Warehouse Pre-Positioning for Disaster Relief in Southern African Development Communities

by

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Executive Summary

At any given time people around the world are adversely affected by the impact of current or recent disasters. This is increasingly true as increase in population density, population migration, and technological development amplify the severity, and in some cases the frequency, of disasters.

The number of people killed in disasters is estimated to be three to four times higher in developing countries than in the developed ones and the number affected is estimated to be forty times higher in the former. In addition, the severity of the consequences is also higher. The objective of disaster response in the humanitarian relief chain is to rapidly provide relief to areas affected by large-scale emergencies, so as to minimise human suffering and death.

This project focused on finding an appropriate way to determine the required number of pre-positioned emergency supply warehouses and adequate locations to place these warehouses in order to enable the quick movement of the required aid supplies from these facilities to areas in Southern African Development Communities (SADC) affected by the occurrence of disasters.

To achieve this, a Maximal Covering Location Problem (MCLP), that includes spatial objects rather than single points, partial coverage, and weights assigned to disaster areas, was used to suggest potential locations for warehouses in SADC that will maximise the coverage of the more disaster-prone areas. The problem was subsequently solved, still using spatial objects and the same weights, but without partial coverage, to compare and validate the results of the models.

Acronyms

AIDS Acquired Immune Deficiency Syndrome

CRED Centre for Research on the Epidemiology of Disasters

EM-DAT Disaster Events Database

GA Greedy Adding

GAS Greedy Adding with Substitution

GIS Geographic Information Systems

HIV Human Immunodeficiency Virus

IPCC The Intergovernmental Panel on Climate Change

LP Linear Programming

MCLP Maximal Covering Location Problem

OR Operations Research

SADC Southern African Development Communities

SCMS Supply Chain Management System

UN United Nations

UNDP United Nations Development Program

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Chapter 1

Introduction

“Nations have passed away and left no traces,
Any history gives the naked cause of it –
one simple reason in all cases;
they fell because their people were not fit.”

Rudyard Kipling

1.1 Background

At any given time people around the world are adversely affected by the impact of current or recent disasters. Each year hundreds of disasters occur at locations without sufficient local ability or resources to prevent the death and destruction of their communities [1]. The duration of these disasters range from a few seconds to many years. The severity of the impact of these events varies according to the degree to which man has created an environment vulnerable to damage. That is, an environment in which life and property are at risk [2].

A definition of disaster, including both the physical event and the social and economic consequences is given by Fritz [3]:

> . . . An event, concentrated in time and space, in which a society (or community) undergoes severe danger and incurs such losses to its members and physical appurtenances that the social structure is disrupted and the fulfilment of all or some of the essential functions of the society is prevented.

From as early as 1986, it was acknowledged that the concern about disasters is becoming increasingly relevant as growth in population density, population shifts, and technological development make it likely that disasters will be encountered more frequently and that they will be more severe [4]. The Intergovernmental Panel on Climate Change (IPCC) also declared that climate change significantly alters the geographic distribution, frequency, and intensity of natural disasters [5].

According to the United Nations Development Program (UNDP) [6], the development status and the disaster risk of a country is closely related. Statistics show that 11 percent of people in underdeveloped countries exposed to natural hazards, account for more than 53 percent of the total recorded deaths. This corresponds to Dilley et al.'s [1] finding that disasters represent a major source of risk for the poor and that, in developing countries, it wipes out development gains and accumulated wealth.

This project will focus on the pre-positioning of emergency supply warehouses, in Southern African Development Communities (SADC), to help aid in disaster response. A variation of the Maximal Covering Location Problem (MCLP) of Church and ReVelle [7] will be used to find potential locations for warehouses in SADC that will maximise the coverage of disaster-prone areas. By pre-positioning these warehouses in SADC, amelioration of existing vulnerability, and the reduction of death and illness as result of hazards is addressed.

1.2 Overview of disaster types

The definitions of various types of disasters have been widely discussed by, amongst others, Turner and Pidgeon [8], Richardson [9], the World Health Organization [10] and the Federal Emergency Management Agency [11], [12]. In these discussions, it is established that all types of disastrous events can be classified as either natural, man- made, or hybrid (See Table A.1 in Appendix A for types of disasters [13]).

Shaluf [13] describes these three disaster classes as follows. Natural disasters are catastrophic events resulting from natural hazards. These natural hazards result from internal (beneath the earth's surface), external (topographical), weather related (meteorological or hydrological) and biological phenomena. Natural disasters are beyond human control and are often termed "Acts of God" and include events such as earthquakes, tsunamis, landslides and so on.

Man-made disasters, on the other hand, are those catastrophic events that result from human involvement and can either be sudden or long-term disasters. Sudden man-made disasters include structural, building and mine collapses, occurring independently without any outside force. In addition, air, land, and sea disasters are all man-made disasters. Long-term man-made disasters tend to refer to national and international conflicts.

The third class, hybrid disasters, is a compound of human decisions and natural forces.

An example of a hybrid disaster is the extensive clearing of jungles causing soil erosion, and subsequently heavy rain causing landslides. The common denominator of all types of disasters is the severity of their impact on people, property, and the environment [14].

1.2.1 Typical disasters in Southern African Development Communities

The vulnerability of SADC countries to disasters are exacerbated by factors such as high levels of multidimensional poverty, the spread of Human Immunodeficiency Virus (HIV)/Acquired Immune Deficiency Syndrome (AIDS), environmental degradation, seismic activity, climate change, floods, drought, food shortages, civil strife, internally displaced persons and refugees, slow economic growth and political instability, to name a few [15].

The frequency and magnitude of disasters in SADC differ from country to country and, except for a few of the above-mentioned disaster types, almost all of them occur in at least one SADC member. These disasters claim thousands of lives, cause material losses in the billions of dollars, and inflict a terrible toll on SADC countries, particularly as they divert attention and resources from development needed desperately to escape poverty [16].

The disaster risk of SADC countries is increased by the countries' development. Economic growth and social improvement generate new disaster risks. The growth of informal settlements and inner city slums, caused by rapid urbanisation and population growth, leads to the increase of unstable living environments. These settlements are often located in ravines, on steep slopes, along flood plains or adjacent to noxious or dangerous industrial or transport facilities [6].

Because the development status and the disaster risk of a country is so closely linked, it is important to find ways to improve disaster relief in developing countries such as SADC countries. Widespread disaster-related mortality can affect households and communities for years, decades, and even generations [1].

The UNDP [6] found that natural disasters can be held directly responsible for the destruction of infrastructure, erosion of livelihoods, damage to the integrity of ecosystems and architectural heritage, injury, illness and death. These disaster losses then interact with and aggravates other stresses and shocks such as financial crisis, political or social conflict, disease (especially HIV/AIDS), and environmental degradation. In turn, these stresses and shocks set back social investments intended to ameliorate poverty and hunger, provide access to education, health services, safe housing, drinking water and sanitation, protect the environment and enable economic investments that provide employment and income [6].

Therefore, by pre-positioning emergency supply warehouses in SADC countries, the time that aid can be provided to victims of natural disasters can be decreased significantly and so the occurrence, effects and severity of other disasters can and will be reduced.

1.3 The Function of Pre-Positioned Warehouses in Disaster Relief

Disaster management is aimed at reducing, or avoiding, the potential losses from disasters, assuring timely and appropriate assistance to victims of disaster, and achieving quick and effective recovery. Figure 1.1 [17], illustrates the disaster management cycle. This cycle is described as the ongoing process by which governments, businesses, and civil society plan for and reduce the impact of disasters, react during and immediately following a disaster, and take steps to recover after a disaster has occurred [18]. If the appropriate actions at all points in the cycle are applied it leads to greater preparedness, better warnings, reduced vulnerability or the prevention of disasters during the next iteration of the cycle [18].

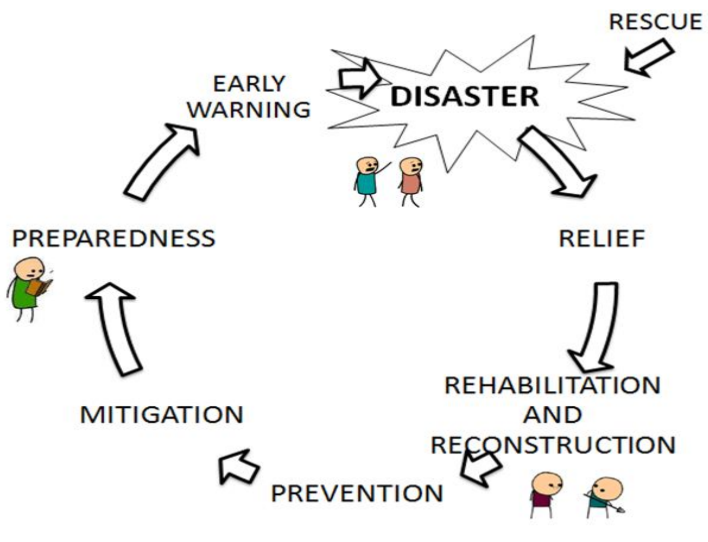

Figure 1.1: The Disaster Management Cycle

Beamon [19] described the life cycle and relative resource requirements for a relief mission by means of four distinct phases, of which the last three are corroborated by Thomas [20] (Refer to Figure 1.2). The first phase is assessment. Minimal resources are required to identify what aid and skills are needed based on the disaster characteristics. Secondly, during deployment, resource requirements are ramped up to meet the identified need. The third phase, sustainment, describes the period of time when relief efforts are sustained at a certain level. Finaly, reconfiguration is the fourth phase during which operations are reduced and then terminated.

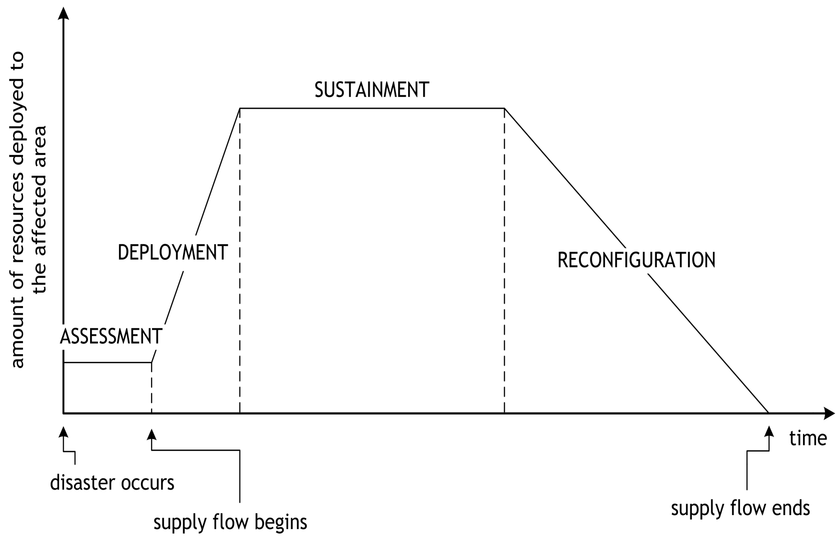

Figure 1.2: Relief Mission Life Cycle

Supply Chain Management System (SCMS) [21] reported the following, subsequent to the catastrophic earthquake in Haiti on 12 January 2010:

> . . . Within 48 hours following the catastrophic earthquake, the SCMS team in Haiti. . . identified emergency requirements and. . . began delivering emergency kits of medicines and supplies to hospitals in Port-au-Prince [capital city of Haiti]. . . By January 25 [thirteen days after the earthquake], more than 67, 000 pounds [about 30, 400 *kg*] of medicines and emergency medical supplies from warehouse stock had been distributed to more than 40 health facilities. . . Emergency kits came from existing supplies in the warehouse and included antibiotics and other essential medicines, blood transfusion sets, first aid supplies, infusion solution and oral rehydration salts and syringes.

The challenges of global procurement in the post-disaster environment stem primarily from the time-consuming processes involved, which include competitive bidding and customs clearance, and transportation capacity requirements for shipping large quantities of bulk supplies [22]. Therefore pre-positioned warehouses are crucial in the initial days of the deployment phase. These warehouses supply the immediate demand spikes for food, water, clothing, and medical supplies [23]. Time is of the essence during the deployment phase when a few hours' delay could cost many lives.

The pre-positioned warehouses not only provide relief items during the deployment phase but also serve as storage locations and distribution centres for relief items received by the various global relief organisations during the sustainment phase.

1.4 Research Methodology

The aim of this project is to discover, interpret and develop new methods and systems that can be used for the advancement of human knowledge. The reason for using Operations Research (OR) is to mathematically obtain an optimal solution to a problem, which improves or optimises the performance of the system. Rajgopal [24] defined the following steps for an approach to OR:

Orientation The primary focus of the project is to find an appropriate way to determine the required number of pre-positioned emergency supply warehouses and adequate locations to place these warehouses to enable the quick movement of the required aid supplies from these facilities to areas in SADC affected by the occurrence of disasters.

Problem Definition The problem is to determine the number and location of pre-positioned warehouses in SADC to maximise the benefits provided to the affected people. Research must be done on different methods that can be and have been used to solve this type of problem. The different kinds of disasters in SADC and their influences must also be researched and understood. All the requirements and constraints are identified in this step and used to formulate an all-inclusive problem statement. Constraints will typically include distance or response time to disaster area, and number of warehouses to be located.

Data Collection Data is required to translate the defined problem into a model that can objectively be analysed. There are a number of organisations and databases that provide information on disasters. The Disaster Events Database (EM-DAT) provides statistics on the type of disaster, number of people killed, number of people affected and the damage in US Dollars of all fifteen SADC countries from 1900 up to 2010. There are also numerous articles and research available on different models and methods used to solve this kind of problem or problems similar to this one.

Model Formulation To solve the warehouse pre-positioning problem, a mathematical model must be constructed. Rajgopal [24] explains that with mathematical models one captures the characteristics of a system or process through a set of mathematical relationships. These models tend to be characterised by four main elements: decision variables, constraints, an objective function and parameters.

The model for this problem will be built around MCLP models. A thorough study will be conducted to find the best variant, or combination of variants, of the MCLP model for this kind of warehouse pre-positioning problem.

Solution The model will be solved either using a heuristic approach, or else, linear programming.

Optimum-seeking techniques, are typically used to solve mathematical programs in order to find the optimum values for the decision variables [24]. Particular techniques include linear, nonlinear, dynamic, integer, goal and stochastic programming, as well as various network-based methods [24].

When applying one of these particular techniques, finding a good solution is often adequate, even if it is not guaranteed to be the best solution. If neither resource-availability nor time were a concern, one would of course look for the optimum solution. But this rarely is the case in practice, and in most cases timeliness is of the essence. Therefore, it is often more important to quickly acquire a solution that is satisfactory as opposed to applying a lot of effort to determine the optimum one, particularly when the marginal gain from doing so is small [24]. The economist Herbert Simon [25] used the term "satisficing" to describe this concept - one searches for the optimum but stops along the way when an acceptably good solution is found [24].

Validation and Output Analysis After a solution has been acquired, before developing a final policy or course of action for the implementation, the following must be considered. Verify that the solution makes sense. Rajgopal [24] explains that this often is not the case. He explains that the most common reason for this is that the model used was either not accurate or did not capture some major issue.

Validation is something that should be done before the actual solution, whenever possible. Validation can be explained as the process of ensuring that the model is an accurate representation of the system. However, sometimes it will be necessary to solve the model to discover the inaccuracies in it. If some important constraint was ignored in the model formulation, it will lead to a solution that will clearly be recognised as being infeasible. This will mean that the analyst must go back and modify the model and re-solve it. The cycle must continue until the analyst is certain that the results are sensible and come from a valid system representation [24].

Implementation and Monitoring The last step in the OR process is to implement the final recommendation and establish control over it [24]. This model will not be implemented as part of this project, as it only serves as research for this area of study.

1.5 Research Design

A number of research contributions on warehouse pre-positioning are found in literature, but each model is unique and cannot be applied directly to this case. The purpose of this project is to find and adjust a MCLP model that can be applied to solve the warehouse pre-positioning problem in SADC so that coverage of disaster-prone areas will be maximised. The deliverables for this project are:

1. A problem statement.
2. An adapted MCLP model.
3. Validation of the model.
4. Execution of model.

1.6 Problem Statement

Given the uncertainties and resource limitations in a disaster relief environment, the problem is to determine the number and location of pre-positioned emergency supply warehouses in SADC to maximise the benefits provided to affected people [26].

Because of the uncertainties and variability in the relief environment, most logistical decisions are made after disasters occur. In commercial supply chains, logistic operations are relatively established and can usually be planned in advance of demand, unlike most logistical decisions in the relief chain, which are made within shorter time frames [26]. However, decisions on warehouse location pre-positioning in the relief chain is a critical component of disaster preparedness and thus require long-term planning to achieve improved performance in disaster response. Since warehouse locations affect relief chain costs and response times, realistic forecasts of potential demand locations will contribute to the effectiveness and efficiency of warehouse location decisions [26].

All things considered, we end up with this research question:

> *What would be an appropriate way to determine the required number of pre-positioned emergency supply warehouses and adequate locations to place these warehouses to maximise the coverage of disaster-prone areas in SADC?*

1.7 Document Structure

Chapter 2 looks in detail at variations of MCLP models and also solution strategies followed by others in current literature with regards to the MCLP. The focus will be on the formulation of the problem and the model that will be used to search through the solution space in order to find the best locations for emergency supply warehouses in SADC countries. Chapter 3 presents the conceptual model and discusses the methods used for gathering the disaster data. Finally Chapter 4 includes the validation and execution of the model and Chapter 5 discusses future work.

Chapter 2

Facility Location Problems in Literature

Operations Research techniques have for years been applied to a large variety of problems to determine the optimal geographical locations for facilities (See [27], [28], [29], and [30] for surveys on facility location research). Facility location problems obtain their importance firstly from their direct impact on the system's operating cost and secondly due to their effect on the timeliness of response to the system's demand [31]. Facility location models addressing private sector problems generally seek to minimise cost or maximise profit, while models addressing public and emergency services focus instead on user accessibility and response time (See [32] and [33] for emergency service facility location problems) [26].

Models with coverage-type objectives are used extensively in facility location research and applications, especially when the primary performance criteria is response time (See [34] and [35] for discussions and reviews of covering models). In these covering-type facility location models, a source of demand can be defined as covered only if it is located within a specified response distance or time from a facility [26].

These models seek to choose facilities among a finite set of candidate sites in such a way that all demand sources are covered with a minimum number of facilities. In disaster relief, this would imply that each potential demand point must be within a specified target response time or distance of a facility in the relief network [26]. However, to cover the entire demand area of every potential disaster scenario from pre-positioned warehouses might not be practicable. Therefore, Balcik and Beamon [26] found that a maximal covering-type model that selects facility locations – pre-positioned warehouse locations – to maximise the number of covered disaster areas, subject to resource limitations – the number of warehouses and costs associated with building these warehouses – is more suitable for relief chain network design.

2.1 Maximal Covering Location Problem

The Maximal Covering Location Problem (MCLP), first presented by Church and ReVelle [7], maximises the total number of people served within a maximal service distance, given a fixed number of facilities or budget limitations [26]. The MCLP has a broad range of applications and has been studied extensively. Since its original formulation, the MCLP has also been modified and customised to cater for more realistic problem situations [36].

Defined on a network of nodes and arcs, a mathematical formulation of the basic MCLP can be stated as follows:

Problem I:

$$max \quad z = \sum_{i \in I} a_i y_i$$

subject to:

$$\sum_{j \in N_i} x_j \geq y_i \quad \forall \quad i \in I \tag{2.1}$$

$$\sum_{j \in J} x_j = p \tag{2.2}$$

$$x_j \in (0, 1) \quad \forall \quad j \in J \tag{2.3}$$

$$y_i \in (0, 1) \quad \forall \quad i \in I \tag{2.4}$$

where:

$I \triangleq$ set of demand nodes;

$J \triangleq$ set of facility sites;

$S \triangleq$ distance beyond which a demand point is considered “uncovered” (the value of S can be chosen differently for each demand point if desired);

$d_{ij} \triangleq$ shortest distance from node i to node j;

$$x_j \triangleq \begin{cases} 1 & \text{if a facility is allocated to site } j \\ 0 & \text{otherwise;} \end{cases}$$

$N_i \triangleq \{j \in J | d_{ij} \leq S\}$ set of facility sites j which can cover demand nodes i by virtue of being within the distance standard S;

$a_i \triangleq$ population to be served at demand node i;

$p \triangleq$ number of facilities to be located.

N_i is the set of facility sites that are eligible to provide cover to demand point i. A demand node can then be considered covered when the closest facility to that node is at a distance less than or equal to S. A demand node is thus uncovered when the closest facility to that node is at a distance greater than S.

As stated previously, the objective of the MCLP is to maximise the number of people either served or covered, within the desired service distance. Constraint (2.1) allows y_i to equal 1 only when one or more facilities are established at sites in the set N_i (in other words, one or more facilities are located within S distance units of demand point i). The number of facilities allocated is restricted to equal to the specified amount, p, in constraint (2.2). The solution to this problem specifies not only the largest amount of population that can be covered but also the number of facilities that achieve this maximal coverage.

An equivalent formulation of the maximum covering location problem can be derived by substituting $1 - \bar{y}_i = y_i$ where

$$\bar{y}_i = \begin{cases} 1 & \text{if demand node } i \text{ is not covered by a facility within } S \text{ distance} \\ 0 & \text{otherwise.} \end{cases}$$

Constraint (2.1) can then be written as

$$\sum_{j \in N_i} x_j \geq 1 - \bar{y}_i \quad i \in I$$

which is equivalent to

$$\sum_{j \in N_i} x_j + \bar{y}_i \geq 1 \quad i \in I.$$

This inequality implies that either

$$\sum_{j \in N_i} x_j \geq 1 \quad \text{or} \quad \bar{y}_i = 1.$$

Stated verbally, either one or more facilities are built within S units of demand point i, or demand i is uncovered and $\bar{y}_i = 1$. After variable substitution, the objective can be written as

$$max \quad (\sum_{i \in I} a_i + \sum_{i \in I} -a_i \bar{y}_i).$$

Note that the first sum is a known constant. Since the maximisation of a negative quantity is equivalent to a minimisation of the positive quantity, the objective function can be simplified to

$$min \quad \sum_{i \in I} a_i \bar{y}_i.$$

This objective can be interpreted as minimising the number of people that will not be served within the maximal service distance. The complete problem developed by variable substitution is:

Problem II:

$$min \quad z = \sum_{i \in I} a_i \bar{y}_i$$

subject to:

$$\sum_{j \in N_i} x_j + \bar{y}_i \geq 1 \quad \forall \quad i \in I \tag{2.5}$$

$$\sum_{j \in J} x_j = p \tag{2.6}$$

$$x_j \in (0,1) \quad \forall \quad j \in J \tag{2.7}$$

$$\bar{y}_i \in (0,1) \quad \forall \quad i \in I \tag{2.8}$$

This problem seeks to minimise the population left uncovered if p facilities are to be located on a network.

As can be seen, the formulations are equivalent since one can be transformed mathematically into the other by variable substitution. The second formulation was utilised in solving this problem with linear programming. The MCLP has been solved optimally by linear programming and also heuristically by several methods [7].

2.2 Variations of MCLPs

As stated previously the MCLP has been extended in several directions to cater for more realistic problem situations [36] since its original formulation. To solve the warehouse prepositioning problem a variation, or a combination of variations, of the MCLP is required.

The original MCLP formulation defines a demand point as covered if it is within a certain distance D from at least one server and not covered otherwise. However, this "black and white" perspective that either considers a demand point as covered or not covered may be considered somewhat crude. Alexandris and Giannikos [36], explain it as follows: the original MCLP formulation implies that demand points at a distance D - ϵ from a server are fully covered, whereas points at a distance $D + \epsilon$ are not covered at all, where $\epsilon > 0$ may be arbitrarily small. This issue has been addressed with different approaches.

The MCLP problem was generalised by introducing additional options in ReVelle and Serra [37], Marianov and ReVelle [38], Kolen and Tamir [39], and Hochbaum and Pathria [40]. ReVelle and Serra [37] recognised uncertainty in the demand or population at the nodes of the network. Marianov and ReVelle [38] looked at the use of stochastic models, based on queuing theory. Kolen and Tamir [39] solved MCLPs on tree networks with equal setup costs. Hochbaum and Parthria [40] analysed the quality of a k-stage covering algorithm that relies, at each stage, on greedily selecting a subset that gives maximum improvement in terms of overall coverage. Berman [41] studied the relationship between the MCLP and the partial centre problem. Megiddo et al. [42] discussed the problem on a tree network. Drezner [43] [44] discussed the single facility MCLP in the plane and Watson-Gandy [45] discussed its multiple facility version. Kolen and Tamir [39] and Current et al. [46] discussed MCLPs in discrete spaces, which generally have a finite set of sites at which facilities can be located, and a finite set of clients, whose demands have to be met by the facilities. In addition, Plastria [47] [48] focused on MCLPs in continuous spaces where the points to be sited can generally be placed anywhere on the plane or network.

Figure 2.1 [49] shows a number of different coverage decay functions [50]. Figure 2.1a exhibits the usual coverage function with the coverage being satisfactory below the service standard $\bar{D}$, but then dropping off to zero as the service standard is exceeded. Figure 2.1b shows a stepwise coverage function with break points $\bar{D}1$, $\bar{D}2$, and $\bar{D}3$ used by Church and Roberts [51] and Berman and Krass [52]. Figure 2.1c depicts the "quality of service" function of Pirkul and Schilling [53], Araz et al. [54], and the coverage equivalent of the cost function of Drezner et al. [55]. Finally, the coverage function in Figure 2.1d is neither convex (curvature that extends outward) nor concave (curve that extends inward) and it

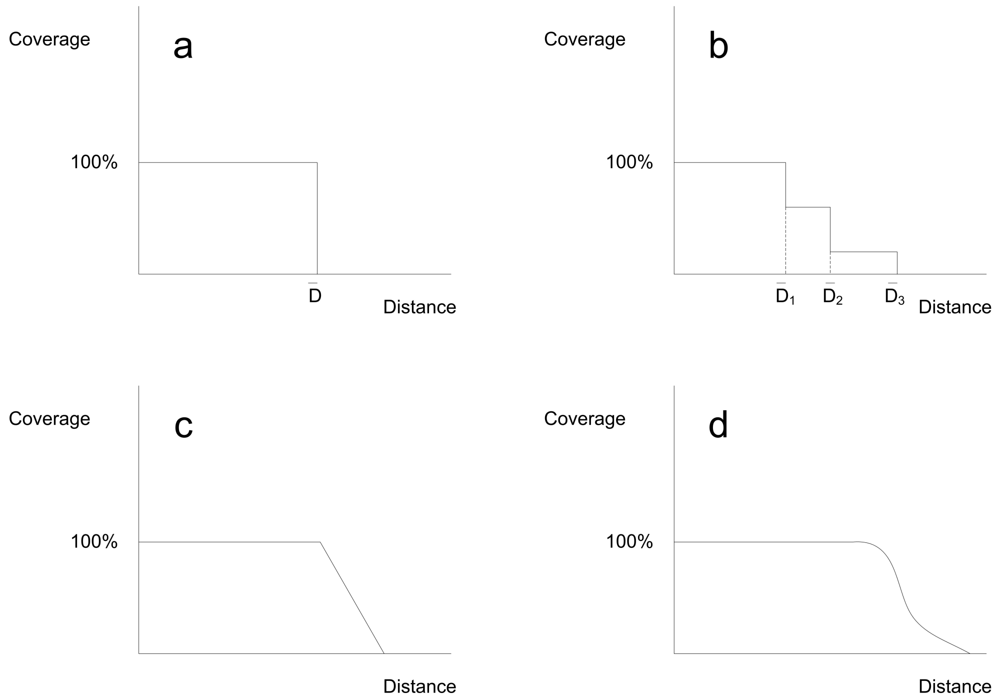

Figure 2.1: Coverage functions

is similar to the gradual covering decay function employed by Berman et al. [56].

In general, different levels of coverage may either be included in the constraints or in the objective function [49]. Murray [57] found that if an area is partially covered by a sufficient number of servers, it is highly likely that this area will be fully covered.

Alexandris and Giannikos [36] studied the effects of demand representation on maximal covering models. Specifically, they considered the general MCLP and demonstrated that it produced results which varied considerably according to the definition of the demand space and also implied considerable coverage gaps. They introduced an integer programming model, based on the representation of demand through spatial objects rather than single points, which exploits the capabilities of Geographic Information Systems (GIS). Their model also includes Murray's [57] model for partial coverage. Results of this model provided better, more robust coverage using fewer servers than the conventional maximal covering models. The coverage gaps also reduced significantly [36].

2.3 Model Requirements

The model developed by Alexandris and Giannikos [36] to address the maximal covering location problem with spatial objects, was found to be the most suitable for the pre-positioning of warehouses in Southern African Development Communities (SADC). By using a grid, disaster areas can be defined more correctly than just using single points. The inclusion of the partial coverage mechanism should ensure better coverage, using fewer warehouses. The model also includes a weight that is assigned to each demand area, ensuring that the model maximises coverage of areas affected more severely by disasters.

2.4 Solution Techniques

Karasakal and Karasakal [58] explain the three methods available for solving location problems, namely exhaustive enumeration, Linear Programming (LP), and heuristic approaches. The first resort, exhaustive enumeration, is explained as a brute force method that requires the calculation of the objective function for each feasible combination of p (number of facilities to be located) out of all potential facility sites, J. But, the number of combinations can be quite large if J and p are large. Hence, exhaustive enumeration usually require excessive computation. The second resort is LP. The problem with commercial general-purpose LP packages is that it cannot solve large size problems. Heuristic approaches on the other hand, can solve large size problems, but do not guarantee that an optimal solution will be reached [58].

2.4.1 Heuristic Approaches

A heuristic process can be defined as a process that include running tests and getting results by trial and error. The more sample data gets tested, the easier it becomes to create an efficient algorithm to process similar types of data. Heuristic algorithms are not always perfect, but they work well most of the time. The goal of heuristics can be stated as the development of a simple process that generates accurate results in an acceptable amount of time [59].

Two heuristic approaches can be employed to solve the MCLP. The first, known as Greedy Adding (GA), begins by sitting an initial facility at that node which covers the largest number of demand sites. Successive facilities are then added, one at a time, in order to achieve the largest incremental gain in the number of demand nodes covered [60].

Church and ReVelle [7] found that the GA algorithm never removes facility sites from the solution set. Therefore, it is possible that a facility site already added to the solution set in the early iterations of the algorithm may not still be justified later in the algorithm. The presence of a "no longer justified" site in the solution set would imply non-optimality. This can be reduced by improving the GA algorithm by including a technique that would reduce the probability of maintaining "no longer justified" sites in the solution set [7].

The next heuristic, called Greedy Adding with Substitution (GAS), follows the GA procedure but then includes a "node swapping" step. Following each successive facility placing, an improvement is sought by making trial exchanges of a facility node for a non-facility node [60].

The GAS algorithm, like the GA algorithm, automatically calculates maximal coverage for problems with one, two, ... to p facilities. Again, however, global optimality is not guaranteed [7].

2.4.2 Linear Programming

A LP problem may be defined as the problem of maximising or minimising a linear function subject to linear constraints and these constraints may be equalities or inequalities [61]. LP is one of the most successful disciplines within the field of Operations Research (OR) [62].

LP may be applied to the MCLP and will obtain globally optimal solutions [7].

2.5 Solution Requirements

Galvao and ReVelle [63] discovered that they usually resort to the use of the LP formulations when focusing on methods used to solve MCLPs to optimality.

ReVelle et al. [60] agreed, LP was found to be effective in producing integer-optimal solutions for problems involving a 55-node network in about 80% of cases. When LP produced fractional (quotient of two quantities) solutions, only modest amounts of branching and bounding were needed to find integer-optima.

To solve the warehouse pre-positioning problem in SADC a variation of the original MCLP model will be used and the preferred approach to solve this model is LP.

2.6 Conclusion

To find the best locations in SADC for the pre-positioning of warehouses to aid in disaster relief, a MCLP model that uses spatial objects rather than single points, includes partial coverage, and that assigns different weights to the different disaster areas, will be used. The problem will in addition be solved using this MCLP model but excluding partial coverage, to validate and compare the results. To solve these models the LP solution technique will be used. Chapter 3 contains the conceptual model and discusses the data gathering of disasters in the SADC countries needed to solve the model.

Chapter 3

Conceptual Model

The basic Maximal Covering Location Problem (MCLP) model seeks the maximum population which can be served within a stated service distance or time given a limited number of facilities.

To solve the problem of pre-positioning emergency supply warehouses in Southern African Development Communities (SADC), the MCLP model of Alexandris and Giannikos [36], will be used. In addition, this model will be solved excluding partial coverage to compare the difference in results.

3.1 The Maximal Covering Location Problem with Spatial Objects Model

3.1.1 Notation

Parameters:

$S \triangleq$ number of warehouses to be located.

$b \triangleq$ minimum acceptable coverage percentage (by a warehouse).

$\theta \triangleq$ minimum number of partial coverage pre-positioned warehouses needed for complete coverage.

$$a_{ij} \triangleq \begin{cases} 1 & \text{if a warehouse located at } j \text{ can fully cover disaster area } A_i, \text{ where } i \in \boldsymbol{I} \\ 0 & \text{otherwise.} \end{cases}$$

$w_i \triangleq$ weight assigned to the disaster area A_i, where $i \in \boldsymbol{I}$.

Sets:

$\boldsymbol{I} \triangleq$ set of disaster areas.

$\boldsymbol{J} \triangleq$ set of candidate warehouse locations.

$\boldsymbol{N}_i \triangleq$ set of warehouse locations that can cover disaster area A_i, where $i \in \boldsymbol{I}$.

$\boldsymbol{W}_i \triangleq$ set of candidate warehouse locations j partially covering disaster area A_i at least b, but less than 100%, where $i \in \boldsymbol{I}$.

Decision variables:

$$x_{ij} \triangleq \begin{cases} 1 & \text{if a warehouse is located at location } j \in \boldsymbol{J} \\ 0 & \text{otherwise.} \end{cases}$$

$$y_i \triangleq \begin{cases} 1 & \text{if disaster area } A_i \text{ is covered by at least one warehouse, where } i \in \boldsymbol{I} \\ 0 & \text{otherwise.} \end{cases}$$

$$v_i \triangleq \begin{cases} 1 & \text{if disaster area } A_i \text{ is covered at least } \theta \text{ times , where } i \in \boldsymbol{I} \\ 0 & \text{otherwise.} \end{cases}$$

$C \triangleq$ the percentage of the total weighted coverage achieved by the located warehouses.

Parameters b and θ express the extent to which partial coverage by more than one warehouse may be considered as equivalent to full coverage. The values of b and θ are normally such that $b \cdot \theta = 100\%$.

3.1.2 Model Formulation

In the context of maximal coverage, a model that considers partial coverage may be formulated on the basis of spatial objects rather than single demand points [36]. Demand is represented as a union of areas A_i for $i \in \boldsymbol{I}$.

The complete model can be formulated as follows:

$$max \quad z = \sum_{i \in \boldsymbol{I}} w_i y_i \tag{3.1}$$

Subject to:

$$\sum_{j \in \boldsymbol{J}} a_{ij} x_j \geq y_i - v_i \quad \forall \quad i \in \boldsymbol{I} \tag{3.2}$$

$$\sum_{j \in \boldsymbol{J}} x_j = S \tag{3.3}$$

$$\sum_{j \in \boldsymbol{W(i)}} x_j \geq \theta \cdot v_i \quad \forall \quad i \in \boldsymbol{I} \tag{3.4}$$

$$C = 100 \frac{\sum_{i \in \boldsymbol{I}} w_i y_i}{\sum_{i \in \boldsymbol{I}} w_i} \tag{3.5}$$

$$x_j \in (0, 1) \quad \forall \quad j \in \boldsymbol{J} \tag{3.6}$$

$$y_i, v_i \in (0, 1) \quad \forall \quad i \in \boldsymbol{I} \tag{3.7}$$

The objective function (3.1) considers all fully and partially covered disaster areas. Constraint (3.2) ensures that a fully covering facility is located to cover disaster area A_i when it is not partially covered (v_i=0). When v_i=1, y_i will be equal to 1, which means that area A_i is covered. Constraint (3.3) ensures that the specified number of warehouses are located, whereas constraint (3.4) imply that if v_i=1, disaster area A_i is partially covered by at least θ warehouses (Figure 4.1).

Coefficient w_i expresses the desirability, or benefit, of providing full coverage to disaster area A_i. This coefficient is equal to the risk weight factor assigned to disaster area A_i. Constraint (3.5) calculates the percentage of the total benefit achieved, through covering demand areas, by the specified number of located warehouses. This percentage is used to compare the cost of building a number of warehouses against the percentage coverage achieved. Finally, constraints (3.6) and (3.7) are included to ensure that some decision variables are binary.

3.2 Southern African Development Communities Disaster Data Gathering

To pre-position emergency supply warehouses to aid in disaster relief, data on different disasters occurring in the SADC countries is required. This data is used to assign weights to the different areas. The MCLP with spatial objects model requires data detailed enough to map within each country.

The Disaster Events Database (EM-DAT) (available at [64]) of the Centre for Research on the Epidemiology of Disasters (CRED), was developed in 1988 and contains records of disasters that required international assistance from 1900 to present [64] [65] [66]. The main objective of the database is to serve the purposes of humanitarian action at national and international levels. It is an initiative aimed to rationalise decision making for disaster preparedness, as well as providing an objective base for vulnerability assessment and priority setting [64]. EM-DAT uses various sources, including United Nations (UN) agencies, non-governmental organisations, insurance companies, research institutes and press agencies, as sources on disaster events, and includes information on fatalities, injuries, homelessness, persons affected and financial losses [64] [66].

The only data detailed enough to map within each country, is data related to natural disasters. However, as discussed in section 1.2.1, natural disasters are considered to exacerbate other disasters, and contribute to cause them, therefore the risk factor that will be used to determine where warehouses should be pre-positioned will consider only natural disaster data. By pre-positioning warehouses in this way, the aid provided after the occurrence of a natural disaster, will help in reducing the occurrence and the extent of other disasters.

3.2.1 Natural Disaster Data

Of all the natural disasters listed in Table A.1 (Appendix A), only six are considered major natural hazards that cause disasters. They are earthquakes, volcanoes, landslides, floods, drought, and tropical cyclones. Volcano data is excluded from the data used to solve the model because, although data exist, the variability of volcanic hazards is too complex to be entered into a general model, according to the United Nations Development Program (UNDP) [6]. The UNDP [6] identified African states as having the highest vulnerability to drought, and a high concentration of deaths associated with it, but because it is a slow onset disaster that can occur anywhere it is also excluded [5]. The impacts of drought are very different from those of sudden impact disasters [5], and assessment by the UNDP strongly reinforced field study evidence that the translation of drought to death is meditated by armed conflict, internal displacement, Human Immunodeficiency Virus (HIV)/Acquired Immune Deficiency Syndrome (AIDS), poor governance and economic crisis (in other words, drought rarely leads directly to mortality) [6]. The warehouses are pre-positioned to enhance relief response during sudden impact disasters and therefore will not be of much use for slow impact disasters such as drought.

Peduzzi and Deichmann [5] analysed (using EM-DAT) the mortality and economic loss risk, experienced in past disasters, for multiple hazards, including earthquakes, landslides, floods, and tropical cyclones. They determined the disaster risk for a given location with the probability that a hazard event of a given magnitude will occur, the number of people exposed or the value of the assets exposed, and the vulnerability. They calculated risks for grid cells, rather than for countries as a whole, and thus were able to estimate risk levels at sub-national scales.

Human mortality data provides a clearer picture of the risk of disasters, especially when looking at developing countries [6]. Therefore the dataset (available for download at [67] in different formats), developed by Peduzzi [5] and used to create the global map of the distribution of multiple hazards' mortality risk (GIS analysis and cartography [68]), is used to determine the weights assigned to the different disaster areas in SADC.

3.3 Conclusion

The MCLP with spatial objects model that considers partial coverage was formulated on the basis of spatial objects rather than single demand points. The data for the weights of the disaster areas included in the model, will only consist of natural disaster data, including earthquakes, landslides, floods, and tropical cyclones. Chapter 4 discusses the model validation and execution.

Chapter 4

Model Execution

The dataset [67] that Peduzzi [5] developed was used in Geographic Information Systems (GIS) and layered with a grid of 100 km × 100 km cells that represents the disaster areas.

A total of 153 disaster areas and 21 potential locations for warehouses were identified, using the grid as reference, throughout the fifteen Southern African Development Communities (SADC) countries. The potential locations for the warehouses were firstly selected so as to cover all disaster areas and then a number of locations was added to cover the more disaster-prone areas. Figure 4.2 illustrates the disaster areas, warehouse locations and the coverage area of the warehouses. Examining Figure 4.2, warehouse location 15 in the Democratic Republic of the Congo, can be taken as an example of an area with a high risk to earthquakes. Madagascar (warehouse locations 16, 18 and 19) on the other hand, has a low to medium risk of cyclones, that extend over the whole island.

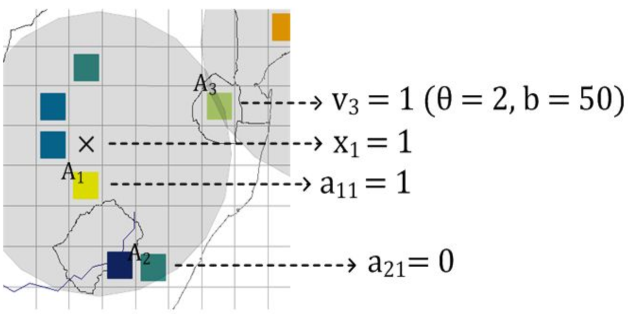

Figure 4.1: Full and partial coverage

The coverage provided by a pre-positioned warehouse is described by a circle. Figure 4.1 illustrates the fully and partially covered concept that is included in Alexandris and Giannikos's [36] MCLP model. For this model a disaster area is also considered fully covered if it is partially covered by $\theta = 2$ warehouses, with $b \geq 50\%$.

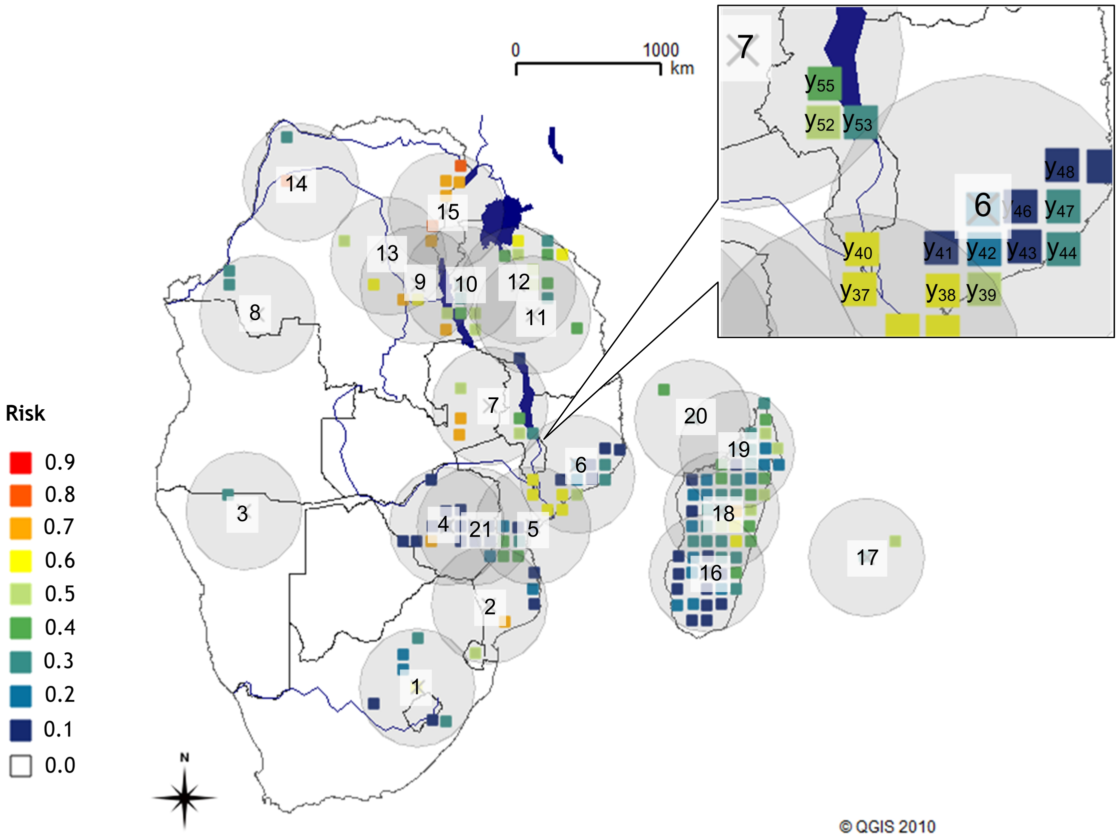

Figure 4.2: Illustration of disaster areas, warehouse locations, and warehouse coverage radius

4.1 Assumptions

Some assumptions had to be made. They include:

- The positions of the pre-positioned warehouses are assumed to be at the centre of the 100 $km \times 100$ km grid cell,
- the maximum distance a warehouse can be positioned from a disaster area is 400 km,
- the cost to build a warehouse is assumed to be R 350, 000, 000, and
- a disaster in a region does not affect the warehouse(s) in that region.

4.2 Validation

Validation, as mentioned previously, is something that should be done, whenever possible, before the actual solution of the model. This is to ensure that the model is an accurate representation of the system. Before using the data acquired to solve the pre-positioning of emergency supply warehouses problem, various different data sets were used to verify that the answers obtained from solving the model makes sense. This was done by changing certain information and then examining the results to confirm the model adapts to these changes. For the Alexandris and Giannikos [36] model that includes partial coverage, it had to be confirmed that if two disaster areas are partially covered, they are correctly counted as fully covered.

The models adapted to the changes and covered the more disaster-prone areas first, therefore the student is certain that the results obtained are feasible and come from a valid and accurate system representation.

It will however sometimes be necessary to solve the model to discover the inaccuracies in it. If some important constraint was ignored in the model formulation, it will lead to a solution that will clearly be recognised as being infeasible. The models can now be solved using the acquired data.

4.3 Results

Each model was executed 21 times in LINGO 8.0 optimisation software to determine the relative coverage that can be achieved by increasing the number of warehouses located. No inaccuracies were found during the examination of the results. The percentage weighted coverage achieved for different numbers of warehouses located is depicted in Figure 4.3, while Table 4.1 and Table 4.2 show the order in which the warehouses were located.

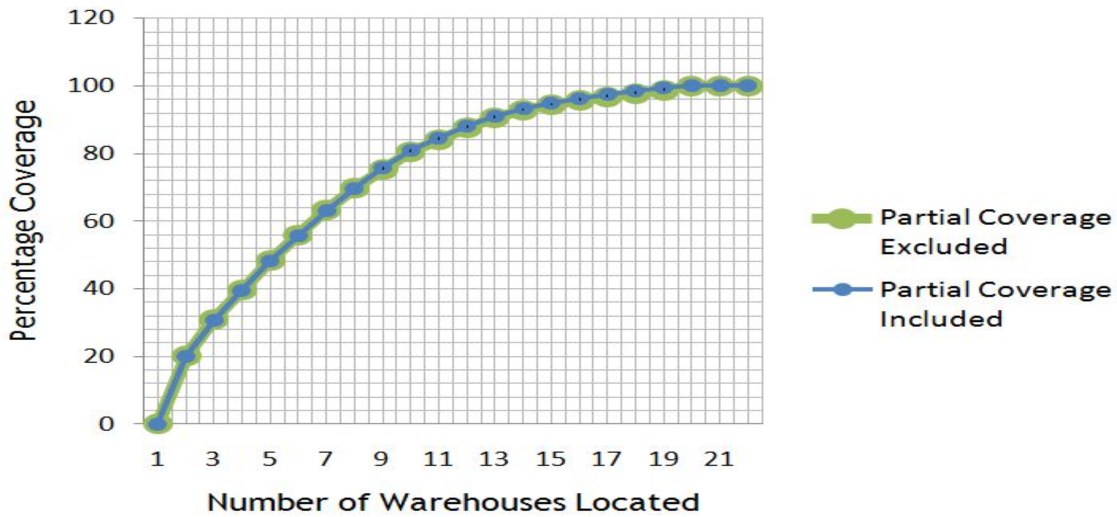

Figure 4.3: Comparison between the percentage weighted coverage achieved and the number of warehouses located

Table 4.1: Order in which warehouse locations are chosen for the MCLP model excluding partial coverage

# Warehouses	**Location**																				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
1																		x			
2					x													x			
3					x							x						x			
4					x							x			x			x			
5					x					x		x			x			x			
6					x					x		x			x			x	x		
7						x				x		x			x			x	x		x
8						x	x			x		x			x			x	x		x
9						x	x			x		x			x	x		x	x		x
10	x					x	x			x		x			x	x		x	x		x
11	x					x	x			x		x	x		x	x		x	x		x
12	x	x				x	x			x		x	x		x	x		x	x		x
13	x	x				x	x			x		x	x	x	x	x		x	x		x
14	x	x				x	x			x		x	x	x	x	x	x	x	x		x
15	x	x				x	x			x		x	x	x	x	x	x	x	x	x	x
16	x	x				x	x	x		x		x	x	x	x	x	x	x	x	x	x
17	x	x				x	x	x		x	x	x	x	x	x	x	x	x	x	x	x
18	x	x		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
19	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
20	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
21	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

It is clear when examining Table 4.1 and Table 4.2 (compare to Figure 4.2) that the more disaster prone countries, like Madagascar (warehouse locations 16, 18 and 19), Mozambique (warehouse locations 2, 5, 6 and 21) and the northern parts of Tanzania (warehouse locations 10, 12 and 15) and the Democratic Republic of the Congo (warehouse location 15) are covered first. This is expected as the weights associated with these areas are much higher, therefore the "benefit" achieved by covering those areas are much higher than the "benefit" realised when covering less disaster prone areas, with lower weights.

Table 4.2: Order in which warehouse locations are chosen for the MCLP model including partial coverage

# Warehouses	Location																				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
1																		x			
2					x													x			
3					x							x						x			
4					x							x			x			x			
5					x							x			x			x	x		
6					x					x		x			x			x	x		
7						x				x		x			x			x	x		x
8						x	x			x		x			x			x	x		x
9						x	x			x		x			x	x		x	x		x
10	x					x	x			x		x			x	x		x	x		x
11	x					x	x			x		x	x		x	x		x	x		x
12	x	x				x	x			x		x	x		x	x		x	x		x
13	x	x				x	x			x		x	x	x	x	x		x	x		x
14	x	x				x	x			x		x	x	x	x	x	x	x	x		x
15	x	x				x	x			x		x	x	x	x	x	x	x	x	x	x
16	x	x				x	x	x		x		x	x	x	x	x	x	x	x	x	x
17	x	x				x	x	x		x	x	x	x	x	x	x	x	x	x	x	x
18	x	x		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
19	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
20	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
21	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

When evaluating the cost associated with building a warehouse it can be seen, portrayed in Figure 4.4, that at some point the percentage weighted coverage achieved by locating another warehouse might not be reasonable when considering the cost of building that extra warehouse.

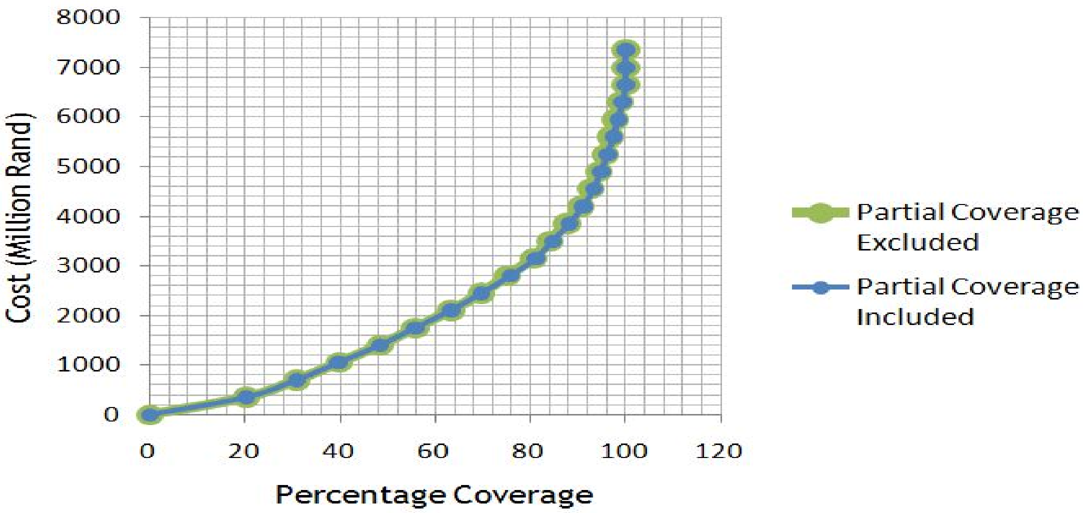

Figure 4.4: Comparison between the cost of building a warehouse and the percentage weighted coverage achieved

4.4 Evaluation of the Maximal Covering Location Problem models

From Table 4.1 and Table 4.2 it is clear that the order in which the emergency supply warehouses are placed does not differ significantly when partial coverage is included or excluded. Examining Figure 4.3 and Figure 4.4 it is comprehensible that the results of the percentage coverage achieved and the costs associated with building the warehouses, when partial coverage is included or excluded, corresponds narrowly.

This can be ascribed to the assumption that was made that the warehouses are placed at the centre of the 100 $km \times 100$ km grid block. When the warehouses are placed anywhere but at the centre there will be more disaster areas that will be partially covered. Therefore Alexandris and Giannikos's [36] MCLP model that includes partial coverage will provide better coverage.

4.5 Conclusion

The MCLP that includes spatial objects, weights assigned to disaster areas, and partial coverage, proved to be a good method for solving the emergency supply warehouse pre-positioning problem. The results of the two models, including and excluding partial coverage, corresponded narrowly. This can be ascribed to the fact that the partial coverage was not exploited fully because the warehouses are assumed to be located at the centre of the 100 $km \times 100$ km grid block. The results also proved that beyond a critical number of warehouses, the coverage achieved might not increase significantly enough to justify the cost associated with locating another warehouse. Chapter 5 discusses future work and the conclusion.

Chapter 5

Future Work

After comparing the results obtained from solving the problem with both Maximal Covering Location Problem (MCLP) models that includes and excludes partial coverage, it is clear that when the emergency supply warehouses are placed at the centre of the 100 $km \times 100$ km grid block the results will correspond narrowly. The MCLP model of Alexandris and Giannikos [36] proves to be a good way of finding locations to pre-position emergency supply warehouses to aid in disaster relief. However, there are opportunities for improvement of coverage, with less warehouses, with partial coverage.

5.1 Data Limitations

"In God we trust;

all others must bring data."

W. Edwards Deming

Data limitations combined with the unpredictable and unique nature of hazards, imply that much uncertainty remains. Given the limitations and uncertainties, the estimates of exposure and risk provided can only be taken as indicative [6]. Therefore, the data should only be used in identifying higher risk disaster areas.

It is of paramount importance to gather, maintain and manage credible data-records of disastrous events for an effective risk assessment and mitigation of disaster impacts [69]. If more effort is focused towards the collection of sub-national disaster data, it will help build datasets and indicators with a national level of observation and a local scale of resolution that can enable the visualisation of complex patterns of local risk [6]. This will help capture data on secondary disaster events and also highlight the ways in which natural, man-made and hybrid disasters interact, giving a clearer view of reality.

5.2 Warehouse Locations

Future work would include research on the specific locations of the warehouses. According to Whybark [70], the issues of distribution are complicated by political relationships between countries of the warehouse location and countries of the inventory destination. Whybark [70] found that often despite the need, the government in the country of the disaster refuses the disaster relief because of the source of the inventory that is part of the relief. This issue of acceptability is related to the decision of the pre-positioning of warehouses, locations must carefully be considered before being chosen.

5.3 Generic Application of Model

Although this paper only focus on Southern African Development Communities (SADC), this model can be used for other countries as well. The disaster data used to determine the risk factors, is a global map (Peduzzi and Deichmann's [5] map of the distribution of multiple hazards' mortality risk), therefore this model can be applied globally.

5.4 Conclusion

The number of people killed in disasters is estimated to be three to four times higher in developing countries [71] such as SADC countries. It is said that for every person killed, 3000 more are exposed to natural hazards [6], but in spite of this, very little has been invested in the prevention, mitigation and preparedness of disasters in SADC.

The aim of this paper was to find an appropriate way to pre-position emergency supply warehouses in SADC countries to aid in disaster relief. This was achieved using Alexandris and Giannikos's [36] MCLP model, that includes spatial objects rather than single points, partial coverage, and weights assigned to disaster areas. This model was in addition solved excluding partial coverage to compare and validate the results.

It was found that beyond a critical number of warehouses, the coverage achieved might not increase significantly enough to justify the cost associated with locating another warehouse.

Future work includes the collection of detailed disaster data on sub-national levels, and thorough research on the countries and specific locations for warehouses.

Although living with risk is the order of the day, we must learn to reduce these risks through appropriate measures to reduce contemporary risk with compensatory disaster risk management, such as disaster preparedness and response [6]. Let us do as the Global Assessment Report of 2009 [5] clearly states, invest today for a safer tomorrow.

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Appendix A

Types of disasters

Table A.1: Types of Disasters

Disaster Type	**Sub-Disaster**	**Name of Disaster**
Natural	Natural phenomena beneath the Earths surface	Earthquakes Tsunamis Volcanic eruptions
	Topographical phenomena	Landslides Avalanches
	Meteorological/hydrological phenomena	Windstorms (cyclones, typhoons, hurricanes) Tornadoes Hailstorms and snowstorms Sea surges Floods Droughts Heat waves/cold waves
	Biological phenomena	Infestations (locust swarms, mealy bug) Epidemics (cholera, dengue, ebola, malaria, measles, meningitis, yellow fever, HIV/AIDS, tuberculosis)
Man-made	Socio-technical and Technological disasters	Fire Explosions (munitions explosions, chemical explosions, nuclear explosions, mine explosions) Leakage Toxic release Pollutions (pollution, acid rain, chemical pollution, atmospheric pollution) Structural collapse of physical assets

Disaster Type	Sub-Disaster	Name of Disaster
	Transportation disasters	Air disasters Land disasters Sea disasters
	Stadia or other public places failures	Fire Structural collapse Crowd stampede
	Production failure	Computer system breakdown Distribution of defective products
	Warfare – National	Civil war between armed groups from the same country Civil strikes Civil disorder Bomb threats/terrorist attack
	Warfare – International – Conventional war	War between two armies from different countries Sieges Blockades
	Warfare – International – Non-convential war	Nuclear Chemical Biological
Hybrid	Natural and man-made events	Floods ravage community built on known floodplain Location of residential premises, factories, etc., at the foot of an active volcano, or in an avalanche area Landslides