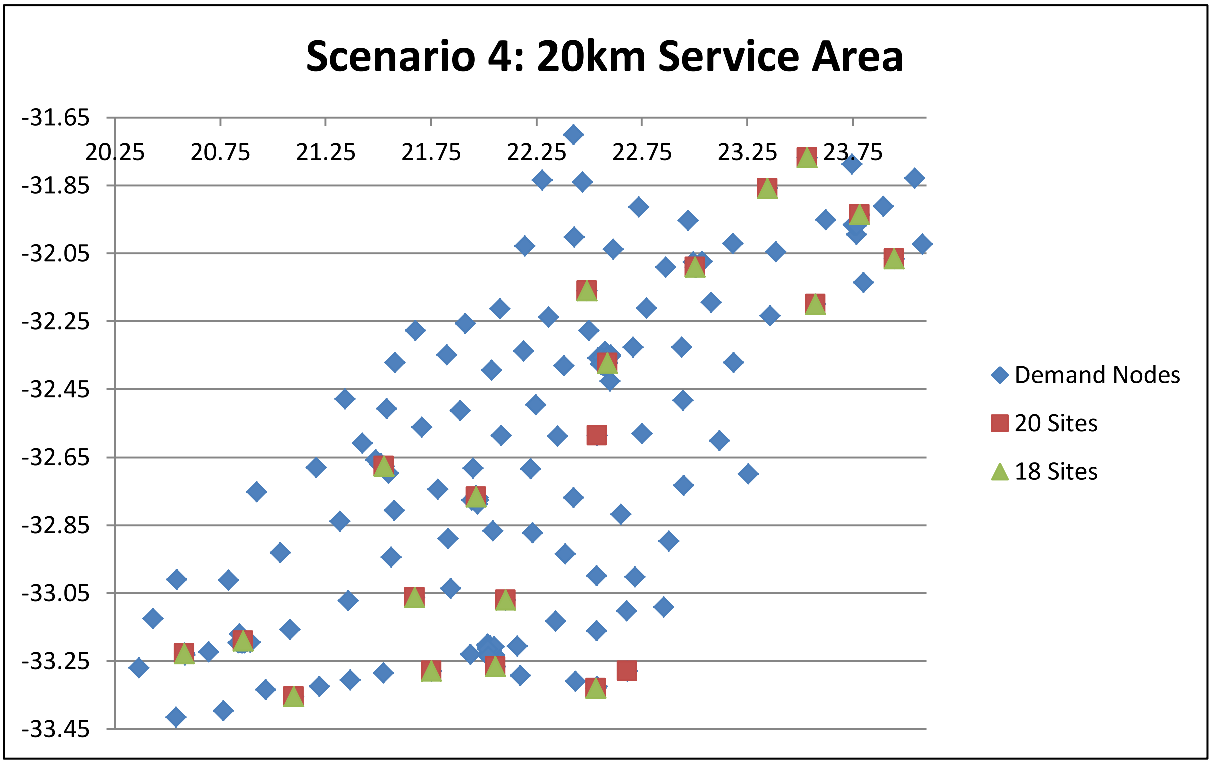

Diagram F. 7: MCLP model results for scenario 4 – 20 & 18 sites

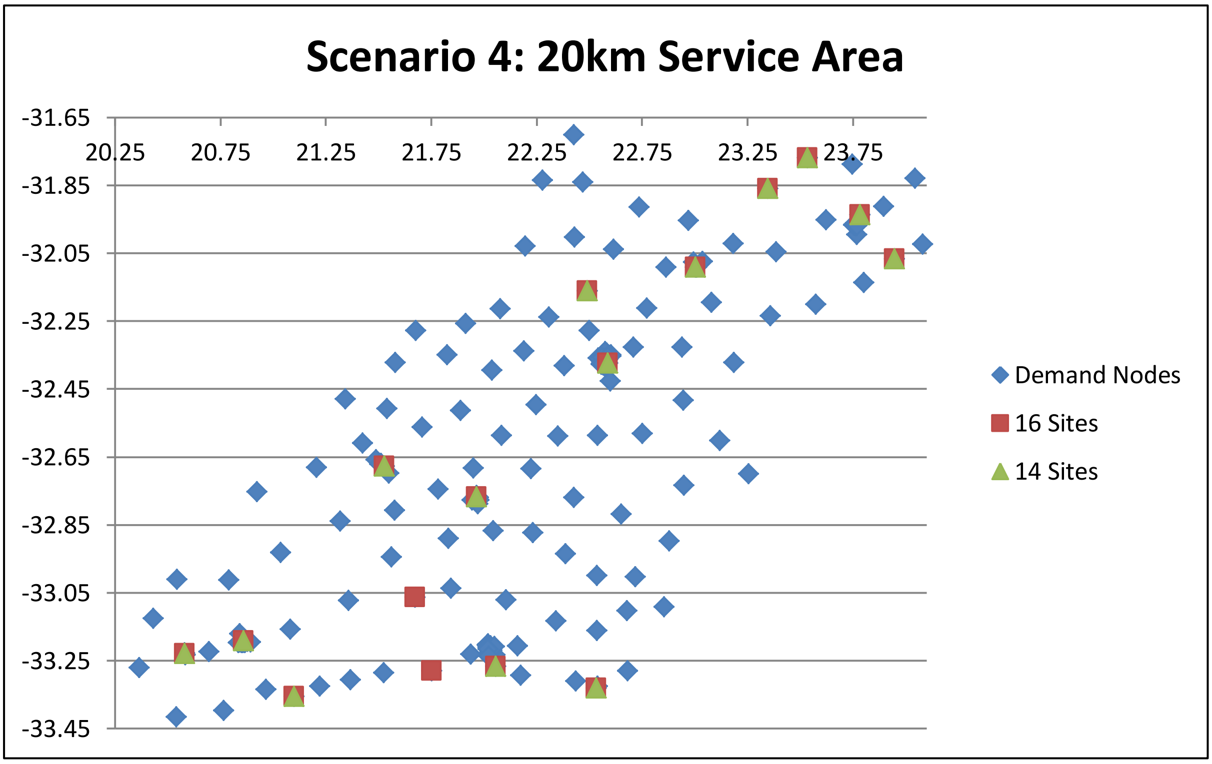

Diagram F. 8: MCLP model results for scenario 4 – 16 & 14 sites

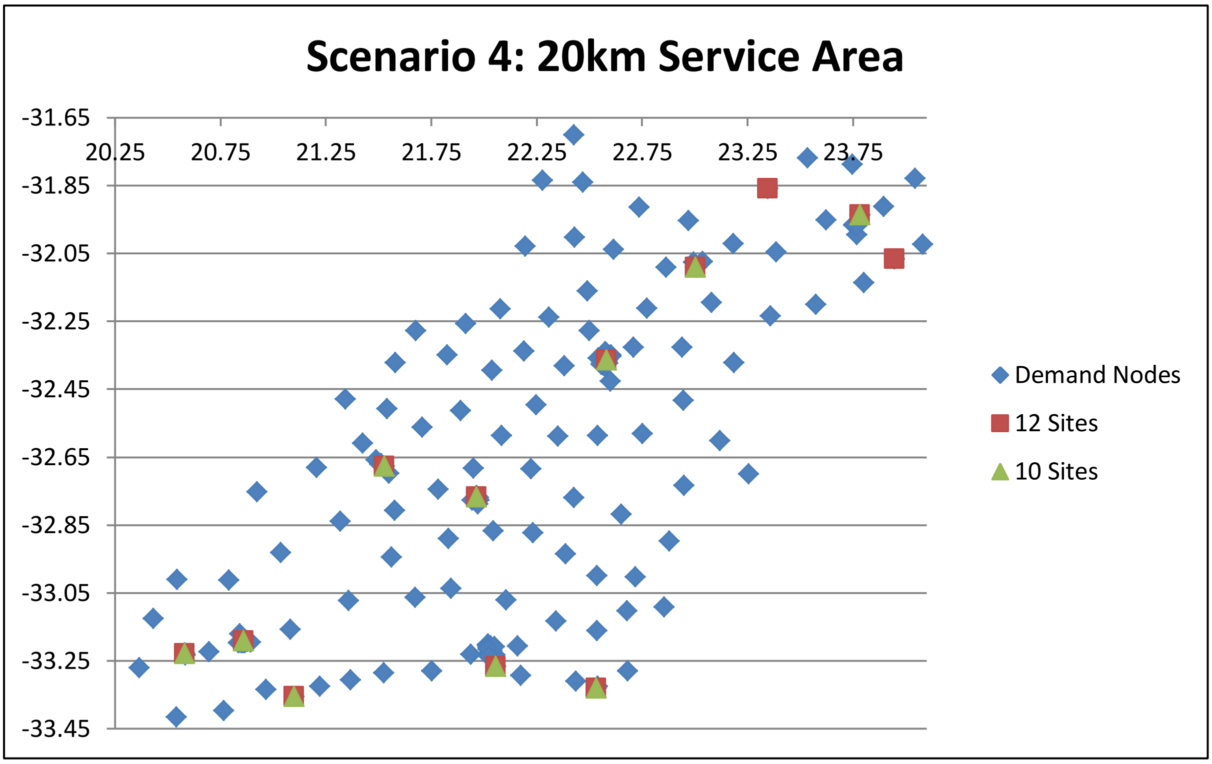

Diagram F. 9: MCLP model results for scenario 4 – 12 & 10 sites

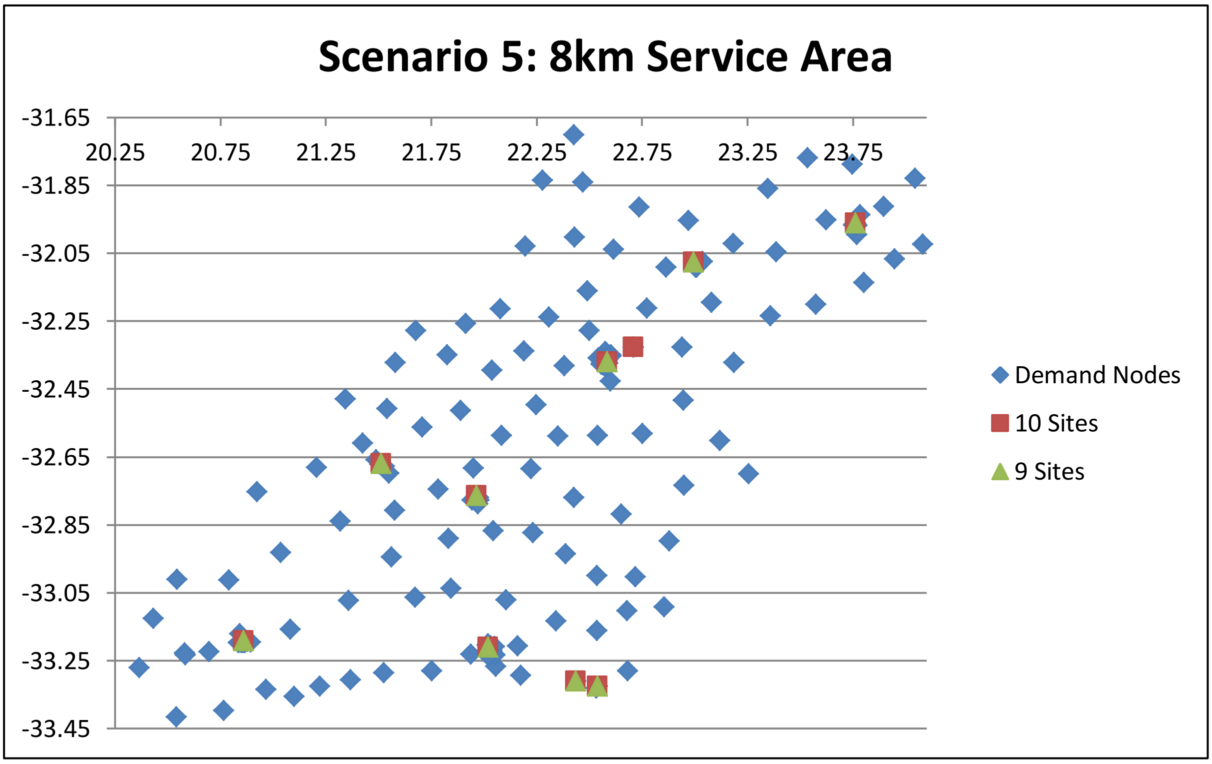

Diagram F. 10: MCLP model results for scenario 5 – 10 & 9 sites

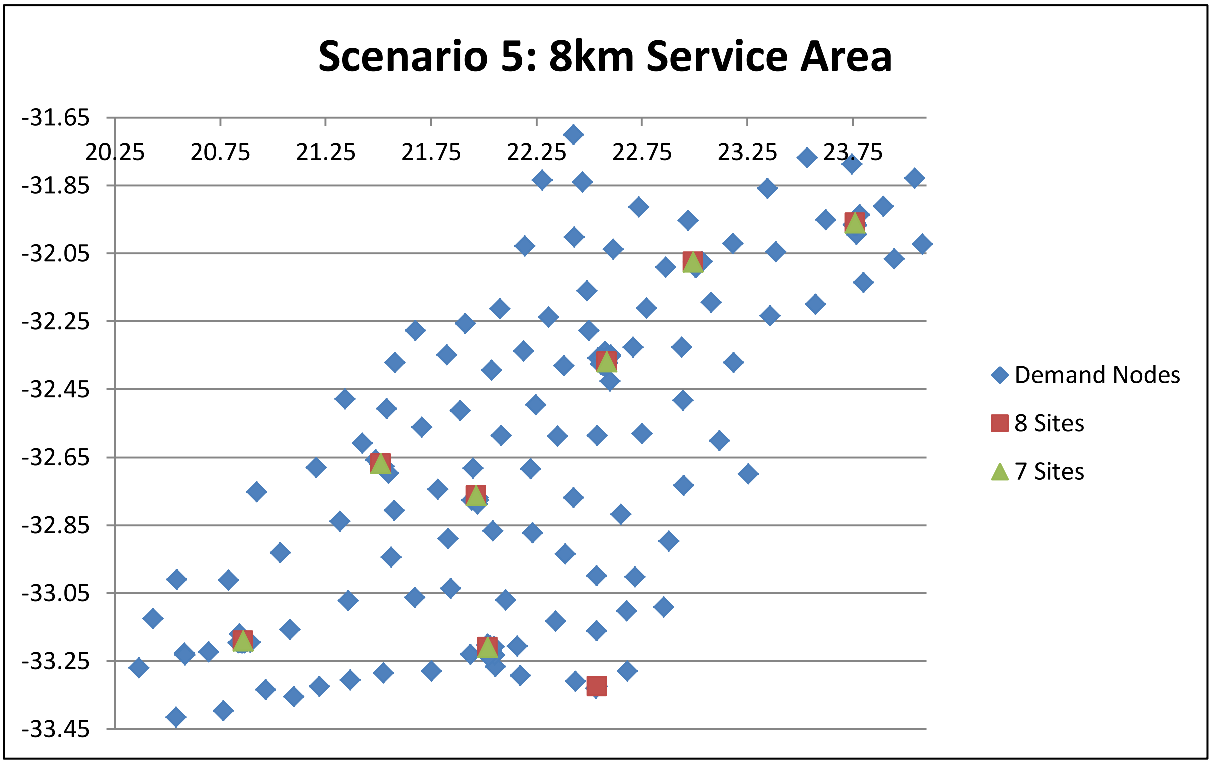

Diagram F. 11: MCLP model results for scenario 5 – 8 & 7 sites

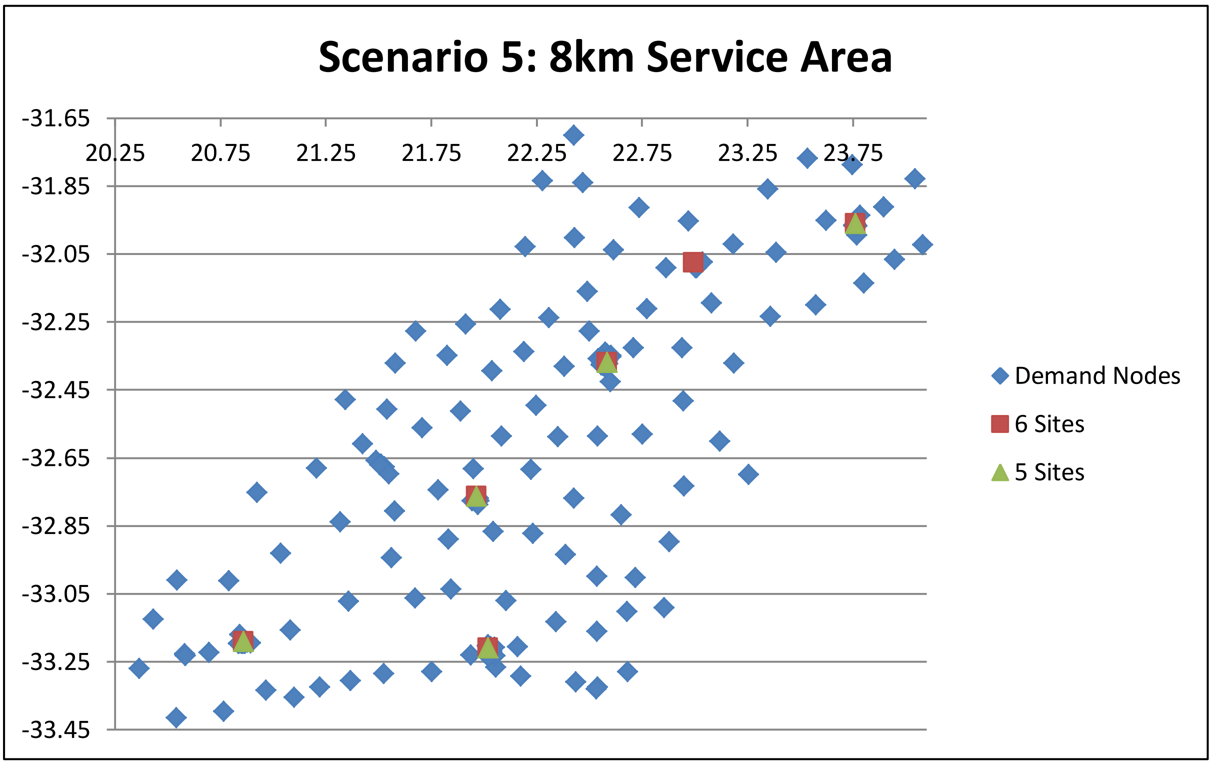

Diagram F. 12: MCLP model results for scenario 5 – 6 & 5 sites

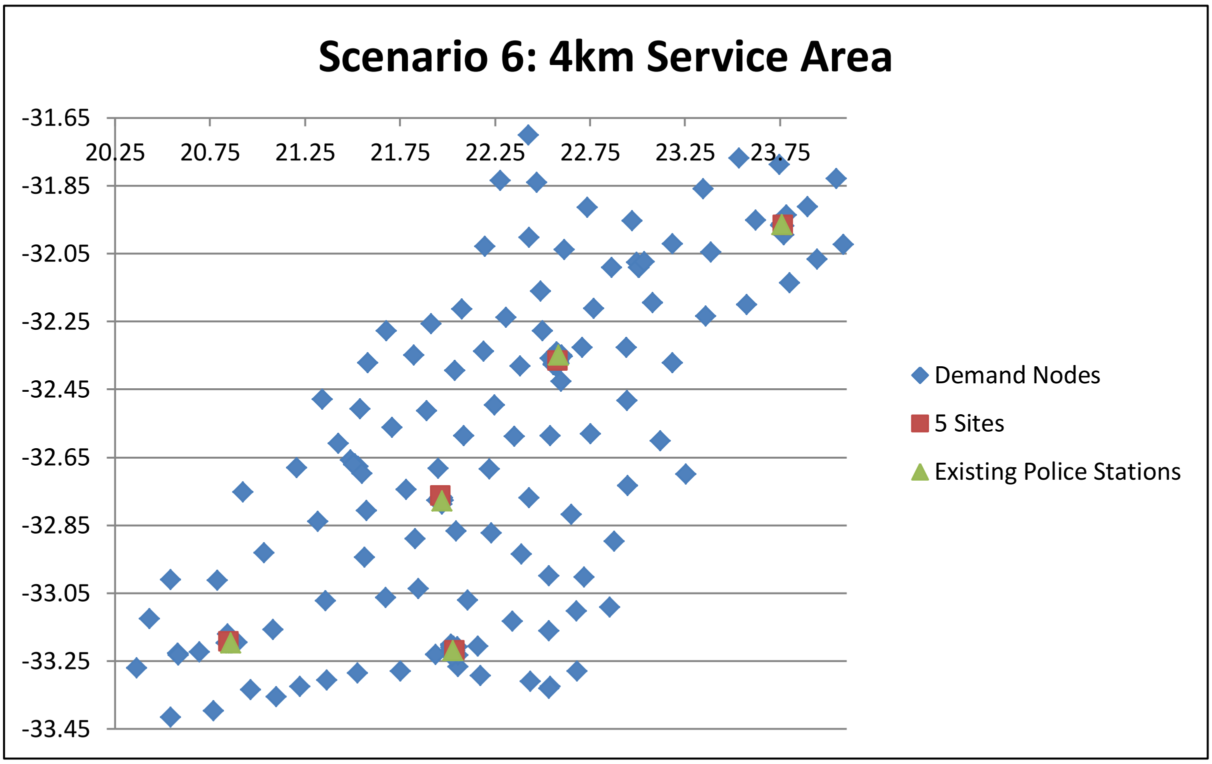

Diagram F. 13: MCLP model results for scenario 6 and existing police stations