Integrated stochastic distribution network design: A two-level facility location problem with applications to maize crops transportation in Tanzania

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Declaration

I, SAID ATHUMAN SIMA, hereby declare that this thesis is my own, unaided work and it has not been submitted before for any degree or examination in any other university. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg.

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Abstract

A two-level facility location problem (FLP) arose in the transport network of maize crop in Tanzania has been studied. The three layers, namely, production centers (PCs), distribution centers (DCs) and customer points (CPs) are considered in the two-level FLP. The stochastic effect on the two-level FLP due to rainfall in the network links, between the DCs and CPs, has been studied. The flow of maize crop from PCs to CPs through DCs is designed at a minimum cost under deterministic and stochastic scenarios. The three decisions made simultaneously are: to determine the locations of DCs (including number of DCs), allocation of CPs to the selected DCs, allocation of selected DCs to PCs, and to determine the amount of maize crop transported from PCs to DCs and then from DCs to CPs.

We have modelled the problem and generate results by optimizing the model with respect to optimal location-allocation strategies. We have considered two networks, the existing network and an extended network. In the existing network there are four PCs, five DCs and ninety three CPs. In the extended network three additional DCs are considered. For the modelling purpose we have used the rainfall data from 2007 - 2010 in each week for 17 weeks. The optimized results for the existing network have shown improvements in cost saving compared to the manually operated existing network. In the extended network, the results have shown much more efficient and cost saving distribution system compared to the results of the existing network.

Dedication

To my late parents, Athuman Sima Daffi and Fatuma Mwanga Kidua, I dedicate this thesis.

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In The Name of Allah SWT The Most Merciful The Most Compassionate Peace and Blessings be Upon His Beloved Prophet SAW.

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Chapter 1

Introduction

1.1 Background to the problem

Distribution network design problems consist of determining the best way to transfer goods from the supply to the demand points by choosing the structure of the network such that the overall cost is minimized [5]. Here, the network is considered from a graph theory point of view. It is a connected graph with sets of vertices (nodes) and edges (arcs). Production centers, warehouses (distribution centers) and customer points/demand points are assumed to be vertices while edges or arcs can act as roads and/or railways. Associated with this network, there are two main problems: facility location [21, 45, 63, 75] and vehicle routing [47, 63]. There are a number of papers that deal with these two problems, both individually or combined [9, 21, 47, 59, 71, 75].

In the classical facility location problem (FLP), it is required to determine the optimal location of facilities or resources so as to minimize costs in terms of money, time, distance and risks with relation to supply and demand points [4, 63]. In other words, as defined in Sajjadi [71], 'given a set of facility locations and a set of customers who are served from the facilities, then which facilities should be used?, which customers should be served from which facility so as to minimize total cost of serving all customers?' Other names of the FLP are the warehouse location problem and a spatial resource allocation problem [18]. Some examples of such facilities are schools, warehouses, hospitals, markets, industries, stadium or open space, terminal bus stand (hub), railway stations, military centers, post offices, fire stations and worship places [18, 42, 71]. In a FLP, the constraints such as distance between facilities and customers are often imposed. Other typical constraints are the number of customers (people using these facilities) and their demands, the number of facilities and their capacities [18, 42, 57, 58, 75]. The problem studied in this thesis is a FLP that involves a distribution system design.

The vehicle routing problem (VRP) can be simply defined as the problem of designing least-cost delivery routes from a depot (or depots/supply points), to a set of geographically scattered customers, subject to a number of constraints (capacity, distance, time). In the VRP, a number of vehicle routes are created such that: (i) each route starts and ends at a depot, (ii) each customer is visited exactly once by a single vehicle, (iii) the total demand of a route does not exceed vehicle capacity, and (iv) the total length of a route does not exceed a preset limit [47]. A route is a sequence of locations that a vehicle must visit along with the indication of the service it provides. The VRP arises as a generalization of the travelling salesman problem (TSP) which requires the determination of a minimal cost of a cycle that a salesman passes through each vertex (city or customer) of a given graph exactly once. Since VRP was introduced by Dantzig and Ramser 1959, there have been major developments in both exact and heuristic solution methods as detailed in [47]. For more studies of VRPs refer to [49, 51].

The location-routing problem (LRP) integrates FLP and VRP in a single framework. The classical LRP seeks to minimize the total cost by simultaneously solving the location and routing problems. In the LRP models, three decisions are made simultaneously: to determine the locations of facilities (including number of facilities), to allocate customers to facilities, and to determine routing from facilities to customers. The main constraints are: (i) customer demands are satisfied without exceeding vehicle or facility capacities, (ii) the number of vehicles, the route lengths and the route duration not exceeding the specified limits, and (iii) each route begins and ends at the same facility [9]. In the two main components of the LRP, the FLP is considered as the master problem and the VRP is a sub-problem within the LRP [63].

The LRP as an optimization problem has attracted many academicians and practitioners in recent years. LRPs have been studied with different mathematical approaches in the literature, see [9, 34, 63]. The models, solution procedures, and applications of LRP began to appear in the literature in the 1970's. LRP models can be deterministic or stochastic [9]. Within the LRP models, the stochasticity in customer demand has been reported in [8, 48, 71]. On the other hand, stochasticity in travel times in the context of VRP has been reported in [49, 51, 82]. A study on travel time reliability is mostly detailed in the PhD thesis by Tu [82]. Similar studies were also carried by Vandaele et al. [86], and Van et al. [87]. Their observations were based on real life environment where travel times from one point to another is not reliable due to unpredictable traffic jams (due to car accidents and the number of cars in relation to road capacity). These factors, no doubt, affect the speed of a vehicle. In their study [86, 87], the authors used queueing theory on traffic flow to model the expected travel time and standard deviation of the travel times in order to measure the travel time reliability.

The two main solution approaches to LRP are exact and approximate (heuristic) methods. LRP arises in many applications in various forms. Most recent papers on LRP focus on distribution of consumer goods as its practical applications [4, 34, 35, 53, 55, 59, 63, 67, 88]. Further classification and more details on LRP can be found in the review paper by Nagy and Salha [63].

The FLP is a broad study area within the location analysis, where the location, allocation and shipment or transportation decisions are solved simultaneously. Usually, the allocation of customers to a specific facility, is an implication to direct transportation of goods from that facility to the respective customers. In this context, each customer is supplied directly from a facility without depending on other customer's demand [6, 42, 58]. This is a strategic issue faced by distribution companies in designing their distribution networks [42]. Strategic issues or decisions are defined as decisions that have a long-lasting effect on the company. These are decisions which include the number, location and capacities of warehouses and manufacturing industries, or the logistics network [58]. Klose and Drexl [42] mention the core components of distribution system design as location of facilities and allocation of customers to the facilities. The mathematical models for location-allocation are formulated in various forms from simple to complex. These are from simple linear, single-level or multi-level, single-product or multi-product, uncapacitated or capacitated, deterministic or stochastic models to nonlinear models [42, 58]. There are various algorithms which are exact and/or heuristic that are local search and mathematical programming based approaches [42].

In the literature, there are a wide range of variants and extensions of FLPs. The main classifications are based on attributes of facilities and customers. Major attributes are location types e.g. continuous or discrete, number and capacities, etc.

Klose and Drexl [42] consider continuous facility location models as models in the plane which are characterized by two essential attributes. First, the solution space is continuous, that is, it is feasible to locate facilities on every point in the plane; secondly, a distance is measured with a suitable metric [42]. The common metric measures used are right-angled distance metrics (the Manhattan) and the Euclidean or straight-line distance metric. The continuous location models use coordinates to calculate distances between facilities and customers. The other counterpart category is the discrete facility location models. This is the most studied area as mixed-integer programming models and network location models [42, 58]. In discrete facility location problems, nodes represent demand points and potential facility sites correspond to a subset of the nodes. The models are characterized by binary decision variables. Distance metric between nodes also applies in the discrete optimization [42, 58].

Multi-stage or multi-level distribution system models consist of facilities on several hierarchically layered levels. Hierarchical system is defined as a system of different types of interacting facilities [69]. These hierarchical layers are also known as echelon [26, 81]. Generally, when there are more than one hierarchical layers, then it is a multi-stage or multi-level model. In other related classification scheme, the multi-stage models are named as multi-level models. This is mostly used when location decisions are done to each facility layer [43, 69]. The words stage and level are interchangeably used such as single-stage or single-level, and multi-stage or multi-level. However, in this work we are using mostly single-level and multi-level.

In their review paper, Klose and Drexl [42] list sub-categories of discrete FLPs as single or multi-stage models, uncapacitated or capacitated models, multiple or single-sourcing, single or multi-product models, static or dynamic models, and, last but not the least, models without and with routing options included [42].

In single-level models, FLPs have only one level or one group of facilities that will service customers. Goods supplied from distribution centres (DCs) to customers without considering the manufacturing or production centres are single-level models. When there is no limit on the facilities' capacity, it is known as an uncapacitated facility location problem (UFLP), otherwise it is known as a capacitated facility location problem (CFLP). The classical UFLP is also known as the fixed-charge location problem [42, 58, 76]. If each customer can be supplied by exactly one DC, then it is single-sourcing; but if many DCs can supply to one customer, then it is multi-sourcing. In these models, there can be deliveries of single or many products. Furthermore, when a specific number of facilities are needed in serving customers, then it is termed as p-median FLP. This requires a number of p facilities or DCs, out of say N, to be selected in possible potential sites for serving the specified number of customers.

The layers of a distribution network are known by various names such as plants or supply-points, transit points and demand points or customers points, and depots or distribution centres [71]. For instance, if a distribution network consists of plants, distribution centres and customer points, then it is a three-layer network. In this case, plants is the first layer, the distribution centres form a second layer, and the customers or demand points is the third layer. There will be a flow of goods from one layer to another. The routes between one layer and another creates routing or transportation levels which can be direct (known as replenishment route) or tour (routes with several stops) routes. When the transportation routes between two points, say A and B, have no stops between origin and destination, then it is a direct or replenishment route. The study in this thesis considered only direct routes between its layers. The direct delivery, or point to point, method of goods distribution involves the movement of goods from an origin, plant or warehouse or DC, to a specific destination without stopping [75].

Generally, multi-level FLPs are present if facilities (plants or DCs) have to be located or allocated simultaneously on several layers of the distribution system. A two or three-level capacitated facility location model can be specified if the flow of products are from two or three capacity-constrained echelons, before the final delivery to the customer points [42]. The production centres or plants are considered as higher level facilities. The lower level facilities are known as DCs, warehouses or transit points that act as intermediate points for goods to be delivered to the intended customers. There are several studied models as found in [25, 26, 42, 58, 81]. A related area to the FLP is the supply chain management (SCM) as presented by Melo et al. [58]. The FLP is said to be SCM when other attributes such as procurement, production, inventory, distribution and routing are included in the model [58]. The model researched in this thesis is a two-level capacitated FLP with multi-sourcing and single-product. The study considered both deterministic (static) and stochastic modelling.

The review study by Snyder [76] considers stochastic components in facility location models. He classifies the decision-making environments into three categories as certainty, risk and uncertainty. The certainty situations are when all parameters are deterministic and known. On the other hand, both risk and uncertainty are when randomnesses occur. The risk situations occur when uncertain parameters whose values are governed by some known probability distributions. In uncertainty situations, parameters are uncertain, and probabilities are not known. Snyder [76], further categorizes problems with a risk situations as stochastic optimization problems. In such problems, a common goal is to optimize the expected value of some objective function. The problems with uncertainty are known as robust optimization problems [76]. The study we are dealing with, is also a stochastic optimization study.

Most of the problems as reviewed by Snyder [76], are stochastic problems due to demand [76]. Other randomnesses considered are the randomness in travel times, production costs, travel costs, capacities and location points. However, there are few stochastic studies in multi-level facility location problems. Practical applications of FLP where the distribution network is stochastic in nature are rarely seen compared to LRPs and VRPs. The stochastic distribution network is when there is no guarantee that, a subsection of a route/link or sub-route can be used with certainty for various reasons. For instance, as studied in LRPs, presence of traffic jam due to car accidents, road block by traffic authority and even floods may affect the route to be reachable or accessible. Unfortunately, the current mathematical formulation of the multi-level FLP; does not address the stochasticity due to the weekly rainfall effect, particularly in the context of real-life problems.

1.2 Research motivation and objectives

1.2.1 Research motivation

The research involves the study of a two-level FLP with stochasticity in the network links between the distribution centres to the customers so as to achieve the food security at the customers' demand locations. The motivation for this study is that the current literature in multi-level FLP does not address stochasticity in routing (direct delivery) due to unexpected occurrences such as rainfall; and that a real life problem from Tanzania is considered. This is aside from the fact that many studies on deterministic and stochastic cases for both VRPs and LRPs, on real life problems; have been carried out in Western Europe and North America [63, 76]. No similar studies for multi-level FLPs have been carried out in the context of Africa, to the best of our knowledge. The objective of this study is to come up with food distribution systems that are economical and cost effective in Tanzania.

The two-level FLP involving the maize crop transportation network that originally arose in a government ministry in Tanzania; has been studied. The practical problem considered have a number of features which make the research worthwhile as this was not considered before. The research is two-fold. Our first task is to model the problem mathematically. The second task is to generate solutions and analyse them critically.

The case study investigates two types of distribution networks: the existing network and an extended network.

The first exercise involves an analysis of the existing distribution set-up to see whether it is optimal and to see if it will be sustainable for a future period. This network has five existing DCs where it is possible to vary their capacities during optimization. Thus we optimize the flow of maize crop from production centres to customer points through distribution centres. There are two tasks in the analysis of the existing network:

- The first task is the optimization of the flow of maize crop in the existing distribution network. An analysis of the manually operated network using a mathematical model is done for the cost and location-allocations comparison. Through optimization of the model, the conditions under which it is optimal compared to the manually operated network will be found. In this situation, we will consider only the capacities of DCs to be constant.

- The second task is the improvement of the existing network. Here we want to choose the best possible configuration of the facilities in the existing network through optimization tools. The aim is to satisfy the customers' demand while minimizing the overall network cost. The same five DCs will be used but with variable capacities in order to find the best capacities for minimum cost. The capacities in this case are considered as decision variables in the model.

The optimized results for the existing network will enable us to give better suggestions on cost reduction to the Tanzanian government.

As an alternative to the existing network, an extended network using eight DCs will be studied. Three new DCs in addition to the five existing DCs will be considered. The use of additional DCs is based on the high production capacities of maize crop (see Table 4.4), and also the government's plan for additional DCs (see Figure C.2) as a result of increased demand of maize and other cereal crops. For the extended network, DCs' capacities are also decision variables in the model.

1.2.2 Objectives

The objective is to determine whether to keep the current structure (and perhaps updating their capacities) or to use the extended network. Scientific methods will be used to come up with an answer to the above mentioned question.

We model the problem and solve it with respect to optimal location-allocation strategies. The specific objectives are therefore:

- To develop a two-level FLP integrated with stochastic transportation network [1];
- To apply the model to a real life problem for both deterministic and stochastic cases;
- To critically analyse and compare the optimal results obtained by deterministic and stochastic models.

The research uses the terms plant, supply point and production centre interchangeably. The same is true for distribution centre (DC), warehouse and depot. The terms-; customer points and demand points are also used interchangeably.

We have used an exact method in our solution approach. This based on the fact that a software (IBM ILOG CPLEX Optimization Studio) we are using give the same results when the model is solved repeatedly. It is also the software defined the solution being optimal after computations.

1.3 Organization of the thesis

The rest of the chapters are organized as follows: in the next chapter (2) we present the literature review on multi-level FLPs. This chapter discusses more on theoretical

[1]By stochastic transportation network we mean, either a subsection of a network takes non-deterministic time to travel or an alternative sub-network or link has to be used resulting in longer travel times.

and related literature on multi-level FLPs, and also presents both the deterministic and stochastic mathematical models from the previous studies. Chapter 3 presents the two-level FLP that arose in Tanzania in maize crop distribution network. Chapter 4 is for the deterministic model together with the results for maize crop production and distribution system in Tanzania. Chapter 5 presents the stochastic model together with the results. The research conclusion, recommendations and future proposed research directions are in Chapter 6.

1.4 Summary

This chapter; has introduced the problem of this thesis by describing a background of the problem and related literature. This is a facility location problem (FLP) and other related problems which are VRPs and LRPs. The main features in each problem are explained and the literature where these problems appeared is provided. A specific FLP studied in this thesis is a two-level FLP where both deterministic and stochastic models are analysed. An application to the problem is maize crop transportation in Tanzania. The specific objectives to be achieved are also provided in this chapter.

Chapter 2

Multi-level FLPs: A literature review

2.1 Background to the multi-level FLPs

As explained in Chapter 1, a multi-level or multi-stage facility location problem is considered to be an extension of the classical FLP (single-level model). It is categorized in the literature as the hierarchical location-allocation problem or as hierarchical facility location models [28, 29, 64, 69]. Generally, the hierarchical system of facilities consist of k different types of interacting facilities (levels) in which the lowest level is called level 1 and the highest is level k. This classification of facilities does not include demand or customer points. The demand or customer points are assigned to be level 0 in this regard, and the underlying structure is assumed to be a network whose nodes represent facilities and customer points [69].

The hierarchical systems are complex systems that require an effective coordination of services provided at different levels. They need an integration in the spatial organization of the different facilities and the flow of goods or services provided in the respective levels [69]. The major applications are found in service provisions and products distribution systems. The specific application areas as mentioned by Narula [64], and Sahin and Süral [69] are production-distribution systems, health-care delivery systems, solid waste management systems, education systems, emergency medical service systems, telecommunication networks, postal services and banking systems. More detailed referenced studies on each application area can be found in Sahin and Süral [69].

There are classification schemes of the hierarchical facility location problems as studied by Sahin and Süral [69], Marianov [56], and Narula [64]. The four attributes associated with the classification schemes and the common terms used in this area are defined as itemized below.

- Flow pattern: This considers the customers and/or goods flow through layers or levels of the hierarchical systems. This is either in a single flow or multi-flow pattern. The single-flow pattern starts from lowest level (level 0) and passes through all levels and ends at the highest level (level k). It can also be in the reverse direction: starting at level k and ending at level 0. On the other hand, multi-flow can be from any lower level m to any higher level n where $n, m \in \{0, 1, 2, ..., k\}$. Similarly, the reverse direction is also possible for multi-flow. The two flow patterns can also have referral or non-referral systems. In a referral system, some proportions of customers served at any level, are referred to higher levels, while in a non-referral system no referrals between levels are considered [69].

- Service varieties: With regard to types of services to be provided, a system is classified as nested or non-nested. In a nested hierarchy system, a higher-level facility provides all the services provided by a lower level facility. In addition, this level must have at least one additional service which is different from the lower level services. In a non-nested hierarchy, facilities at each level offer different services [56].

- Spatial configuration: Here, coherency refers to the spatial configuration of levels. As described by Sahin and Süral [69], "In a coherent system, all demand sites or customer points that are assigned to a particular lower-level facility are assigned to one and the same higher-level facility. Thus, coherency resembles single-sourcing in managing demand satisfaction in capacitated facility location problems. Non-coherent systems are less constrained on the spatial configuration of levels".

- Objective function: There are three well-known types of objective functions used to locate facilities. These are median, set covering, and fixed charge objectives. The median models aim to minimize the demand weighted total distance (transportation cost) between customer points and facilities. In set covering models, a customer is considered covered by a facility if the facility is located within a particular proximity. The main objectives here are to minimize the number of facilities needed for coverage of all customers and to maximize covered customers with a particular number of facilities (maximum covering). In covering models, it is not necessarily for the facility to provide services to the nearest demand site. This might be due to facility capacity and also the quantity of demand by customer. However, a customer should be served by at least one facility within a given critical distance [69]. The goal of the fixed charge location models is to minimize total facility construction and transportation costs [69].

Generally, there are several classification schemes found in hierarchical facility location problems and there is no unique way of doing the classification [64]. Classifications, other than what is presented above, can be based on the problem formulation and solution procedures which depend upon the hierarchical relationship between the facility types involved. Classifications may depend on the flow of goods and services allowed among levels [64].

The study in this thesis is concerned with production-distribution system, where product flow is from higher level to lower level. It is a single-flow and non-nested network, where customers will only be serviced by lowest facility (level 1). The non-nested hierarchy is when facilities at each level offers different services.

In the literature, the multi-level problems are also named as multi-stage problems. As described by Klose (2000) [43], location decisions can be determined in both levels of facilities or only determined in one level while the other levels are fixed [43]. The multi-level studies can be two-level, three-level, uncapacitated and capacitated facilities. Both exact and heuristic solution methods are applied in deterministic and stochastic models [1, 5, 36, 37, 56, 58, 64, 69, 76]. For more detailed and references of multi-level FLPs, a study by Sahin and Süral [69] can be consulted.

2.2 The previous studies of Multi-level FLPs

The multi-level FLPs discussed in this section are mostly related to this thesis. The literature reviewed in this section is classified into three categories as itemized below:

- Deterministic multi-level problems with exact solution methods;
- Deterministic multi-level problems with heuristic solution methods;
- Stochastic and robust multi-level problems with both exact and heuristic solution methods.

2.2.1 Deterministic multi-level problems with exact solution methods

The multi-level FLPs are deterministic if all their input data is known by certainty. In some literature, the deterministic models are also known as static models [71]. The exact solution method is the solution procedure that guarantees the optimal solution [71]. There are several deterministic studies as discussed below.

In 1974, Geoffrion and Graves [25] presented a multi-level facility location problem as a distribution system design multi-commodity problem that is solved optimally. It is a two-level FLP which optimizes the location of DCs. The problem is formulated as a four-indexed mixed integer linear program with multi-commodity flow from plants to customers through DCs [25]. It is a capacitated constrained problem on both plants and DCs. The problem studied by these authors is single-sourcing and single-period model. The model solution method is developed based on Benders decomposition techniques [25]. They solved a real life problem of a major food company using their model and algorithm. The optimal solution to the real problem is found with up to a composition of 17 commodities, 14 plants, 45 possible DC sites, and 121 customer points [25].

Köksalan et al. [45] in 1995 studied an application problem of a brewery company based in Turkey. It is a two-level location-distribution problem formulated as a mixed integer programming model. The malt factories are the higher level facilities and breweries are the lower level facilities that supplies to customer zones. They evaluated the existing transportation costs for shipping malt from the two malt factories to the three breweries, and shipping beer from the breweries to 300 different customer zones [45]. The model is solved optimally using interacting mathematical programming software (FORTRAN and LINDO). The company's plan is to explore the best sites for opening new breweries. After the results of the study, two new breweries were then opened [45].

A production-distribution system design problem studied by Elhedhli and Goffin [22], is a two-level FLP. It is a supply chain based problem that is multi-product plant, single-sourcing DC with capacitated constraints. The optimal solution to the problem is based on Lagrangian relaxation, interior-point methods, and branch and bound.

A study by Hindi and Basta [29] considered a similar problem as the Geoffrion and Graves [25], but with three indexed formulation. The other difference is the absence of single-sourcing of DCs-to-customers' service. The multi-products were transported from capacitated plants to capacitated DCs before the final destination to the customer points with the known demand. The problem considered locations of DCs and their associated fixed costs. In the model the shipping costs from a plant to a possible DC and thereafter to the customer points were also considered. The problem is a mixed-integer programming model solved by a branch and bound algorithm. Again in 1998, Hindi et al. [28] presented a similar study that considered single-sourcing DC-to-customers' service. In the model, they used a four indexed formulation where it was possible to trace the plant origin of each product quantity delivered to the customers. Generally, the objective was to choose the locations for opening DCs such that the total cost in the distribution system was minimized. An other similar study by Jiang et al. [38], used both heuristic and exact solution techniques.

A study by Tragantalerngsak et al. [81] is focused on a two-echelon, single-source, and capacitated facility location problem. The problem is formulated as a mixed integer linear program, with capacitated constraints. The model is solved optimally by a Lagrangian relaxation-based branch and bound algorithm. In their problem, the deliveries of products are made from the first-echelon facilities (they call them depots) to customers through the second echelon facilities (called facilities in the model). The main goal is to determine simultaneously, the number and location of facilities in each echelon, the flow of products between the facilities in different echelons, and finally the assigning of the customers to open facilities in the second echelon [81]. This problem has the following identified features:

- Two-echelon and single-source: In this case, each customer must be served by only one facility from second echelon facilities. On the other hand, each facility in second echelon, will also receive products (deliveries) only from one depot in the first echelon depots. So, single-sourcing is applied to both layers of the distribution system.

- Capacitated and uncapacitated facilities: The second echelon facilities have specific capacities that must not be violated, but the first echelon facilities (named as depots) are uncapacitated.

- Decision variables: There are three decisions to be made. The first decision is the location decision for opening of facilities (second echelon); the second is the allocation of customers to open facilities, and the third is the allocation decision of allocating open facilities to depots (first echelon). All the decisions are made simultaneously.

The main applications mentioned in the study are in the telecommunication, distribution and transportation industries [81].

Ambrosino and Scutella [5] considered a complex distribution network design problem with capacitated facility location, warehousing, capacitated transportation and inventory levels. It is a network made up of four layers, namely; plants, central depots, regional depots and customers. The three types of routes are plant to central depots, central depots to regional depots, and finally, the routes from regional depots to customers. The major tasks on facility location, allocation, transportation (routing) and inventory were carried out optimally for some small instances using CPLEX software. The authors pointed out that, for solving larger problems and real instances, the only helpful methods have been heuristics [5].

The review paper by Klose [42] presents different problems of locating facilities and allocating customers that covers the core topics of distribution system design. He pointed out that, "model formulations and algorithms which address the issue vary widely in terms of fundamental assumptions, mathematical complexity and computational performance" [42]. In the paper, multi-level models are well discussed with the concerned variations. Other review papers that discuss this class of problems are by Melo [58], Narula [64], and Sahin and Süral [69].

2.2.2 Deterministic multi-level problems with heuristic solution method

Heuristic is the term used in the field of optimization to characterize a certain kind of mathematical problem-solving procedures. As presented by Silver [73], "the term heuristic means a method which, on the basis of experience or judgement, seems likely to yield a reasonable solution to a problem, but which cannot be guaranteed to produce the mathematically optimal solution". Generally, due to the complexity of a great number and variety of difficult mathematical problems, the heuristic solution method is needed in practice. The problems needed to be solved efficiently, and this has led to the development of efficient procedures in an attempt to find good or reasonable solutions, even if they are not optimal [71, 73]. In these methods, the process speed is an important measure in relation to the quality of the solution obtained. Heuristics are also known as approximate algorithms. They are mostly concerned with obtaining applicable solutions to the well defined mathematical representations (models) of real-world problem situations [73].

Klose [44] formulated a mixed integer programming model of a two-level capacitated facility location problem (TSCFLP). The model considered a single-product and single-source constraints. It is a linear programming based heuristic with three tasks. The first task is to find the optimal locations of depots from a set of possible depot sites in order to serve customers with a given demand; the second is the optimal assignments of customers to depots, and third, the optimal flow of product from plants to depots [44]. The model is solved by a heuristic approach based on the Lagrangian relaxation of the demand constraints. The procedure was tested on some problems with up to 10 plants, 50 possible depot sites and 500 customer points. "The computational results show that this method is able to compute near-optimal solutions and useful lower bounds for the TSCFLP in short computation times, even in the case of larger problem instances" [44]. In 2000, Klose [43] solved another similar problem but considering a Lagrangian heuristic based on the relaxation of the capacity constraints. It is named as Lagrangian relax-and-cut approach. The resulting Lagrangian sub-problem is then solved efficiently by branch-and-bound methods. Next, the results are computed by means of a weighted Dantzig-Wolfe decomposition approach [43].

The studies by Amiri [7] and Lashine [50] are two-level FLPs addressed as the problem of designing a distribution network in a supply chain system. Lashine [50], also includes in his study, the routing decision. The studies by Amiri [7], Litvinchev et al. [52], and Landete & Marin [46], determined simultaneously the best location of both plants and warehouses, and the best strategy for distributing the products from the plants to the customers through warehouses. Amiri's study allows the multiple levels of capacities available to the warehouses and plants [7]. In this case, it is possible to have several capacity values in plants and depots/warehouses. The study considers different values of DCs' capacity during optimization of the model. Amiri [7] implemented an efficient heuristic solution procedure based on Lagrangian relaxation of the problem. The tested problems are up to 500 customers, 30 potential warehouses, and 20 potential plants. The two-level problem studied by Landete & Marin [46] is uncapacitated FLP where its solution was obtained by a heuristic approach that involves cuts . The study by Litvinchev et al. [52] considered a two-level CFLP with a single-product also uses a heuristic Lagrangian relaxation. The distribution network design problem studied by Jayaraman [37] uses simulated annealing (SA) to obtain nearly optimal distribution system design.

Hinojosa et al. [30] studied a multi-period and multi-commodity two-echelon capacitated facility location problem. This study considered multi-period planning horizon which has not yet been observed in the previous surveyed literature. They assumed that the capacities of plants and warehouses change over time (T) periods. This is also applied to demands and transportation costs. Seasonal known demands grouped in four periods are considered to influence the capacities and other parameters and/or variables determination for each period

[30]. Both plants and warehouses location were determined in each period. The authors have not provided any real life application, but the model presented applies to the situations where intermediate distribution and seasonal demand exist [30]. It is a cost minimization mixed integer programming problem where results were obtained by a Lagrangian relaxation with heuristic procedures.

A study by Ozsen et al. [65] was a two-echelon single product logistics system involving a single plant and several of potential warehouse sites. Only the location of warehouses is determined. It is a supply chain network design problem that is nonlinear integer-programming and solved by heuristic Lagrangian relaxation. This model considered multi-sourcing as customers (retailers) are sourced by more than one warehouse [65].

A two-level transportation problem studied by Gen et al. [24] is modelled in the supply chain system. The study aims to determine the distribution network that involves transportation problem and facility location to satisfy customers' demands at minimum cost. The major constraints are the capacities of plants and DCs, and the minimum number of DCs to be selected. The constraints regarding the number of DCs to be selected is one of the component which distinguishes this study from the other models. It is very important when a manager has limited available capital [24]. In the three layers, the nature of transport is direct shipping without multiple stops. The model is solved by a heuristic method such as priority-based Genetic Algorithm (pb-GA) [24].

Generally, the deterministic problems found in the literature are the total cost minimization based on location and transportation strategies. They are also categorized as mini-sum problems [42, 69]. The target is satisfaction of customer demands with high quality service provision. Regardless of the number of commodities involved, and other attributes, the objective of the multi-level FLP is to design a distribution network for efficient transfer of goods from supply to demand points. The structure of networks such as the number of facilities at different layers, their locations and capacities need to be determined optimally.

All of the previously discussed problems are deterministic that do not take into account the uncertainties or risks in the modelling or planning process. The next subsection considers studies that involve randomness (uncertainties or risks) concept.

2.2.3 Stochastic and robust multi-level problems with exact and heuristic solution methods

Having discussed the various deterministic multi-level FLPs under exact and heuristic solution methods, we now present the stochastic models and their solution approaches. In FLPs, plants, DCs, transportation network and other facilities can work for several years or decades, during which time the environment in which they operate may change significantly [76]. The parameters such as costs, demands, travel times, and other inputs to hierarchical facility location models, may be highly uncertain. Thus, the development of models for multi-level facility location under uncertainty are of great importance [69, 74, 76]. There are a large number of approaches that have been proposed for optimization under uncertainty in general, which have also been applied to hierarchical facility location problems [76].

As defined by Snyder [76], risk and uncertainty are situations where randomness occurs. The problems with risk situations are the one with known probability distributions to the decision maker, and such problems are known as stochastic optimization problems. Under uncertainty conditions, parameters are uncertain, and probabilities are not known. These problems are termed as robust optimization problems [10, 76]. This part of the literature study discusses the various stochastic and robust problems which appeared in the context of hierarchical facility location problems.

A study carried out by Min and Melachrinoudis [60] is a three-level hierarchical location-allocation application problem based on the banking industry. It addresses the internal dynamics and functional dependence of different hierarchies of banking services. Three layers considered for banking services are automatic teller machines (ATMs), branch bank offices, and main banks [60]. "In the banking industry, banking services are often rendered to the clients through successive levels of banking facilities" [59]. In the lower level, ATMs or drive-in banks allow clients to deposit or to receive cash, and get a statement of current-account balance. Branch bank offices at the next level of hierarchy, provide a variety of larger order services such as opening accounts and maintaining safe deposit boxes. These are in addition to basic services provided by ATMs. At the highest level of the hierarchy, the main bank offers the extended services such as corporate loan financing, credit approvals, and long-term investment consultation [60].

The banking facilities location-allocation decisions, should comparatively be evaluated according to the following conflicting criteria: the maximization of the market profitability of open banks, the maximization of the customer drawing power of open banks, and the minimization of all the risks associated with resource commitments made to open banks [60]. Through the planners guidelines for evaluating the profitability, accessibility and risk of bank location-allocation, a chance-constrained goal programming (CCGP) model is developed [60]. However, due to the stochastic nature of risk, a chance-constrained (probabilistic constraint) risk goal is developed. The objective function is a deterministic nonlinear integer goal programming model computed optimally using LINGO's (a software) modelling language. A similar study in this area by Hochreiter and Pflug [31] based on heuristic algorithms, can be consulted.

Hosseinijou and Bashiri [32] presented a stochastic transfer point location problem in a planar topology. They used the expected value approach to formulate the problem's objective. The model considered coordinates for the three layers namely; facility, transfer point and demand points. The coordinates from the three layers are used in computing distances. The coordinates of demand points are independent random variables (stochastic), with a bi-variate uniform distribution. Thus the problem is to find the optimal location of the transfer point, such that the maximum expected weighted distance from the fixed facility to all demand points through the transfer point is minimized. In this problem, only the single facility is considered, one transfer point, and several demand points. The model is computed numerically using "fminimax" in Matlab software package [32]. The problem can be applied to a situation where a city and its dwellers are uniformly distributed in the square region, and a transfer point is to be located. This transfer point (e.g. helicopter pad) is to be located so as to serve accidents such as earthquakes, floods, medical emergencies, etc [32].

A study by Tadei et al. [77] addressed the problem of locating transshipment facilities for freight transportation from origin to destination through transshipment facility for maximization of the total net utility. This is done by taking the expected total shipping utility minus the total fixed cost of the facilities [77]. The problem considers the handling utilities (costs) at the transshipment facilities as stochastic variables. The handling operations are organized in alternative scenarios, and finite capacity and congestion effects make costs to be stochastic variables with unknown probability distributions [77]. This process can be termed as the robust optimization problem as defined by Snyder [76]. The problem is computed heuristically using Lagrangian relaxation. A similar problem by Tadei et al. [78] is presented with general transportation costs from origin to destination as a stochastic variable.

A stochastic supply chain network model under risk, with three tiers of suppliers, distribution centres (DCs) and customers is studied by Azad & Davoudpour [8]. They considered the customers' demands as stochastic variables using a financial risk measure (conditional value at-risk (CVaR) measure). The problem is formulated as a convex mixed integer programming and a heuristic method is developed to solve the problem. In the model, different DC capacity levels were used as in Amiri [7]. The authors also considered the routing design between DCs and customers [8].

A multi-period study by You et al. [89] is a global multi-product chemical supply chain with demand and freight rate as stochastic variables. It is a case study where the multi-period planning model takes into consideration the production and inventory levels, the transportation models, the times of shipments and customer service levels [89]. This real world application study originates from the Dow Chemical Company, which supplies multiple products to world-wide customers [89]. The company has several global business units (DCs) to supply to its customers, and even customers can be supplied directly from manufacturing plants (multi-sourcing). In the solution methods, the authors incorporated the Monte Carlo sampling in a stochastic programming. They also proposed a simulation framework based on an iteration method for solving deterministic and stochastic problems [89]. The study considers a planning horizon as one year, and a month as a planning period.

A robust optimization model by Butler et al. [15] focuses on the strategic-production and distribution planning for a new product in the market environment. There is no historical data for the new product, and hence the probability distribution is not known. The study is a supply chain based on a new product having uncertainties in the demand, as well as the cost and changes in the market conditions over time to be addressed [15]. The model is implemented as the robust Lagrangian model using the mixed integer programming solver of CPLEX 7.5 (ILOG, Inc., 2001) [15].

In the literature, the stochastic or probabilistic situations have also been observed in customer demand, travel times, number of customers and other input data in the context of VRPs and LRPs [19, 47, 51, 70, 71, 74, 82]. The stochasticity due to travel times have been considered in VRPs where there is a delay to the destination due to several factors. Factors revealed from literature associated with the delay are: traffic jams due to road capacity, road blocks as a result of traffic authorities, car accidents; and weather and floods [33, 47, 51, 70, 82]. The consideration for these factors are mostly on a daily basis. So there will be the increase of travel times and hence travel costs that need to be considered prior to planning decisions.

Generally, the stochastic multi-level FLPs discussed in the literature have considered various random variables or parameters. The research in this thesis, considers the stochastic transportation links between the DCs and customer points (CPs) during the rainy season in Tanzanian maize crop transportation network. On the other hand, the transportation links between production centres (PCs) to DCs are reliable since inter-regional roads are paved, and it usually takes place during the summer season. It is a multi-period planning horizon (rainy season), where the period of time is 17 weeks. Each week's shipping of goods is required to meet the known demands at CPs. The weekly actual amount of rainfall data over 4 years will be used in our study.

2.3 Stochastic programming

2.3.1 Theoretical background to stochastic programming

The solution processes or procedures for stochastic problems are known as stochastic programming (SP) [17, 19]. Optimization where some input data is assumed not available with certainty during the decision time; is termed as stochastic programming [19, 74]. Shapiro and Philpott [72] defined SP as an approach for modelling optimization problems that involves uncertainty. The uncertainty is mostly characterized by probability distributions for the random parameters [17]. Many real life problems have parameters that are not known precisely due to various reasons. Corrigall [17] in his dissertation suggested two main reasons, first is the lack of reliable data or simple measurement error. The second reason termed as a fundamental reason, is for some data being representing information of unobserved events. For example, future product demand and market price are difficult to be known in certainty [17]. Thus, the presence of random variables or parameters among the input data in the model gives the necessity of stochastic optimization or programming.

Generally, stochastic programs are mathematical programs in which some coefficients or parameter values incorporated into the objective model and/or constraints are usually uncertain. The modelling or optimization of these stochastic programs is termed as stochastic programming [17, 19]. So the stochastic programming is the study of optimal decision-making for stochastic programs that deal with algorithmic optimization procedures [17].

This type of modelling and solution approach has increasingly been used recently in real life problems where uncertainties are likely to occur. The viability of SP owes much to caused several reasons including the current advancement of computer hardware and software technologies; as well as the sophisticated and advanced software for solution methods in particular, that has contributed much to the current situation [19]. SP simultaneously combines the operation research or management science models and statistical randomness models to create a robust decision making tool [19, 74]. The operation research or management science models are deterministic models which are mostly linear and integer programmings. On the other hand, statistical randomness models are based on probability distributions where historical data is known or can be estimated. In this case, scenario generations are possible so long as there are finite number of discrete realizations [19].

Thus, as proposed by Silverwood, [74], "stochastic programming is the replacement of deterministic values in an optimization problem with random variables or probability distributions describing the true nature of the parameter; thus it allows management decisions which are usually made in uncertain environments to be considered more accurately with fewer assumptions".

In his dissertation, Corrigall [17] mentioned two types of stochastic programs. These are recourse problems and chance-constrained problems. For both problems, there are two ways of making decisions regarding the random parameters. The first decision making is before the observation of the outcome of the random parameters known as "here-and-now" solution. The second is a "wait-and-see" solution where the decision making is done after the outcome of the random parameters are observed. The recourse problem requires the decision to be made now and it minimizes the expected costs resulted from the consequences of that decision [17, 19].

The solution obtained from different stochastic problems are known as uncertainty or stochastic measures in comparison to the deterministic or with other stochastic solutions [11, 17, 19]. These are the differences between the solutions of deterministic and stochastic models and also between the solutions of stochastic models themselves. The two known stochastic measures are the *value of the stochastic solution* (VSS) and the *expected value of perfect information* (EVPI).

VSS is defined as the difference between a solution of the deterministic model (expected deterministic solution) and a solution of the stochastic model obtained under "here-and-now" method. If Z_{EV} is the expected solution of the deterministic model and Z_{HN} is the solution of the stochastic model through "here-and-now" procedures, then $VSS = Z_{EV} - Z_{HN}$. The solution of "here-and-now" problem is also regarded as a solution of recourse problem (Z_{RP}).

This difference is considered as a measure of how much it can be saved by implementing the "here-and-now" solution as opposed to the deterministic expected value solution [19]. On the other hand, EVPI is defined as the difference between the "wait-and-see" and the "here-and-now" solutions. Given that Z_{WS} is a solution of the stochastic model for the "wait-and-see", then $EVPI = Z_{WS} - Z_{HN}$. The EVPI usually considered as the measures of the maximum amount a decision maker would be ready to pay in return for complete and precisely information about the future [11]. "A relatively small EVPI indicates that better forecasts will not lead to much improvement; a relatively large EVPI means that incomplete information about the future may prove costly" [19].

2.3.2 SP approaches and other classification of problems

Domenica et al. [19] explained the classical methods of dealing with uncertainty effects in linear and integer programming as sensitivity analysis and probability distributions. However, Domenica et al. [19] comments on sensitivity analysis that; "this approach shows a number of limitations, and may provide misleading conclusions in respect to the nature of the solutions. In general, sensitivity analysis is not a suitable approach for understanding the effects of random behaviour of the model parameters. In many real world problems, the uncertainty relating to one or more parameters can be modelled by means of probability distributions". This observation recommends that the better way of dealing with uncertainty effects is by probability distributions that are based on the possible future of realization scenarios [11, 66]. The real life applications of SP are mostly in the fields of financial planning, supply chain management, transportation logistics, telecommunications, network design, environmental planning and energy systems planning [17, 19, 72]. The study carried out in this thesis is based on transportation logistics and location-allocation decisions.

SP as an approach, has several techniques that have been developed, practiced and suited to different applications and purposes [11, 74]. Several approaches or ways of solving have been used in dealing with the effects of uncertainty. The first approach mentioned for solving SP is the expected value model which optimizes the expected objective function subject to their expected restrictions if any [19, 74].

The other methods are sample average approximation (SAA) [3, 72], chance constrained programming (CCP) [3, 17, 19, 47, 72] which dealt with uncertainty by specifying the confidence level at which the particular stochastic constraint will lie [74]. The detailed description of SAA can be found in [3, 41, 72]. More methods have been mentioned by Silverwood [74] as dependent chance programming (DCP) and scenario based analysis. Other classifications are robust stochastic programming, fuzzy programming, and stochastic dynamic programming [70]. Domenica at al. [19] gives more on pictorial framework classification of SP problems and solution methods titled " a taxonomy of SP problems" as shown in Figure 2.1. The more detailed explanations of these classifications can be found in the paper by Domenica et al [19].

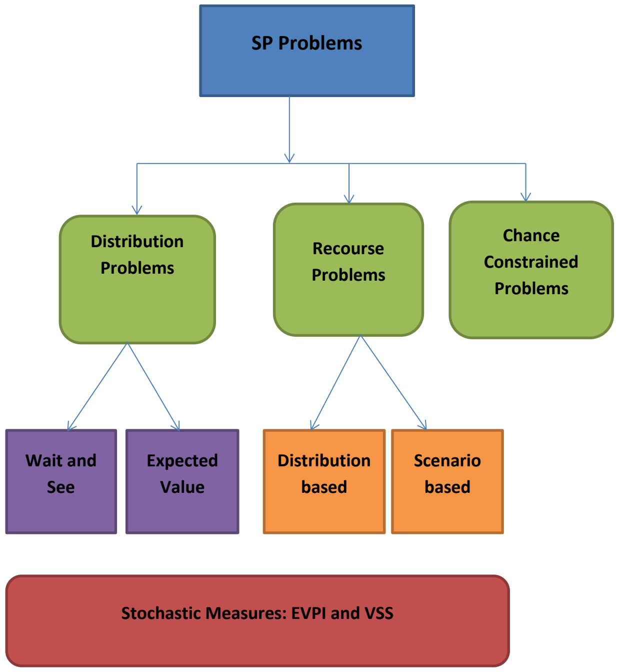


Figure 2.1: *Taxonomy of SP problems by Domenica et al. 2007*

2.4 Summary

This chapter describes in detail the literature review of multi-level FLPs. Both deterministic and stochastic models with their solution methods are described. The solution methods described are heuristic and exact. Since the stochastic model is the main challenge in this thesis, it is described in several stochastic models and their solution approaches or procedures. The main stochastic solution approaches are "here-and-now" and "wait-and-see". In this thesis, the "here-and-now" solution approach is applied.

Chapter 3

A two-level FLP for the maize crop distribution network in Tanzania

3.1 Background information

Tanzania is a country in East Africa. It is situated between latitudes 1^0 - 12^0 south of the Equator and longitudes 29^0 - 41^0 east of the Greenwich Meridian. Tanzania is a unitary republic formed after the union of two countries in 1964, Tanganyika (Tanzania mainland) and Zanzibar (made of two Islands, Unguja and Pemba). The country's total land area is 945,000 km^2 with a population of 44,928,923 (Tanzania mainland is 43,625,354 and Zanzibar is 1,303,569) as per August 2012 national population and housing census (PHC) [83]. This study considers only the Tanzania mainland part. So in this study, Tanzania means Tanzania's mainland (excluding Zanzibar).

Food is one of the basic human needs as it supports the survival of mankind in relation to other human activities. In September 2000, the United Nations set the so called Millennium Development goals (MDGs), where food security was set to be a first goal among the eight goals [84]. Each goal was set to have a specific targets and indicators in its achievement. The challenges of food security are its availability, accessibility and affordability. Tanzania is part of the MDGs that needs to prioritize food security to her people.

Food security is concerned with its availability, procurement, storage, usage and the associated distribution costs up to the final consumers. The Ministry of Agriculture, Food Security and Cooperatives (MAFSC) of Tanzania, is responsible for food security. The major cereal crops produced in the country are maize (corn), rice (paddy), millet, finger-millet, sorghum and wheat. The country's major food crops (main staple crops) are maize and rice. The real life problem considered in this thesis is maize crop production and distribution system in Tanzania. The research considers only maize crop distribution for hunger emergency as per available data. The maize crop is the only current food crop which is stored in the distribution centres (DCs) that are managed by the National Food Reserve Agency (NFRA) under the MAFSC for emergency situations [54]. Other cereal crops are not stored due to budget and space constraints [23, 85]. The emergency situations considered are acute food shortage in some places in the country (due to drought and other disasters), and corn flour price stabilization in markets, especially in urban areas. In the country, there are some common deficit zones due to drought and other weather effects like small rainfall in semi-arid areas. So, the government is responsible for food reserve and coordination.

3.2 Maize crop production and storage in Tanzania

The food crops production in the country is highly concentrated in the southern highland regions (Rukwa, Mbeya, Iringa, Morogoro and Ruvuma) and the peripheral areas of the country as shown in Figure 3.1. On the other hand, the traditional food deficit areas are located mostly in the central corridor regions (Singida, Dodoma and Tabora) and northern part (Arusha, Manyara, Kilimanjaro and Tanga), and other parts as shown in the map of Tanzania (Figure 3.1). The specific location of existing DCs (warehouses) are also shown in Figure 3.1. The DC in this context is a storage building where commodities can be stored for sometime before being taken to customers. The specific demand points (customer points); are not shown; rather some major demand zones have been marked, but the production centres are within the marked production zones, particularly in the southern highlands. It is difficulty to indicate all the 93 customer points in the map.

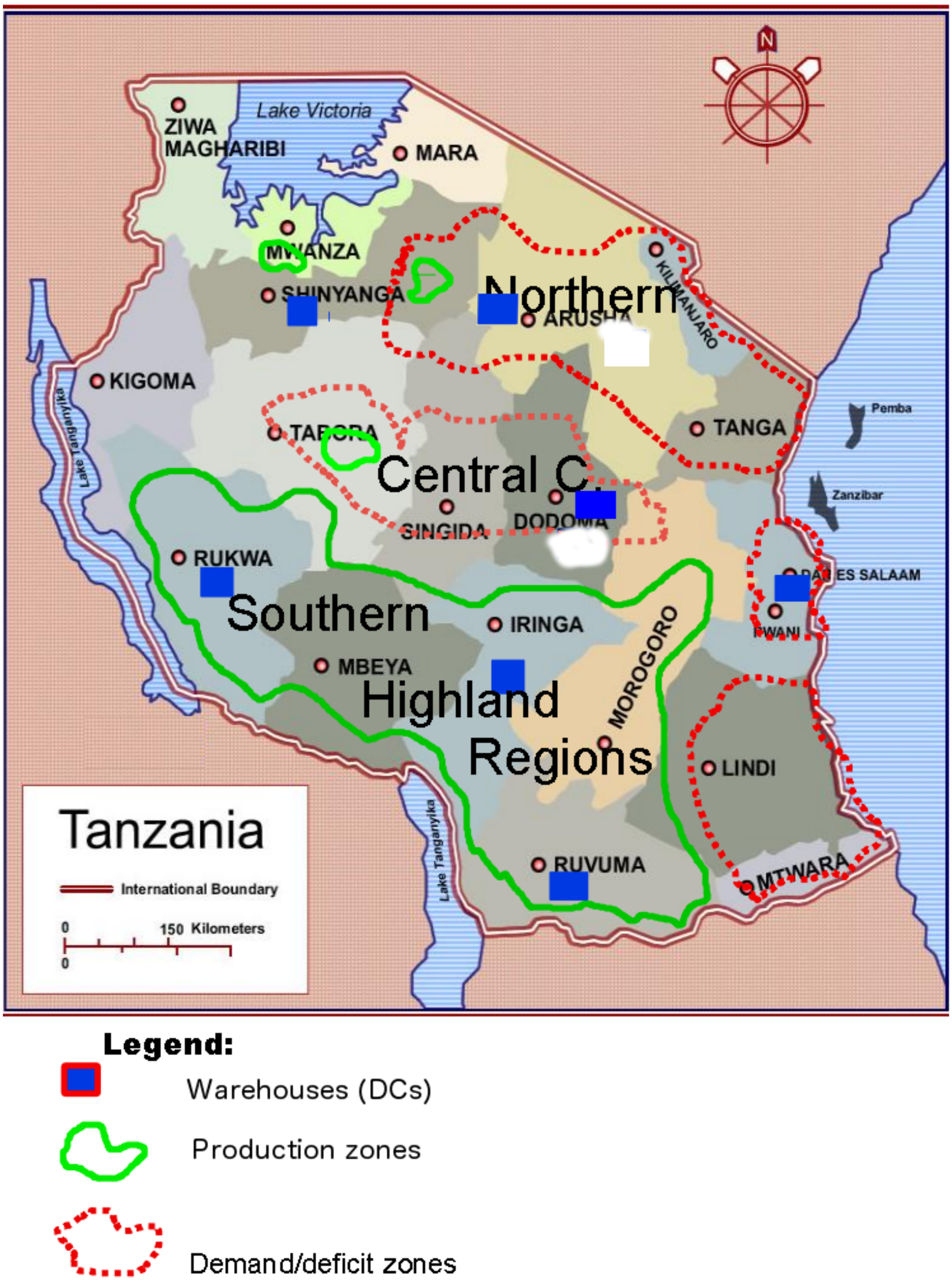


Figure 3.1: *The map of Tanzania showing the food production zones, DCs and demand zones.*

The major maize surplus production is from the four regions (known as 'The Big four') namely, Rukwa, Mbeya, Iringa and Ruvuma [23, 61, 85]. These are the specific production centers (PCs) that form a production zone in the southern highland part of the country. In this study, the PCs will form the first layer among the three layers in the two-level FLP. The maize crop are bought from this production zone by the NFRA for storage in the DCs or warehouses. Usually farmers bring their maize crop in the buying centre that is allocated in the region headquarters (town or city) of the given PC. The farmers leave the maize to dry well before removing it from the cob to be ready for selling to the NFRA.

Before reaching the customer points (CPs), the maize crop from PCs are stored in DCs which are scattered in different parts of the country. Usually the storage in the DCs is done for a year (a harvest season to the next harvest season). There are seven existing DCs with a total capacity of 241 thousand tons. These are Arusha (39 tons capacities), Dar Es Salaam (52 tons), Dodoma (39 tons), Shinyanga (14.5 tons), Makambako-Iringa (34 tons), Songea (24 tons) and Sumbawanga (38.5 tons). These DCs, as shown in in Figure 3.1, form the second layer of the two-level FLP model of the study. The first five DCs are used for storage of maize crop to be supplied to the deficit CPs throughout the country. The last two DCs, Sumbawanga and Songea, are used as reserve DCs to buffer the other five DCs. These two DCs are located in the production zones.

The third layer of the model in this study is CPs. These are specific demand points in the country to be supplied by DCs during food deficit time. As indicated in Figure 3.1, the major deficit zones are central corridor zone and the northern zone. The three layers form the distribution system that needs to be designed at minimum cost while satisfying the customers' demands.

3.3 Transportation network for maize crop in Tanzania

Throughout the production zone, there are plants or PCs where maize crop are bought from public market and then destined for the DCs. On the other hand, there are demand zones where there are specific points referred to as customer points where the stored maize crop will be transported from DCs to CPs. This section describes the three-layer transportation network.

In Tanzania, physical access to food is affected by inadequate transportation infrastructure. Due to long distances between the food producing centers, DCs and deficit zones, together with inadequate and unreliable transportation network, high transportation costs are unavoidable. For instance, the existing distribution system have distances ranging from 120 kilometers (km) to 1,348 km between PCs and DCs. The distances between DCs and CPs, on average, also range from 136 km to 360 km. This results, at times, in high food prices in deficit areas, and therefore affects access to food by both low income, rural and urban populations [61, 84]. However, the actual various data used in this thesis is presented in Appendices A, B and C are referred accordingly in Chapters 4 and 5.

In the country, the harvest season is usually between May and September every year. This is the summer season when surplus maize crop are bought from production centres and transported to DCs by mid-November for storage. The southern highland zone is the major producer of surplus maize crop and hence is the main supplier to DCs. The specific PCs in this zone are Iringa, Mbeya, Rukwa and Ruvuma which are shown in Figure 3.1. Most of the roads from PCs to DCs are well paved as most of them are linking cities/municipals of the regions in the country (see Figure 3.2). The transportation network in the summer season; in general, is reliable, and most places including the common deficit zones are not in crop deficit. This forms the first level transportation in relation to this study. The nature of route is a direct shipment as a full loaded truck will unload the whole truck to a specific DC.

Figure 3.2: *Tanzania paved roads condition (Source: Michuzi Blog 2013, Southern Highland road)*

The critical maize crop deficiencies occur mainly from the middle of December up to April, the following year [84]. During this time, the maize crop is now transported from DCs to CPs (see appendix D.4, D.5 and D.6). Throughout the demand zones or deficit areas, there are specific customer points. These CPs are district town locations (e.g. district towns which are the next large towns after provincial/state or regions' towns) where maize crop from DCs is destined. Most of the deficit zones are semi-rural areas where the roads are in poor conditions [61, 84, 85]. In addition, the deficiencies occur during the rainy season where the transportation reliability is questionable in most of the places due to rains and floods. The deficiency during the rainy season is from the fact that most of the maize crop harvested from the recent previous harvest have been consumed and also sold for various purposes. The destined maize crop to CPs are usually can be sold at subsidised price or distributed freely (See D.4, D.5 and D.6). There should be a regular weekly maize crop flow from DCs to CPs. However, this might not be possible during the rainy season as the road networks are likely to be impassable; and vehicles might have to be delayed or have to take many alternative long distance routes resulting in high travel costs due to longer travel times.

The transportation of maize crop from DCs to CPs during the rainy season forms the second level transportation of the two-level FLP and distribution network. This causes the network being stochastic. The transportation between DCs and CPs are direct shipment as in first level. This is due to long distance route to be covered and the large quantity of customer demands.

Figures 3.3 and 3.4 display the transport conditions during rainy season.

Figure 3.3: *Tanzania unpaved roads condition during rainy season (Source: Michuzi Blog 2010)*

Figure 3.4: *Tanzania unpaved roads condition during rainy season (Source: Michuzi Blog, January, 2013 at Lindi-Mtwara road)*

3.4 Framework of the proposed FLP model

Given the demand scenario and the nature of the distribution network, an optimal number of DCs, their locations throughout the country and sizes are imperative. This is from the fact that the road links between these DCs to the CPs are stochastic in nature. Under these circumstances, the problem is to find the number of DCs; and their sizes and locations optimally so as to meet all demands at CPs per week during the rainy season.

Figure 3.5 is an illustrative sketch of the study as a network framework. There are three layers and its transportation links as shown in the figure. From the figure, the locations-allocations as shown by bold arrows are optimized by optimization techniques. The direct shipping (transportation) take place from PCs to DCs and then from DCs to CPs. The dashed arrow from DCs to CPs represents the stochastic transportation link, while the links from PCs to DCs, are deterministic (not dashed arrow).

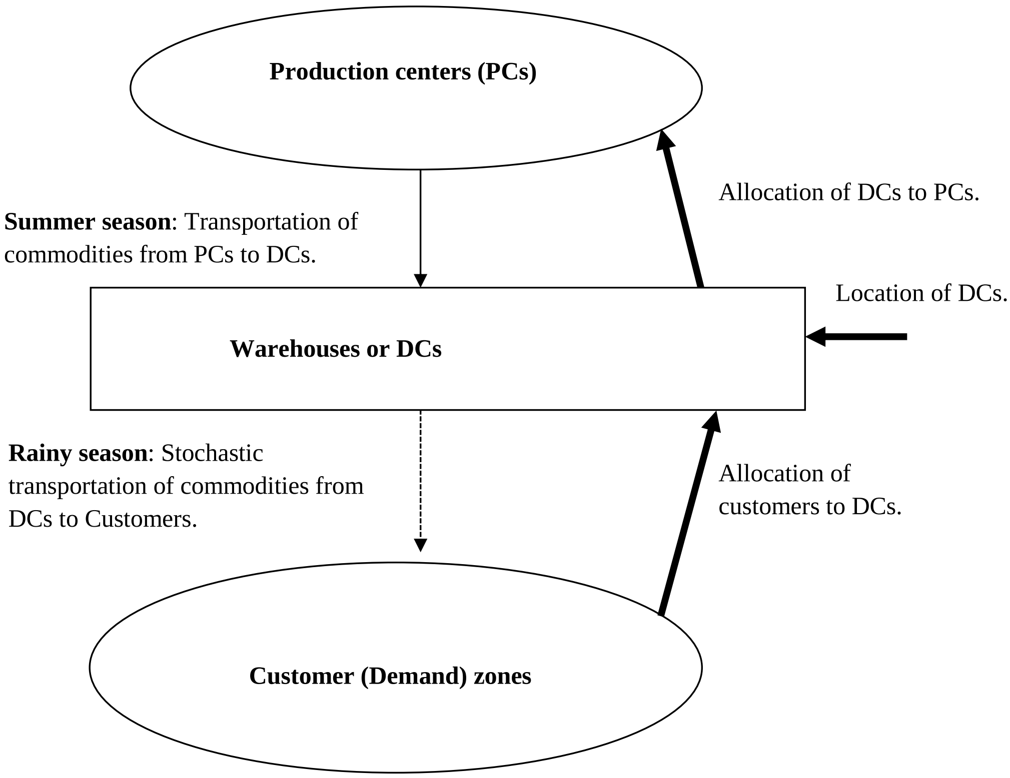


Figure 3.5: *The framework of three layers and two-level FLP model*

The decision tasks are: where to locate the DCs (location decisions), how to allocate the DCs to the production centers and demand points to the DCs (allocation decisions); and hence to design the direct routes for serving the distribution network. The routing or shipping levels (direct delivery) are from the PCs to the DCs in summer season, which is deterministic; and from DCs to CPs in rainy season when road links are stochastic. The number and sizes of DCs are also determined optimally.

Table 3.1 gives the summary of PCs, DCs and CPs; and their location zones within the country. The southern highland zone is the only zone with PCs and also 3 DCs out of the 7 DCs. Notably, the Ruvuma, Rukwa, Kigoma and the Dar Es Salaam regions have no CPs. All the mentioned regions except Dar Es Salaam, are self-sufficient in cereal crops production and the surplus production is always expected. The Dar Es Salaam region is the place of city dwellers that is populated mostly by employed people who earn incomes. Food deficiencies are mostly realized by people living in the rural areas. The list DCs and their respective CPs of the collected actual distribution data from 2004 to 2010 is summarized in Tables B.5 and B.6.

Table 3.1: *PCs, DCs and CPs distribution in the country*

Zone	**Specific Regions**	**# of PCs**	**# of DCs**	**# of CPs**
Southern Highland	Iringa, Rukwa, Mbeya, Ruvuma	4	3	9
Central Corridor	Dodoma, Singida, Tabora	0	1	17
Northen	Arusha, Manyara, Tanga, Kilimanjaro	0	1	24
Southern Corridor	Mtwara, Lindi	0	0	8
Eastern	Dar Es Salaam, Coast, Morogoro	0	1	11
Lake Victoria	Shinyanga, Mwanza, Mara, Kagera, Kigoma	0	1	24
Total		4	7	93

3.5 Significance of the study

This study is useful as it will provide a mechanism for reducing food prices within the country. This will contribute to the June 2009 Tanzania's policy of prioritizing the importance of agriculture also known as ‘Agriculture First’ (Kilimo Kwanza) and as stipulated in its ten implementation pillars. For instance, one of the pillars states the need for the identification of priority areas for strategic food commodities in order to increase the country’s food self-sufficiency. The pillars also state a price stabilization mechanism, which includes the expansion of storage capacity and improvement of railway and road systems [2]. Furthermore, in the 2012/2013 Ministry of Agriculture budget speech, the price stabilization for maize flour (milled maize crop) in cities was addressed. The availability of maize crop in the DCs was also to be used for milling in order to get maize flour. The government is not responsible for milling rather it is done by the private sector. Subsequently, the government sold 41,000 tons of maize crop in the public market. As a result the maize flour price decreased by about 38% in different regions [14].

3.6 Summary

Chapter 3 contains the explanations for the practical problem of maize crop transportation in Tanzania. It describes the three main nodes which are production centres, the distribution centres and customer points in relation to maize crop. The distribution network in the three nodes is formed by paved and unpaved roads in the network that are affected by rainfall. This results in stochastic distribution network for maize crop transportation in Tanzania.

Chapter 4

Deterministic model for the two-level facility location problem

4.1 Mathematical model

In Chapter 3, a two-level facility location problem we are studying has been described. This chapter presents the mathematical model and its solution.

Deterministic models for multi-level or two-level FLPs as presented in the literature are for either single or multi-product, and for single or multi-period. Here, we consider a deterministic model with a single-product and a single-period planning horizon. Our aim is to design a deterministic capacitated two-level FLP model and to optimize location, allocation and hence transportation decisions for the distribution network. The model will locate the most economical set of DCs (optimal DCs to be selected), and then assign customers to the selected DCs. Concurrently, the selected DCs will be allocated to PCs without violating capacities in both PCs and DCs. From these locations and allocations, the direct transportation decisions will be implemented to meet the customers' demands. In the model, we assume that each customer has a known demand which can be met in a single period independently from other customers.

We now present the deterministic mathematical model for a two-level, single commodity with a single period FLP. The single period for the demand to be met consists of four months - January to April - in a year. The model is adapted from Elhedhli et al. [22] and other references [8, 28, 42, 45, 50, 69].

The notations used in the model are as follows:

J: J is the index set for production centers (PCs), where $j \in J$ and $|J|$ denotes the total number of PCs, i.e., PC_j, $j \in J$. The PCs' locations are fixed together with their capacities.

K: K is the index set for distribution centers (DCs), where $k \in K$ and $|K|$ denotes the total number of possible DC sites, i.e., DC_k, $k \in K$. We also use the convention that DC_k is the DC located at site k.

L: L is the index set for customer points (CPs), where $l \in L$ and $|L|$ denotes the total number of CPs, i.e., CP_l, $l \in L$. CP_l have fixed location together with their associated demand, D_l.

R_k: R_k denotes the set of capacities of DC_k. Hence $R_k = \{V_k^1, V_k^2, ..., V_k^{|R_k|}\}$.

S_j: Supply (production capacity) of a maize crop at PC_j.

D_l: Total demand for four months for maize crop at CP_l transported only once in a week. We considered this amount to be transported in the first week of the four months period (January to April) of a year.

F_k^r: Total fixed annual operating cost in US dollar for a DC with V_k^r, i.e., $r \in \{1, 2, ..., |R_k|\}$.

C_{jk}: A road distance in kilometres from PC_j to DC_k, $j \in J$, $k \in K$.

T_{kl}: A road distance in kilometres from DC_k to CP_l, $k \in K$, $l \in L$.

λ: This is a unit cost for transferring 1 ton of maize crop for a 1 km distance, and the cost is in \$ (per km per ton).

Decision variables for the model:

X_{jk}: Amount in tons flow from PC_j to DC_k.

Y_{kl}: Amount in tons flow from DC_k to CP_l.

Z_k^r: A binary location variable that will be 1 if a DC_k is selected with a capacity V_k^r, and 0 otherwise. When a single capacity[1] per DC_k is used we ignore the superscript r in Z_k^r, V_k^r and F_k^r. Here the choice of capacity is not a decision variable but the choice of site k is.

The resulting mixed integer linear programming can then be formulated as:

$$\underset{X_{jk},Y_{kl},Z_k}{\text{Min}} \quad \lambda\left(\sum_j\sum_k C_{jk}X_{jk} + \sum_k\sum_l T_{kl}Y_{kl}\right) + \sum_k F_k Z_k, \tag{4.1}$$

$$\text{subject to} \qquad \sum_k X_{jk} \leq S_j, \forall j, \tag{4.2}$$

$$\sum_j X_{jk} = V_k Z_k, \forall k \tag{4.3}$$

$$\sum_l Y_{kl} \leq V_k Z_k, \forall k \tag{4.4}$$

$$\sum_k Y_{kl} = D_l, \forall l, \tag{4.5}$$

$$X_{jk} \geq 0, \forall j, k, \tag{4.6}$$

$$Y_{kl} \geq 0, \forall k, l, \tag{4.7}$$

$$Z_k \in \{0, 1\}, \forall k. \tag{4.8}$$

The following are the explanations of the model:

- The objective function (4.1) minimizes the total distribution cost, e.g. transportation cost from PCs to DCs and DCs to CPs, and fixed annual operation costs, F_k, for DCs and the corresponding capacities V_k.

- Constraints (4.2) are the supply constraints (PCs' capacities), where the amount to be transported from a PC_j to the selected DCs, must not exceed its capacity, S_j.

[1]Model for the multiple capacities per DC will be presented later on.

- Constraints (4.3) refer to the amount supplied from PC_j to all selected DC_k, must satisfy the DCs' capacity V_k.

- Constraints (4.4) refer to the amount supplied by DC_k to all CP_l, $l \in L$, without exceeding V_k. V_k (respectively F_k) are the values currently used in the current transportation network with five DCs, e.g. $DC_1, ..., DC_5$. The capacities V_k, $k \in K$, are not necessarily equal. This also holds for the case of three new DCs we are proposing as per Tanzania government's plan.

- Constraints (4.5) represent the amount to be transported from all DC_k, $k \in K$, to the CP_l, must meet a demand, D_l, at the CP_l.

- Constraints (4.6) and (4.7) are the non-negativity restrictions.

- Constraints (4.8) are binary variables.

The total number of decision variables for the model is 490.

4.1.1 The expected optimized results

In the optimization results four decisions are sought. These are as follows:

(a) Location decisions: Where and how many DCs to locate out of $|K|$? The optimal decisions to be made here are the number of DCs and their physical locations (i.e., values of Z_k, or Z_k^r in the case of multiple capacities).

(b) Allocation decisions: Which DCs to be served by which PCs (i.e., the pair (PC_j, DC_k), $j \in J$, $k \in K$) and which CPs are to be served by which selected DCs (i.e., the pair (DC_k, CP_l), $k \in K$, $l \in L$)? The optimal results will give the allocations of DCs to PCs and CPs to DCs simultaneously.

(c) Transportation decisions: From location and allocation decisions, what is the amount to be transported from PCs to DCs (i.e. values of X_{jk}) and DCs to CPs (i.e. values of

Y_{kl})? The transported amounts, X_{jk} and Y_{kl} will be determined. Hence, direct shipment routes designing from PCs to DCs and also from DCs to CPs will be established.

(d) Capacity value decisions: What is the best capacity for each DC_k to be selected from $\{V_k^1, ..., V_k^{|R_k|}\}$. For the case of a single capacity per DC_k the decision variables Z_k will suffice. In this case the total number of variables is $|K|$. For multiple capacities per DC_k, the total number of decision variables is $|K| \times |R_k|$.

The optimal solutions to the above mentioned decisions are important for the government of Tanzania to redesign the current distribution facilities.

4.2 Data and results using the deterministic model

4.2.1 Data for the deterministic model

The considered research data are from Tanzania where the three layers namely: PCs, DCs and CPs are used. Road connections to the three layers form the production, storage and distribution network.

The major maize crop production areas consists of four PCs (Iringa, Mbeya, Rukwa and Ruvuma). Surplus maize crop production from these PCs are bought and then transported through roads or railways to DCs which are allocated in different parts of the country as shown in Figure 3.1 and in Table 3.1. This study considers only transportation by roads as per data availability. In this study, the total capacity of all four PCs, $\sum_{j=1}^{4} S_j$, is 532,000 tons as presented in Table B.4. These data are based on annual production capacity of 2011/2012.

The existing distribution system consists of seven DCs which are Arusha, Dar Es Salaam (Dar), Dodoma, Shinyanga, Makambako, Songea and Sumbawanga. In the existing distribution system, Songea and Sumbawanga DCs are used as reserve DCs to buffer the other five DCs and are not used to supply the CPs. They are also used as storage for export to neighbouring countries. From now on they will be referred to as storage facilities rather than DCs. The total capacity of the remaining five DCs, $\sum_{k=1}^{5} V_k$, is 178,500 tons as presented in Table B.2.

As per the government's plan, due to the increased production capacity and demands, three additional new DCs are to be built with the total capacity of 159,000 tons (53,000 tons each DC, see Table B.2) as documented in Figure C.2. The new DCs are located in the headquarters (city) of the regions (similar to province or state) that have the highest customers' demand based on the 2004 - 2010 maize crop distributions. The proposed new DCs' names are Babati (DC_6), Mwanza (DC_7) and Tanga (DC_8). The construction or establishment costs for new DCs are not included in this study, but the fixed annual operating costs are. There will be a total of eight DCs after the new DCs have been established. Given the sites of the eight DCs and their corresponding capacities, optimal number of DCs have to be found. When there are more than one capacities per DCs, optimal capacity of each selected DC has to be found. The fixed annual operating cost for each of the eight DCs depends on its capacity as shown in Appendix C, Figures C.4 and C.5 together with how these costs have been obtained. The Tanzania shillings conversion rate to USA $ for fixed annual operating cost is based on 2012 exchange rates [13].

The CPs form the last layer of the distribution network. In this study, the customers (CPs) are classified as 93 districts as obtained from 2004 to 2010 maize crop distribution data. This data was collected from the head of the disaster management in the Prime Minister's office, in January 2011 (See copy of attached letter in Figure C.7). The 93 CPs are listed in the first column in Tables B.7, B.8, B.9 and B.10. The total demand from all 93 CPs, $\sum_{l=1}^{93} D_l$, is 145,144 tons. Within the period of 2004 to 2010, each CP had an annual demand. For each CP the annual maximum demand (i.e. maximum annual demand for each CP in our

2004-2010 data) is used to calculate the total demand. Hence 93 such maximum demands are added together to obtain 145,144 tons. Each CP's annual maximum demand value is presented in Table A.13. Within a period of 2004 to 2010 some districts had been in food shortage in all years (as per available data) and others once or more with minimum of 32 tons of Mafia CP in 2006 (see Tables A.14, A.15, A.16 and A.17).

It can be seen that there is a high difference between the total annual demand at CPs (145,144 tons), total DCs' capacity (241,000 tons for all seven DCs) and the total annual production at PCs (532,000 tons). The surplus maize crop are exported to neighbouring countries such as Somalia, South Sudan and Kenya as addressed in 2012/13 budget speech [14]. In addition to the two storage facilities at Songea and Sumbawanga for exporting to neighbouring countries, it is quite clear that additional DCs need to be built. The government of Tanzania also keeps a safety level stock for emergency situations which might happen within the country. For example, in 2012, an estimated 41,000 tons of maize crop were sold at domestic food crop market in certain towns and cities for price stabilization as explained in [14]. So the extra maize crop stocked in DCs are also sold to the private business people for milling and resale the maize flour to public in agreed government instructed prices. Through the NFRA policies, they also hire the unused DCs' capacity to private sector as explained in the general information, Appendix A. On the other hand, the private sector companies and other local private business people are buying surplus maize crop from PCs for trading within and outside the country [62]. Thus the involvement of private sector in the maize crop distribution system help to balance the surplus maize crop in PCs and DCs.

Generally, the research data for the deterministic part is from the four sources based on Tanzania food distribution system. These sources are the Tanzania National Roads Agency (TANROADS), Ministry of Agriculture, Food Security and Cooperatives (MAFSC), National Food Reserve Agency (NFRA) and the disaster management department in the Prime minister's office. The letters requesting access to the respective data sources as presented are shown in attached copies, Figures C.7 and C.8. The details on each source and type of data obtained are found in Appendix A.

4.2.2 Results using the existing distribution network

This subsection considers the existing system of maize crop distribution in Tanzania. The current distribution network has five DCs each having fixed capacities, $\hat{V}_k$. The five DCs are sites listed as $K = \{Dar, Arusha, Dodoma, Makambako, Shinyanga\}$. The listed names are the specific city or town location within a region. Some regions have the same name as its headquarter city. From now on, DCs and PCs will be denoted in terms of their indices as shown in Table 4.1. The computational experiments considers the cases; Case 1 and 2, as explained below.

Table 4.1: *Notations for DCs and PCs.*

DCs	DC_k	**PCs**	PC_j
Dar	DC_1	Iringa	PC_1
Arusha	DC_2	Mbeya	PC_2
Dodoma	DC_3	Rukwa	PC_3
Makambako	DC_4	Ruvuma	PC_4
Shinyanga	DC_5		

There are several common inputs to be used in Case 1 and 2. These are $|J| = 4$, $|K| = 5$, and $|L| = 93$. Other common inputs are the PCs' fixed capacities, S_j, as shown in Table B.4, distances C_{jk} (Table B.1) and T_{kl} (Tables B.7, B.8, B.9 and B.10). The distances in the respective tables are only for the first five named DCs. The CPs' demands, D_l, $l = 1, 2, ..., |L|$, are given as inputs to the model in all computational experiments, and they are given in Table A.13. We have also used the unit transportation cost $\lambda = \$0.10795$ (per *km* per *ton*) based on 2010 conversion rate between Tanzania currency and USA $ [12, 13]. The unit transportation cost estimated is based on NFRA (National Food Reserve Agency) maize crop transportation cost in 2010 as shown in Figure C.1. We have used CPLEX software (IBM ILOG Optimization studio) for all the computational experiments. We have not imposed any stopping criteria; and the program will stop when it cannot enumerate any more improved solutions.

Case 1 and computational results

Here, we consider the five DC sites together with their current capacities, $R_k = \{\hat{V}_k\}$. In this case, the optimization will be performed with respect to (a), (b) and (c) as in subsection 4.1.1. The model stated by (4.1) - (4.8) is used for optimization. The purpose of this case is to see if the current network is optimal.

The optimized results are summarized in Table 4.2 where the first 5 columns contains some inputs to the model.

Table 4.2: *Location allocation results for true capacity in Case 1.*

DC_k	$\hat{V}_k$	$\hat{F}_k$	PC_j	S_j	Z_k	PC_j^s	$\sum_j X_{jk}$	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	52,000	340,340	PC_1	100,000	1	PC_1; PC_2	22,000; 30,000	28	39,361
DC_2	39,000	255,260	PC_2	251,000	1	PC_1	39,000	18	39,000
DC_3	39,000	255,260	PC_3	140,000	1	PC_1	39,000	31	39,000
DC_4	34,000	222,530	PC_4	41,000	1	PC_2	34,000	11	13,283
DC_5	14,500	94,900			1	PC_2	14,500	10	14,500
Total	178,500	1,168,290		532,000			178,500	98	145,144

The last 5 columns in Table 4.2 present the results obtained. For example, the variable values Z_k is used to show if the corresponding DC has been selected. The selected DCs have to be supplied from the PCs and this has been shown in column 7. The notation PC_j^s in this column is used to denote the PC_j that are the suppliers of the respective DCs. For example, it can be seen from the first entry of column 7 that PC_1 and PC_2 served the DC_1. Column 8 shows the amount of supplies received by each DC from the corresponding PCs. For example, the second entry of column 8 shows that DC_2 received 39,000 tons from PC_1. A comparison of columns under $\hat{V}_k$ and $\sum\limits_j X_{jk}$, shows that the full capacity of each DC is utilized.

We have introduced the notation L_k to denote the set of CPs (where $|L_k|$ is the number of CPs) served by DC_k. Hence, the total shipment to these CPs from the DC_k is $\sum\limits_{l=1}^{|L_k|} Y_{kl}$, shown in the very last column. For example, DC_1 supplied to 28 CPs with a total of 39,361 tons which is within its capacity. Note that, a CP can get supply from more than one DC under the so called multi-sourcing. Hence, $\sum\limits_{k=1}^{|K|} |L_k| \geq |L|$, as can be seen at the last entry in column under $|L_k|$ ($\sum\limits_{k=1}^{|K|} |L_k| = 98 > |L|$). In the results, the total demand of 145,144 tons from all CPs are satisfied (see the total value at the last column, Table 4.2).

With respect to the location decision, Table 4.2 shows that all five DCs have been selected as shown in the column under Z_k.

With respect to the allocation decision, it can be seen in Table 4.2 that all five DCs are supplied by PC_1 and PC_2 only as shown on the column under PC_j^s. This clearly shows that the existing network results are different from the manually operated system since the two PCs (PC_3 and PC_4) are never used. This is based on the fact that the current network has been using PC_3 and PC_4 as shown in Table 4.3. Data in Table 4.3 were formed using data from Tables B.5 and B.6, and Appendix C (Figure C.1) for the year 2010. PC_1 and PC_2 are the largest producers among the four PCs as shown in Table 4.4. This table shows the different annual production capacities for all the four PCs [23]. Table 4.2 also shows that

PC_1 is the only PC to supply its full capacity to the DCs.

In addition, results obtained by us are in disagreement with the data used in the current network with regard to shipments between DCs to CPs. This can be seen by comparing the results under $|L_k|$ in Table 4.2 with the data in the last column of Table 4.3. The CPs to DCs allocations under $|L_k|$ for $\hat{V}_k$ are detailed in Table B.11.

Table 4.3: *PCs to DCs supplies from manually operated current network.*

DC_k	$\hat{V}_k$	PC_j	PC_j^s	X_{jk}	$\|L_k\|$
DC_1	52,000	PC_1	PC_1, PC_3, PC_4	6,305; 61; 153	26
DC_2	39,000	PC_2	PC_3	9,867	16
DC_3	39,000	PC_3	PC_3	4,009	12
DC_4	34,000	PC_4	PC_3	7,523	9
DC_5	14,500				30
Total	178,500			**27,918**	**93**

Table 4.4: *The summary of PCs annual maize crop total production capacity in tons.*

PC_j	Year					Average
	2005/06	**2006/07**	**2007/08**	**2008/09**	**2009/10**	
PC_1	412,762	474,270	384,273	443,905	393,164	421,675
PC_2	293,725	349,094	494,810	393,406	621,545	430,516
PC_3	270,564	226,524	351,013	375,732	372,830	319,333
PC_4	211,789	138,269	236,602	176,876	289,588	210,625

In Case 1, the total distribution cost that includes transportation costs and DCs' annual fixed operation cost is $15,570,885.08. This is the minimum objective value obtained after 27 seconds.

In Case 1, all DCs uses $\hat{V}_k$ as their true capacities. However, at times the demand at CPs increases and therefore replenishment are needed at DCs in order to cater for the additional demand at CPs. The capacity of DC_5 is an example of this situation as it can be seen by comparing its capacities shown in Tables 4.2 and 4.5. The replenishment is carried out from the two storage facilities, Songea and Sumbawanga. On the other hand, the actual capacity used may not exceed the true capacity. Therefore the true capacity and the capacity used (actual capacity) may not be the same. Since the capacity used by DC_k varies from year to year, we took the maximum actual capacity, $\bar{V}_k$, used by DC_k during 2004 - 2010. This actual capacity for the existing network, is also considered as the manually operated existing distribution network. We have re-run the program using $\bar{V}_k$ instead of $\hat{V}_k$ (true capacity) and results are summarized in Table 4.5. Other inputs to the model (4.1) - (4.8) remain the same.

Table 4.5: *Location allocation results for actual capacity in Case 1.*

DC_k	$\bar{V}_k$	$\bar{F}_k$	PC_j	S_j	Z_k	PC_j^s	$\sum_j X_{jk}$	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$
DC_1	33,190	217,229	PC_1	100,000	1	PC_1	33,190	26	33,190
DC_2	38,532	252,192	PC_2	251,000	1	PC_1	38,532	18	38,532
DC_3	24,650	161,334	PC_3	140,000	1	PC_1	24,650	13	24,650
DC_4	9,843	64,422	PC_4	41,000	1	PC_1; PC_2	3,628; 6,215	9	9,843
DC_5	38,929	254,790			1	PC_2	38,929	29	38,929
Total	145,144	949,967		532,000			145,144	95	145,144

Columns of Table 4.5 contain the same headings as in Table 4.2. We analyze the results with respect to (a) - (c) of subsection 4.1.1.

In the location decision, all the five DCs are selected as shown in column 6. This is due to the fact that the DC capacities are equal to total CPs' demands. The columns under $\bar{V}_k$ and

$\sum_{l=1}^{|L_k|} Y_{kl}$ have the same values.

The allocation decision in column under PC_j^s, shows that only two PCs, PC_1 and PC_2, have supplied to all five selected DCs as in the case of Table 4.2. This also clearly shows that the current network is not optimal. The CPs to DCs allocations under $|L_k|$ are detailed in Table B.12.

The amount of maize crop transported from DCs to their respective CPs are detailed in Table B.12. The overall total network distribution cost is \$13,224,626.75 with the execution time of 23 seconds. This cost is about 15% less than the cost associated with the true capacity in Table 4.2, i.e., a net saving of \$2.3 million. This reduction in cost is partly contributed by DC_5 which having the larger capacity than in Table 4.2, now serves more CPs, i.e. 29 CPs (see Table 4.5) as opposed to 10 in Table 4.2.

Case 2 and computational results

In this case, the main focus is given to the use of multiple capacities per DC. Unlike Case 1, here capacity of a selected DC is an optimization decision. Hence the mathematical model used in this case is re-written as follows:

$$\underset{X_{jk}, Y_{kl}, Z_k^r}{\text{Min}} \quad \lambda \left(\sum_j \sum_k C_{jk} X_{jk} + \sum_k \sum_l T_{kl} Y_{kl} \right) + \sum_k \sum_r F_k^r Z_k^r, \tag{4.9}$$

$$\text{subject to} \qquad (4.2), (4.5), (4.6) \;\&\; (4.7) \tag{4.10}$$

$$\sum_j X_{jk} = \sum_r V_k^r Z_k^r, \forall k \tag{4.11}$$

$$\sum_r Z_k^r \leq 1, \forall k, \tag{4.12}$$

$$\sum_l Y_{kl} \leq \sum_r V_k^r Z_k^r, \forall k \tag{4.13}$$

$$Z_k^r \in \{0, 1\}, \forall r, k. \tag{4.14}$$

Explanations to the model:

- Constraints (4.11) refer to the amount supplied from PC_j to all selected DC_k, must satisfy the DCs' capacity level V_k^r.
- Constraints (4.12) are now introduced to make sure that only one capacity level of selected DC is chosen. If DC_k is selected then the constraint (4.12) makes sure that only one of its capacity is chosen. i.e. $\sum_r Z_k^r = 1$. If DC_k is not chosen, then $\sum_r Z_k^r = 0$.
- When DC_k is selected along with a capacity level, then constraint (4.13) makes sure that its V_k^r for some r is not violated. The values of , $r \geq 1$, are in different ranges, some less than or equal to $\hat{V}_k$ and some are more than $\hat{V}_k$, the existing true capacity.
- Constraints (4.14) are the binary values to the location variable.

The objective function (4.9) differs from the existing ones in literature in that the last term is modified to account for the dependence of F_k^r on V_k^r.

We have carried out the optimization of the model (4.9) - (4.14) using the inputs data as in Case 1 except for each DC_k, we use 14 different capacities i.e. $R_k = \{V_k^1, V_k^2, ..., V_k^{14}\}$. In the given capacities, the Case 1 capacities, $\hat{V}_k$ and $\bar{V}_k$ are also included. Values in the set R_k are independent of k. These capacities together with corresponding F_k^r are presented in the 3^{rd} to the 10^{th} columns of Table 4.6. In the table, there are three additional new DCs which

are Babati (DC_6), Mwanza (DC_7) and Tanga (DC_8). The set R_k, $k = 1, 2, ..., 8$, contains the capacities that are generated randomly in $[9, 843; 145, 144]$. We have used the interval from 9,843 to 145,144 since this range contains the minimum capacity as observed in DCs' actual capacity, $\bar{V}_k$, and also the maximum actual capacity used.
The optimization in this case is performed with respect to all the four decisions, (a) - (d), as listed in subsection 4.1.1.

We run the program using the original five DCs, i.e. using the data of Table 4.6 up to column 7. The results obtained are summarized in Table 4.7, where the optimized capacity chosen are shown in brackets in the column under V_k^r. The results in Table 4.7 are self-explanatory. Table 4.7 shows that only four DCs are selected.

The optimal decisions for the capacity of DCs are presented in column 8 under $\sum\limits_j X_{jk}$. As shown in Table 4.7, the total optimal capacity of the four selected DCs is 145,144 which is the same as the total CPs' demand. DC_3 has the largest capacity (71,000 tons) for all the selected DCs. This is an increase of 32,000 tons from its true capacity of 39,000 ($\hat{V}_k$). DC_5 also needs to be increased from its true capacity of 14,500 to the capacity of 33,144. The results obtained indicate the need for expansions for the capacities of DC_3 and DC_5.

The overall distribution cost obtained after 16 seconds is \$12,660,522.80. The total cost attained in Case 2 is the best solution for the existing maize crop distribution network in Tanzania. The cost has decreased, in comparison to Case 1, by 4.27% (actual capacity) with a net saving of \$564 thousand which is an important saving to be considered. In the case of true capacity, the saving is 18.69% which is equivalent \$2,910 thousand. The saving is contributed by using many capacities that the program will select the best in each DC as compared to a single capacity as used in Case 1.

Table 4.6: *The V_k^r and F_k^r input sets for eight DCs.*

$(r\downarrow, k\rightarrow)$	$(V_k^r,\ F_k^r)$	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
1	V_k^1	52000	39000	39000	34000	14500	53000	53000	53000
	F_k^1	340340	255260	255260	222530	94900	346885	346885	346885
2	V_k^2	33190	38532	24650	9843	38929	28500	26500	45000
	F_k^2	217229	252192	161334	64422	254790	186533	173443	294525
3	V_k^3	25000	45000	71000	16000	33144	30144	18144	29000
	F_k^3	163625	294525	464695	104720	216927	294525	118752	189805
4	V_k^4	145144	145144	145144	145144	145144	145144	145144	145144
	F_k^4	949968	949968	949968	949968	949968	949968	949968	949968
5	V_k^5	28500	26500	45000	18144	29000	35000	43000	16144
	F_k^5	186533	173443	294525	118752	189805	229075	281435	105662
6	V_k^6	39361	39000	39000	13283	14500	39000	39000	13283
	F_k^6	257618	255255	255255	86937	94903	255255	255255	86937
7	V_k^7	27144	45000	59000	20000	39000	63000	40000	45000
	F_k^7	177657	294525	386155	130900	255255	412335	261800	294525
8	V_k^8	52000	39000	63000	40000	45000	25000	26000	45000
	F_k^8	340340	255255	412335	261800	294525	163625	170170	294525
9	V_k^9	35000	43000	16144	25000	30000	45144	16000	33000
	F_k^9	229075	281435	105662	163625	196350	295467	104720	215985
10	V_k^{10}	32000	43000	16144	24000	30000	33190	38532	24650
	F_k^{10}	209440	281435	105662	157080	196350	217229	252192	161334
11	V_k^{11}	25144	26000	45000	16000	33000	45000	71000	16000
	F_k^{11}	164567	170170	294525	104720	215985	294525	464695	104720
12	V_k^{12}	25000	26144	45000	16000	33000	30000	16000	33000
	F_k^{12}	163625	171112	294525	104720	215985	294525	104720	215985
13	V_k^{13}	25000	26000	45144	16000	29144	9843	38929	28500
	F_k^{13}	163625	170170	295467	104720	190747	64422	254790	186533
14	V_k^{14}	25000	26000	39144	16144	33000	45144	16144	33000
	F_k^{14}	163625	170170	256197	105662	215985	295467	105662	215985

Table 4.7: *Location allocation results in Case 2.*

DC_k	PC_j	S_j	(Z_k^r, r)	V_k^r	F_k^r	PC_j^s	$\sum_j X_{jk}$	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1	100,000	$(1,3)$	$V_1^3(25,000)$	F_1^3	PC_1	25,000	20	25,000
DC_2	PC_2	251,000	$(0,.)$	-	-	-	-	-	-
DC_3	PC_3	140,000	$(1,3)$	$V_3^3(71,000)$	F_3^3	PC_1	71,000	39	71,000
DC_4	PC_4	41,000	$(1,13)$	$V_4^{13}(16,000)$	F_4^{13}	PC_1; PC_2	4,000; 12,000	13	16,000
DC_5			$(1,3)$	$V_5^3(33,144)$	F_5^3	PC_2	33,144	24	33,144
Total		532,000		(145,144)			145,144	96	145,144

NOTE: '-' This means the corresponding DC is not selected.

4.2.3 Results using eight DCs

We continue to find the minimum possible cost for the location and allocation of facilities in the distribution network. In this part, we use the existing five DCs and the three new DCs to comply with government proposal as clearly stated in Appendix C, Figure C.2. The use of the eight DCs; after the three new DCs as explained in sub-section 4.2.1, forms the extended distribution network. We have decided to use more DCs despite the fact that the existing DCs' capacities are enough for the present CPs' demand in order to cater for the general uses of the DCs. The main and primary use of DCs is to store the reserve food crops for the nation in order to supply to the common deficit areas. This is the concern of our study. However, since the production capacity is very high (see Table 4.4), then there is a need to have enough storage capacities. Apart from the stored maize crop for common deficit areas, we have also other grain crops like rice, sorghum and beans that are stored in DCs. Thus the consideration of the new DCs for this study is very important so as to explore the possible cost reduction using the extended distribution network.

The inputs used in the extended network are similar to those given in Case 2, but with additional data for the three new DCs. However, rather than solving the optimization model (4.9) - (4.14) using $|K| = 8$, we run the optimization in three phases. We use three phases in order to find the cost resulted for each new introduced DC for comparison purposes. Each run considers one new additional DC. Hence, Phase 1 has $|K| = 6$ for DC_6 where the 6^{th} DC is a new DC on top of existing five DCs. Phase 2, $|K| = 7$ includes DC_7. And the last phase includes all eight DCs. The number of PCs and CPs are same as used in the existing network. The inputs in Table B.1 for C_{jk} distances, and Tables B.7, B.8, B.9, B.10 for T_{kl}, are used in phases depends on the number of DCs involved. The corresponding inputs are also taken from Table 4.6. The multiple capacities in the model presented in (4.9) - (4.14) are applied to all phases.

We run the program for the three phases; and the results obtained are as follows:

- In Phase 1, the five DCs are selected including DC_6 with the distribution cost of \$12,346,976.95. This cost is less than the cost found in Case 2.
- For optimization in Phases 2 and 3, we obtained the same results with the cost of \$12,303,719.06. Here, the obtained cost is better compared to all previous optimization results.

We summarize the results for all eight DCs in Table 4.8 where out of six selected DCs, two are the new DCs. DC_6 and DC_7 are the new proposed DCs which are selected in this optimal solution as indicated in column under (Z_k^r, r).

The notations used in results presented in Table 4.8 are the same as that in Table 4.7.

The DCs' optimal capacity decisions are presented in brackets as shown in column 5 under V_k^r. The total optimal capacities of the six selected DCs are the same as the total CPs demand which is 145,144 tons. The obtained results, in order to meet the demands at minimal cost, require DC_1 to use the capacity of 25,144 although its actual capacity is 52,000 tons. DC_3 which has the largest capacity of 45,000 tons, should be increased by 6,000 tons from its actual capacity of 39,000 tons. DC_4 will use only 16,000 tons from its actual capacity of 34,000 tons, while DC_5 will use exactly its actual capacity; 14,500 tons. The new DCs, DC_6

Table 4.8: *Location allocation optimal results for eight DCs.*

DC_k	PC_j	S_j	(Z_k^r, r)	V_k^r	F_k^r	PC_j^s	$\sum_j X_{jk}$	$\lvert L_k \rvert$	$\sum_{l=1}^{\lvert L_k \rvert} Y_{kl}$
DC_1	PC_1	100,000	$(1, 11)$	$V_1^{11}(25, 144)$	F_1^{11}	PC_1	25,144	21	25,144
DC_2	PC_2	251,000	$(0, .)$	-	-	-	-	-	-
DC_3	PC_3	140,000	$(1, 5)$	$V_3^5(45, 000)$	F_3^5	PC_1	45,000	25	45,000
DC_4	PC_4	41,000	$(1, 13)$	$V_4^{13}(16, 000)$	F_4^{13}	PC_1; PC_2	1,356; 14,644	13	16,000
DC_5			$(1, 1)$	$V_5^1(14, 500)$	F_5^1	PC_2	14,500	15	14,500
DC_6			$(1, 2)$	$V_6^2(28, 500)$	F_6^2	PC_1	28,500	14	28,500
DC_7			$(1, 9)$	$V_7^9(16, 000)$	F_7^9	PC_2	16,000	10	16,000
DC_8			$(0, .)$	-	-	-	-	-	-
Total		532,000		(145,144)			145,144	98	145,144

and DC_7; and their capacities for the demand satisfaction are 28,500 tons and 16,000 tons respectively.

The optimal cost of \$12,303,719.06 is obtained after 27 seconds. The solution in this optimization has reduced the best solution obtained in Case 2 by almost 3% with a net saving of \$356,803.74. This is a better achievement for savings with approximately \$357 thousand. The actual capacity solution of Case 1 has been reduced by about 7% while the true capacity is reduced by 21%. The use of many capacities in optimization is highly important as it allows the program to select the best capacity in each DC accordingly. If we consider the saving based on current practices (actual capacity in Case 1), it is very significant since it is equivalent to Tshs 1.2 billion. This has been effectively contributed by the two new selected DCs through the optimization tool.

The deterministic optimal solution is very important in terms of cost savings. We also need to reflect on the geographical location of the selected DCs; and their distances to CPs, PCs, and their optimal capacities. The results are very useful for the Tanzanian government to redesign its existing distribution network.

4.3 Results of the deterministic model using combined 17 weeks

The previous section considered the demand for a single period where it is assumed that all the demand D_l at CP_l are transported only once in a week from DC_k to CP_l sometime during the first week. However, from the existing network the transportation has been carried out over four months in order to meet the demand, D_l at CP_l. We now consider the weekly transportation plan that will meet the demand per week. Hence, it is a multi-period transportation plan. This plan will help to know the weekly demand to be supplied to each CP. The results from this plan will also be used for comparison with the stochastic model results due effect of weekly rainfall. In this case, our model considers all the 17 weeks (17 periods) where the demand transported in each week is the same. The week is denoted by e, $e \in E$, $|E| = 17$. We use the decision variable $\bar{Y}_{kl}$ as the weekly amount in tons flow from DC_k to CP_l in week e instead of Y_{kl}. The total demand, D_l, over the entire 17 week period, will be met after the 17 weeks. We have a weekly demand at CP_l denoted by d_l such that $\sum_{k=1}^{|K|} \bar{Y}_{kl} = d_l$ and $|E| \sum_{k=1}^{|K|} \bar{Y}_{kl} = \sum_{k=1}^{|K|} Y_{kl} = D_l$. In this consideration, the transformed models are used in both the existing distribution network and the extended network as it has been done in sections 4.1 and 4.2. In the computational experiments, we use the same data as stated in subsection 4.2.1.

4.3.1 Results for the existing distribution network

We first consider the existing distribution network by using a single capacity per DC. We present the combined model for the 17 week period where the amount of maize crop transported from DCs to CPs at every week is the same. The presented model bellow is similar to a single period model with only the number of weeks,$|E|$, as a new parameter. The model is as follows:

$$\underset{X_{jk},\bar{Y}_{kl},Z_k}{\text{Min}} \quad \lambda\left(\sum_j \sum_k C_{jk} X_{jk} \ + \ |E| \sum_k \sum_l T_{kl} \bar{Y}_{kl} \right) + \ \sum_k F_k Z_k \tag{4.15}$$

$$\text{subject to} \qquad (4.2), (4.3), (4.6)\&\ (4.8) \tag{4.16}$$

$$|E| \sum_l \bar{Y}_{kl} \leq V_k Z_k, \forall k, \tag{4.17}$$

$$|E| \sum_k \bar{Y}_{kl} = D_l, \forall l. \tag{4.18}$$

$$\bar{Y}_{kl} \geq 0, \forall k, l. \tag{4.19}$$

The explanations of the above model are as follows:

- The objective function (4.15) with decision variable $\bar{Y}_{kl}$, minimizes the total distribution cost including the weekly distribution cost from DCs to CPs. The total cost between DCs and CPs can be obtained by multiplying with $|E|$.
- Constraints (4.16) are used as in the previous model, section 4.1.
- Constraints (4.17) refer to the amount supplied, $\bar{Y}_{kl}$, for each week in $|E|$ weeks by DC_k to all CP_l, $l \in L$, not exceeding $V_k \big/ |E|$. The weekly amount $\bar{Y}_{kl}$ transported is the same for each week.
- Constraints (4.18) represent the weekly amount $\bar{Y}_{kl}$ that need to be transported in week e for $|E|$ weeks from all DC_k, $k \in K$, to the CP_l, which must meet the demand, D_l.
- Constraints (4.19) represent the non-negativity restrictions.

As we have done in the single period demand, the existing maize crop distribution system is now being evaluated using the multi-period demand. The multi-period demand data is the annual demand data being divided equally into 17 weeks. The computational experiments are carried out using the same cases; Case 1 and 2; as used in section 4.2.

Computational results for Case 1 under multi-period demand

The computational experiments for Case 1 in this section are carried out using the model defined by equations (4.15) - (4.19). The computational results for Case 1 with a true capacity ($\hat{V}_k$) and actual capacity ($\bar{V}_k$) are shown in Table 4.9.

Table 4.9: *Summary results for Case 1 using multi-period demand.*

DC_k	True capacity, $\hat{V}_k$			Actual capacity, $\bar{V}_k$		
	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} \bar{Y}_{kl}$	$\|E\| \sum_{l=1}^{\|L_k\|} \bar{Y}_{kl}$	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} \bar{Y}_{kl}$	$\|E\| \sum_{l=1}^{\|L_k\|} \bar{Y}_{kl}$
DC_1	28	2,315.35	39,361	26	1,952.35	33,190
DC_2	18	2,294.12	39,000	18	2,266.59	38,532
DC_3	29	2,294.12	39,000	13	1,450.00	24,650
DC_4	11	781.35	13,283	9	579.00	9,843
DC_5	10	852.94	14,500	29	2,289.94	38,929
Total	**96**	**8,537.88**	**145,144**	**95**	**8,537.88**	**145,144**

Table 4.9 gives the summary results for both $\hat{V}_k$ and $\bar{V}_k$ under which the weekly demand to be transported to CPs is determined. The column labels in Table 4.9 are self-explanatory as defined before except sub-columns under $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ and $|E| \sum_{l=1}^{|L_k|} \bar{Y}_{kl}$. These sub-columns denote the total amount of maize crop to be transported from a DC_k to all its respective CPs ($|L_k|$) in a week and the total demand, D_l, in a 17 weeks period respectively. The total demand is satisfied as shown in the sub-column under $|E| \sum_{l=1}^{|L_k|} \bar{Y}_{kl}$. However, from the results we have the same total costs as obtained in the Case 1 for the single period demand as presented in

section 4.2. Thus there are no significant differences in locations and allocations within the layers when compared to the results presented for the single period in section 4.2. Thus, we mostly focus on the weekly demand to be transported from DC_k to CP_l over 17 weeks.

Computational results for Case 2 under multi-period demand

In this case, the computational experiments are carried out using the multiple capacity model with multi-period demand. The model is presented below:

$$\underset{X_{jk},\bar{Y}_{kl},Z_k^r}{\text{Min}} \quad \lambda\left(\sum_j \sum_k C_{jk}X_{jk} \; + \; |E| \sum_k \sum_l T_{kl}\bar{Y}_{kl} \right) \; + \; \sum_k \sum_r F_k^r Z_k^r \tag{4.20}$$

$$\text{subject to} \qquad (4.11), (4.14), (4.16), (4.18)\& \ (4.19), \tag{4.21}$$

$$|E| \sum_l \bar{Y}_{kl} \leq \sum_r V_k^r Z_k^r, \forall k. \tag{4.22}$$

The above mentioned model is now considers the multiple capacities as addressed through Z_k^r, V_k^r and F_k^r. The constraints used are the same as $(4.11) - (4.19)$ with only the added constraints; (4.22), for restriction on the DCs' multiple capacities.

Table 4.10 shows the summarized results where the column labels are the same as defined in the sub-columns of Table 4.9 and also in Table 4.7, section 4.2. In the computational results, we have obtained the same total cost as that found in its counterpart Case 2 for the single period demand. Thus in Table 4.10 we will focus on the column under $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ and other results for the comparison with results of the stochastic model presented in Chapter 5.

Table 4.10: *Summary results for Case 2 multi-period demand.*

DC_k	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert E\rvert \sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1	$V_1^3(25,000)$	20	1,470.59	25,000
DC_2	-	-	-	-	-
DC_3	PC_1	$V_3^3(71,000)$	38	4,176.47	71,000
DC_4	PC_1; PC_2	$V_4^{13}(16,000)$	13	941.18	16,000
DC_5	PC_2	$V_5^3(33,144)$	24	1,949.65	33,144
Total		**(145,144)**	**95**	**8,537.88**	**145,144**

4.3.2 Results using the eight DCs

In this extended network where the new DCs are involved, we optimize the model (4.20) to (4.22). There are three phases considered for computational experiments as it was carried out in subsection 4.2.3. Similarly, as in Cases 1 and 2, the computational results in this section have the same total cost as the one obtained for the single period demand in section 4.2.

Table 4.11 summarizes the results for the eight DCs for the multi-period demand.
The summarized results for the eight DCs computational experiments in Table 4.11; have the same column labels as in Table 4.10. The values in the table are self-explanatory and will be used for comparison with the stochastic results in Chapter 5.

Table 4.11: *Summary results for the extended network using eight DCs.*

DC_k	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert E\rvert \sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1	$V_1^{11}(25,144)$	21	1,479.06	25,144
DC_2	-	-	-	-	-
DC_3	PC_1	$V_3^5(45,000)$	26	2,647.06	45,000
DC_4	PC_1; PC_2	$V_4^{13}(16,000)$	13	941.18	16,000
DC_5	PC_2	$V_5^1(14,500)$	14	852.94	14,500
DC_6	PC_1	$V_6^2(28,500)$	14	1,676.47	28,500
DC_7	PC_2	$V_7^9(16,000)$	10	941.18	16,000
DC_8	-	-	-	-	-
Total		**(145,144)**	**98**	**8,537.88**	**145,144**

4.4 Conclusions and recommendations for the deterministic results

The purpose of this study using the deterministic model is to access the suitability of extending the existing transportation network in Tanzania. This was initiated by the government in considering the increase of demands at the customer level as well as increased production in recent years. The government wanted to make sure that the demands are met but with decreased or minimal cost. Even though we put more emphasis on the stochastic model, the results from the deterministic model can also be used to offer recommendations to the government on the maize crop transportation network.

We have studied the problem from two angles: firstly by using the current or existing network and secondly by using the extended network. For the current network we have optimized the model with increased demand (where we have used maximum demands over a number of years) and in increased capacities of DCs (maximum capacity used). The optimal solution for the existing network shows that one old DC has to be closed and only four DCs are to be operated.

Our second study for the extended network (where we have used eight DCs) suggests that costs can be reduced further if two new DCs are opened and one old is closed. Generally, the optimal solution for the deterministic model shows that some old DCs have to be closed and new ones in different regions need to be opened.

The optimal solution for the deterministic model obtained as a case study is of great importance. The total cost obtained in the computational results considers the three layers simultaneously. This is different from the existing system which is manually operated and has two different departments working independently.

The existing distribution system has two different independent tasks carried out by specific different government departments. The first task is dealing with buying of maize crop from PCs and transporting them for stocking in DCs which is done by the NFRA (first department). The second task is the transportation of maize crop from DCs to CPs done by the disaster management department in the Prime Minister's Office (PMO) (second department). This results in high cost due to fragmented co-ordinations since the two departments operate more independently and they are also under different ministries. This breeds inefficiency. The integrated coordination, as supported by this study, will make cost to be economic and offer a more reliable and flexible system. Based on the discussed facts from optimization results, we recommend the following:

- The use of optimization as a decision tool is an important aspect to be considered by the Tanzania government in its food security system and other sectors. For example, the saving of Tshs 1.2 billion is a significant amount achieved through optimization.

We obtained the weekly amount of maize crop demand to be transported in each week to CPs which is not yet implemented in the manually operated system.

- It is important to have data records that are well-secured for research and for further developmental plans. This needs to be managed by all stakeholders. For example, data availability in NFRA is not well-organized and accessible. There should be a section within the department that will ensure and create effective data bases for the department.

- The results from this study should be applied to redetermine and to recast the current distribution system. In particular, Case 2 can be implemented since the existing DCs can be used together with its storage facilities for the restocking of the DCs like DC_3 and DC_5.

- New DCs construction should be effected as per study since this is the primary demand for the country's self-sufficient in food. The DCs or storage facilities expansion is one of the ten pillars stated in 2009 Tanzania policy on "Agriculture First" document [2]. This can be done through public-private partnerships in order to ensure the immediate implementation of the goal. There is an urgent need for DCs' capacities expansion due to the following reasons:

    1. Firstly, the PCs' capacity is always higher compared to the storage capacities as shown in Table 4.4. For example, the PCs' capacity is 532,000 tons (surplus maize crop production in 2011/12), while the total DCs' and storage facilities' capacity is 241,000 tons. This is only for the major four surplus producer regions and it is only maize crop being stored. The annual total maize crop production capacity for the four PCs as in Table 4.4 also supports the expansion for DCs. Generally, production is always high and during the harvest season most of farmers sell their crops to meet their needs like clothing, school fees for their children and other needs [23, 84].

2. Secondly, there is a need for stocking more food crops (rice, sorghum, beans, etc.) in order to stabilize food crop prices in the domestic food markets in general, and in particular for towns and cities as the need arises. The lack of enough storage capacity causes low prices for maize crop during the harvest season and then faces the high maize crop domestic prices later [23].

3. The third reason is the exports of food crops to other neighbouring countries, such as Somali, Kenya, Burundi, Rwanda, Malawi, Zambia and South Sudan for economic earnings [14, 23].

- It is possible to coordinate activities of food crop production, storage and final distribution to customers. In order to achieve this, data availability, coordinating management and the funding to the coordinating team are of great importance.

Chapter 5

The stochastic model for the two-level FLP with rainfall dependent travel costs

5.1 Background to the stochastic problem

As explained in Chapter 3, the stochastic transportation links arise in Tanzania due to the effect of rainfall. The road condition is directly related to the amount of rainfall which is stochastic. Hence, the usability of road and distance are stochastic. This is because; if there is no rainfall or there is very low rainfall, then the exact distance is known (as in deterministic model). The distance between a DC to a CP is rainfall dependent. For example, for a relatively moderate amount of rainfall, some sections of the link between a DC to a CP will have diversion roads that have to be traversed. Similarly, for a high amount of rainfall a large distance is expected to be traversed due to more diversions or detours. This results in stochastic travel costs.

Both the paved and unpaved road links may be submerged due to rainfall. Some parts of unpaved road links may even not be accessible even with moderate rainfall. Alternative road links are then used thus causing high costs. When the rainfall is high to the extent that the travel might be postponed for a day or more; this might happen if most road links are submerged and probably the bridges are washed away.

Figure 5.1 elaborates the possible road links and the effects of rainfall. For example, deliveries must be done from a DC situated at A to a CP located at D. The shortest path is A to C to D. However, for moderate rainfall of; say 30 mm, the link AC is not accessible and therefore this has to be replaced by the links AB and BC. For a rainfall of; say 85 mm, the link CD is also inaccessible and in this case the long route $ABED$ is used causing more costs.

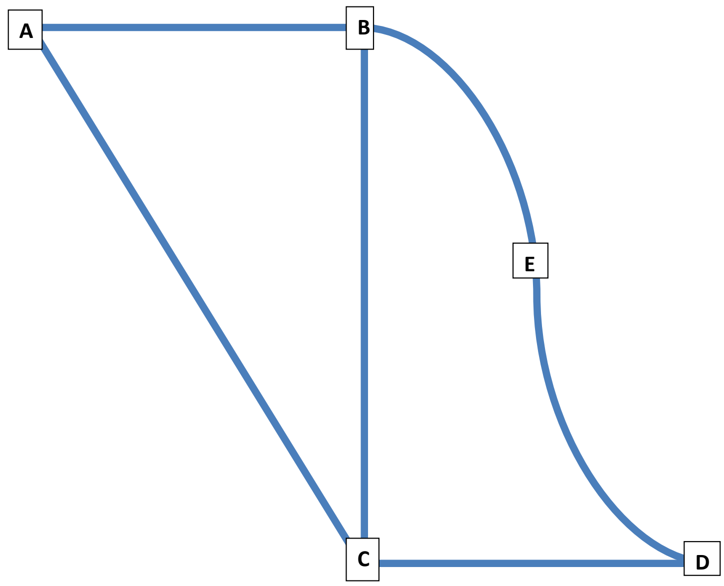


Figure 5.1: *The road links and rainfall effects*

To give a recent example of high rainfall in Tanzania, we cite the rainfall on the night of 21^{st} January, 2014. This caused floods in the Dumila area in the Morogoro region, Tanzania. Many road links within Morogoro became inaccessible [20]. Figures 5.2 and 5.3 show the situation of a bridge on the paved road and one of the government schools after floods caused by the rainfall on 21^{st} January, 2014. However, this heavy rainfall was unique since it had not occurred in that place for more than 50 years [20]. It is not regular kind of rainfall and it is the specific case for bridges. Other heavy rainfall causes impassable roads mostly due to muds as shown in Figures 3.3 and 3.4. No data available in the TANROADS headquarters for number of bridges being washed away by rainfall.

Figure 5.2: *The Dumila area bridge after heavy rainfall, on 22-01-2014. Source: Michuzi Blog - http://issamichuzi.blogspot.com/*

Figure 5.3: *Magole primary school has been submerged after heavy rainfall, picture captured on 22-01-2014. Source: http://mdimuz.blogspot.com/2014/01/jionee-hali-ya-mafuriko-ilivyokuwa-huko.html*

Situations like these cause high transportation costs since long alternative road links are used between origins and destinations [27].

Road networks in Tanzania are mainly classified as trunk roads (TR), regional roads (RR), district roads (DR) and urban roads (UR). In Tanzania, trunk roads are primarily defined as the main highways (national roads) which link two or more regional headquarters in the country. The regional roads (RR) are defined as the secondary national roads that connect TRs and regional and/or district headquarters. RR link regional and the district headquarters [79]. The total classified road network in Tanzania mainland is estimated to be 86,472 *km* based on the Road Act 2007 [79]. The national road network (NRN) is about 33,891 *km* comprising of 12,786 *km* of TRs and 21,105 *km* RRs (see Figure 5.4). The remaining network of about 53,460 km is of urban, district and feeder roads [79]. This study uses only the NRN that comprises of both TR and RR. The status of NRN in km are as presented in Table 5.1.

Table 5.1: *Tanzania NRN classification and status.*

Road status	**Road classes and their distances in km**		**Percent**
	TR	**RR**	
Paved	5,130	840	17.6
Unpaved	7,656	20,265	82.4
Total	12,786	21,105	100

Generally, in the National Road Network (NRN) the paved roads make up 17.6% and the unpaved roads 82.4%. This excludes the rural district roads most of which are unpaved. Figure 5.4 shows Tanzania's NRN. The high percentage of unpaved roads is the cause of stochastic effect even for moderate rainfall.

Figure 5.4: *The map of Tanzania: National Roads Network. Source: TANROADS website*

The rainfall distribution within the country varies with regions and districts, it also varies with time. Therefore, the effect of rainfall in transportation links differs from regions to regions as well as from a month to another. In this study, we have five existing DC zones with different rainfall distributions. These five DC zones are from the current transportation network. A DC zone is defined as a specific DC and its surrounding CPs (districts in a region) that are usually serviced by that DC. Each DC zone will be assumed as having its unique rainfall distribution per week over 17 weeks. This also applies to the newly proposed DCs with their own rainfall distributions. The DC zone at site k, is synonymous to DC_k, $k \in K$, as used in Chapter 4.

Within a DC zone, we consider the weekly amount of rainfall for the first 17 weeks in a year. This is based on the fact that from the field data, the maize crop transportation from DCs to CPs are carried out mostly within the first 17 weeks of each year (January to April) (see appendix D.4, D.5 and D.6). In the field data records, eight out of nine DCs to CPs transfers were done between January and April. The data used in this case was the weekly rainfall from 2007 to 2010. The weekly rainfall data was obtained from the Tanzania Meteorological Agency (TMA) in January 2011 as shown in Appendix C, Figure C.8. Table 5.2 summarizes the rainfall data in millimetre (mm) for each DC zone over 17 weeks. We present the mean, minimum and maximum rainfall in mm for all DC zones in Table 5.2. First we calculate the average rainfall for each week within 17 weeks in each DC zone by considering data from 2007 to 2010. We use the data presented in Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12. From the 17 data values of averages per DC zone, we then calculate the average of averages (mean) and also identify the minimum of averages (minimum) and the maximum of averages (maximum). The values presented in Table 5.2 are only for comparison of variations in rainfall distributions across the DC zones.

The values presented in Table 5.2 show that there are significant variations in rainfall

Table 5.2: *The DC zone showing minimum, mean and maximum rainfall in mm (January - April from 2007 to 2010 rainfall data)*

DC zone (DC_k)	**Minimum**	**Mean**	**Maximum**
DC_1	5.5	29.2	57.2
DC_2	8.1	30.2	83.6
DC_3	0.4	26.0	57.2
DC_4	5.5	30.5	53.2
DC_5	20.7	36.4	61.9
DC_6	3.2	36.0	72.8
DC_7	17.2	34.2	65.7
DC_8	0.3	21.2	101.6

distributions. DC_8 zone has the lowest minimum rainfall of 0.3 mm and also the highest maximum rainfall of 101.6 mm. Generally, each DC zone has different rainfall as it can be observed in Columns 2, 3 and 4, and thus the effect on road links differs accordingly. The variations are also from week to week as shown in the field data presented in Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12. Weekly transportation planning over 17 weeks will now be considered in this chapter to account for the variability in rainfall with respect to each DC zone.

Clearly, the choice of routes (used by vehicles) results in a variable delivery cost from DCs to CPs. These costs, often being dominant, will affect the selection of DCs, their sizes and locations. Therefore allocations of DCs to PCs and CPs to selected DCs are expected to be affected.

5.2 The scenario-based approach in stochastic programming

As it has been explained in section 2.3, there are several approaches in dealing with randomness in stochastic problems. Here, we are considering the scenario-based approach that is pertinent to our problem.

A scenario-based approach is one of the approaches in dealing with randomness or uncertainty. In stochastic programming models, the scenarios are generated to represent the uncertainty in a sensible way while taking into account: the goal of the model and its structure, the available information and the availability of computer software [11, 68, 80].

The scenario-based approach assumes that there are a finite number of decisions that nature can make as the outcomes of randomness [11]. Each of the possible decisions or realizations is called a scenario. Scenarios deal with uncertain aspects of the random variables or parameters that are relevant to the need of the concerned problem [80]. Thus, the future uncertainty in the considered problem is usually described by a set of alternative scenarios. Some examples of scenarios are: the demand for a product is low, medium, or high; the weather is dry or wet; and the market price will go up or down. These are some examples with finite number of future realizations for stochastic modelling. The scenario-based approach can be used in both discrete and continuous random variables provided that there are finite number of realizations. However, even if the nature acts in a continuous manner, often a discrete approximation is mostly used in scenario-based approach [11, 66].

In the scenario-based approach, a scenario tree can be generated which will incorporate all possible realizations of discrete random variables or parameters into the model [80]. For the scenario tree, the number of scenarios as well as the progression of the scenarios from one stage or period to another depends on the requirement of the problem being considered

[11, 68, 80].

To explain the scenario-based approach, we consider a two-stage linear stochastic model with discrete realizations of a random variable. Here, two-stage is based on the stages of decisions taken in solving the stochastic model. The decisions that must be taken *before* the random experiment, denoted by x, are called *first-stage decisions.* The period during which they are taken is called the *first stage.* Decisions that must be taken *after* the random experiment, denoted by y, are called *second-stage decisions* and its corresponding period is the *second stage.* Suppose the result of the random experiment is $s \in S$ where S is the sample space of the random experiment, the sequence of decisions and events can be represented diagrammatically as $x \longrightarrow \xi(s) \longrightarrow y(s,x)$. Thus the second-stage decisions are functions of the outcome of the random experiment and also the first-stage decision [17, 40]. An elementary detailed example for a two-stage stochastic problem is the news-vendor problem found in [11, 17, 68]. We now consider in the next paragraph the general two-stage linear stochastic model that can be transformed into scenario-based approach in dealing with discrete random variables.

Generally, a two-stage stochastic linear program with recourse function can be written as follows [11, 17, 40, 68]:

$$\min_{x} \quad c^T x + E_\xi Q(x,\xi) \tag{5.1}$$

$$\text{subject to} \qquad Ax = b, \tag{5.2}$$

$$x \geq 0, \tag{5.3}$$

where $Ax = b$ is the first stage constraints and $Q(x,\xi)$ is the optimal value of the second stage problem (an extended real valued function or recourse function) given as

$$Q(x,\xi) = \min_{y} \quad q^T y \tag{5.4}$$

$$\text{subject to} \qquad Gx + Wy = h, \tag{5.5}$$

$$y \geq 0. \tag{5.6}$$

where G and W are called *technology* and *recourse* coefficient matrices for decision variables, x and y respectively. h is a right hand real value that limits x, y, G and W values. Here x and y are vectors of first and second stage decision variables respectively.

The second stage problem, (5.4) - (5.6), depends on the data $\xi := (q, h, G, W)$ and some or all elements of which can be random. So ξ is a random vector and E_ξ denotes mathematical expectation with respect to the probability distribution of ξ. This probability distribution is supposed to be known. The two-stage stochastic models where the random variables are fully known or realized, are solved as a "wait-and-see" solution method. On the other hand, when the stochastic models are solved before the realization of random variables, it is a "here-and-now" solution method. In this context, usually the random parameters are estimated using the historical data under probability distributions or density functions [11, 17, 39, 68]. The decisions to be made in "here-and-now" are for single-stage stochastic models [39]. In general, the random parameters or variables for stochastic models can be either in the constraints or in the objective function, or in both [11, 17, 39, 68].

We now consider equations (5.1) - (5.6) to have the discrete distribution in random data with a finite number of $|S|$ possible realizations. These possible realizations, $\xi_s := (q_s, h_s, G_s, W_s)$, $s \in S$, are called *scenarios* with corresponding probabilities P_s for its occurrence $\big(\Pr(\xi_s) = P_s\big)$. The other interpretation would be that the random vector $\xi_s = \xi(s)$ depends on the scenario s, which takes on S different values. In this case, $E_\xi Q(x, \xi) = \sum_{s=1}^{|S|} P_s Q(x, \xi_s)$, $\sum_{s=1}^{|S|} P_s = 1$. This consideration is only for a single attribute. For several attributes, P_s^t or $P_{t,s}$ can be adapted, meaning that the probability of scenario s at period t, where $s \in S$ and $t \in \phi$, where ϕ is the set of period times considered. Other possible attributes or dimensions can also be treated accordingly.

Under scenario-based approach, the model (5.1) - (5.6) can now be written in the form:

$$\min_{x, y_1, \ldots, y_s} \quad c^T x + \sum_{s=1}^{S} P_s q_s^T y_s \tag{5.7}$$

subject to

$$Ax = b, \tag{5.8}$$

$$G_s x + W_s y_s = h_s, \forall s, \tag{5.9}$$

$$x \geq 0, y_s \geq 0, \forall s. \tag{5.10}$$

Problem (5.7) - (5.10) is the two-stage stochastic problem formulated as one large linear programming problem under scenario-based approach. The constraints (5.8) are known as the first stage constraints and (5.9) are the second stage constraints. Such a stochastic decision model is known as the $extensive form$ of the stochastic program since it explicitly describes the second stage decision variables for all scenarios [11].

We would like to point out that the objective function in equation (5.7) is similar to our problem stated in equation (5.22); which is also a scenario-based problem. In our problem the constraints are not stochastic. Examples of scenario-based stochastic problems that are solved numerically can be found in [11, 17, 19, 31, 66, 80].

5.3 Stochastic model with rainfall dependent travel cost

During the rainy season, the transportation links between the DCs and CPs are unreliable since unpaved roads are at high risk, so are the low lying paved roads. The paved roads can also be submerged due to heavy or high rainfall. Some low lying paved roads get submerged under moderate rainfall too. The distance or a link between a DC and a CP in this case varies due to rainfall. We consider this effect in the mathematical modelling of two-level FLP below.

The mathematical model for the two-level FLP in section 4.1, Chapter 4, can be extended to include the stochastic term. The set of indices, parameters and variables for the problem are presented below:

Let J, K, and L, as before, denotes the index sets for PCs, DCs and CPs respectively.

R_k: Same as in section 4.1, Chapter 4.

e: Is the index set representing a week in which maize crop is transported from a selected DC to a CP, where $e \in E$. $|E|$ denotes the total number of weeks.

S_j: Same as in section 4.1, Chapter 4.

D_l: The total demand for four months for maize crop at CP_l transported once in a week. We assumed that a given single period demand is transported in the first week [1] of the four month's period.

F_k^r: Same as in section 4.1, Chapter 4.

C_{jk}: Same as in section 4.1, Chapter 4.

$w(e, k)$: The amount of rainfall during week e in DC zone k, $e \in E$, $k \in K$. Since $w(e, k)$ is stochastic with respect to both e and k, we introduce the stochastic variable $\gamma(k) = w(e, .)$ by fixing e.

$M_{kl}\big(\gamma(k)\big)$: The road distance in kilometres from DC_k to CP_l that depends on rainfall of week e.

λ: Same as in section 4.1, Chapter 4.

Decision variables for the model:

X_{jk}, Y_{kl} and Z_k^r are the same as in section 4.1, Chapter 4.

[1] We have also considered the delivery of the total demand in other weeks.

As stated in section 4.1, Chapter 4, we ignore the superscript r in Z_k^r, V_k^r and F_k^r when a single capacity[2] per DC_k is used. Here the choice of capacity is not a decision variable but the choice of DC_k is.

The two-level FLP is to select the DC sites, the assignment of CP_l to the selected DC_k and the assignment of selected DC_k to the PC_j by considering the stochastic cost involved between the DCs and the CPs.

Therefore, the stochastic single capacity model extended from the deterministic model is as follows:

$$\underset{X_{jk},Y_{kl},Z_k}{\text{Min}} \quad \lambda \left(\sum_j \sum_k C_{jk} X_{jk} + \sum_k \sum_l M_{kl}\big(w(e,k)\big) Y_{kl} \right) + \sum_k F_k Z_k, \tag{5.11}$$

subject to

$$\sum_k X_{jk} \leq S_j, \forall j, \tag{5.12}$$

$$\sum_j X_{jk} = V_k Z_k, \forall k \tag{5.13}$$

$$\sum_l Y_{kl} \leq V_k Z_k, \forall k, \tag{5.14}$$

$$\sum_k Y_{kl} = D_l, \forall l, \tag{5.15}$$

$$X_{jk} \geq 0, \forall j, k, \tag{5.16}$$

$$Y_{kl} \geq 0, \forall k, l, \tag{5.17}$$

$$Z_k \in \{0, 1\}, \forall k, \tag{5.18}$$

$$e \; is \; fixed. \tag{5.19}$$

The following are the explanations to the above model:

[2]Model for the stochastic multiple capacities per DC will be presented later on.

- The objective function (5.11), which is a stochastic model, is the total distribution cost, e.g. transportation cost from PCs to DCs and DCs to CPs, and fixed annual operation costs, F_k, for DCs with the corresponding capacities V_k for a fixed week e.

- Constraints (5.12) are the supply constraints (production centres' capacities), where the total amount to be shipped from a PC_j to the selected DC_k, must not exceed PC_j capacity, S_j.

- Constraints (5.13) is as stated in equation (4.3).

- Constraints (5.14) refer to the amount supplied by DC_k to all CP_l, $l \in L$, without exceeding V_k. V_k (respectively F_k) are the values currently used in the current transportation network with five DCs, e.g. $DC_1, ..., DC_5$. The capacities V_k, $k \in K$, are not necessarily equal.

- Constraints (5.15) represent the amount to be transported from all DC_k, $k \in K$, to CP_l, and this amount must meet a demand, D_l, at the CP_l.

- Constraints (5.16) and (5.17) are non-negative variables.

- Constraints (5.18) are binary variables.

- Constraints (5.19) consider a week e being fixed in the model.

The term $\lambda M_{kl}\big(w(e,k)\big)Y_{kl}$ in equation (5.11) is the stochastic cost of transportation that depends on the amount of rainfall at the e^{th} week in the DC zone k. So there will be an increase in cost which includes drivers' expenses and other related costs. The stochastic distance which takes values from three scenarios for interval, is calculated using:

$$M_{kl}\big(w(e,k)\big) = \begin{cases} T_{kl} & \text{if } w(e,k) \leq A(k), \\ T_{kl}(\alpha+1) & \text{if } A(k) < w(e,k) \leq B(k), \\ T_{kl}(\beta+1) & \text{if } B(k) < w(e,k), \end{cases} \tag{5.20}$$

where T_{kl} is a deterministic road distance in kilometres from DC_k to CP_l, and $A(k)$ and $B(k)$ are parameters used to determine possible ranges of amount of rainfall for the distance calculation as explained in the next paragraph.

The reasons behind the use of equation (5.20) are the historical data and the relationship among T_{kl} and $w(e,k)$ [79]. There are three scenarios realized due to rainfall classification based on the its effect on road links. The first scenario, $w(e,k) \leq A(k)$, constitutes the weekly rainfall data values from 0 (no rainfall) to its median value in the DC zone k. Hence, $A(k)$ is a median data value in a given weekly rainfall data in DC_k over all 17 weeks. The amount of rainfall in this scenario is low and is considered to have no effect on road conditions. Hence, we have a deterministic distance between a DC and a CP. We have decided to use the median value instead of mean since the weekly rainfall data distribution are skewed (not normally distributed).

The second scenario for medium rainfall is $A(k) < w(e,k) \leq B(k)$, where $B(k)$ is calculated as $A(k)$ plus 2.5 times the standard deviation ($B(k) = A(k) + 2.5\sigma$) in a given DC_k using 17 weeks' data. The standard deviation for each DC_k is calculated using the weekly rainfall data values presented in Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12. The third scenario, $B(k) < w(e,k)$, represents the high amount of weekly rainfall. $A(k)$ and $B(k)$ data values for each DC zone, DC_k, as shown in Table 5.3, were computed using the weekly rainfall over 17 weeks as presented in Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12. The three scenarios were considered for realism under low, medium and high amount of weekly rainfall classification [16].

The values in Table 5.3 are specific for each DC zone under consideration since each DC zone has different rainfall distribution. Thus the effect of rainfall on the roads will also differ due to the nature of rainfall distribution in a particular DC zone.

Table 5.3: *The $A(k)$ and $B(k)$ values (weekly rainfall data in mm) in each DC zone over 17 weeks.*

DC zone	$A(k)$	$B(k)$
DC_1	20.2	105.1
DC_2	15.0	117.0
DC_3	13.6	87.2
DC_4	24.1	91.2
DC_5	28.5	123.0
DC_6	36.0	114.2
DC_7	24.9	101.9
DC_8	2.2	82.8

The other parameters of equation (5.20) are α and β. These are estimate parameters used to estimates the distance increases due to various levels of rainfall. The estimate values are $\alpha = 0.824$, $\beta = 1$ by considering Tanzania NRN information [79]. The values are based on the effect of rainfall on the unpaved and paved roads. If the amount of rainfall is moderate, then the estimated distance increase is due to the conditions of unpaved roads. Thus we have estimated the value of distance increase to be proportional to the percentage of unpaved roads, α (proportional to the unpaved roads). For high rainfall, the overall distance increase is estimated due to both paved and unpaved roads effect. Hence, the value of β is 1 (percentage of unpaved roads plus percentage of paved roads). The effect of these parameters are proportional to the amount of rainfall (probabilities) as shown in the equation (5.22). The value of β is a realistic estimate for high rainfall. The accessibility of both paved and unpaved road is very poor for high rainfall [20]. The parameters are therefore tentative estimates used to find the increase in distance caused by rainfall.

5.4 The stochastic model: A scenario-based approach

The rainfall data values which are stochastic in nature are now used to calculate the probability of scenarios. The three scenarios in equation (5.20) result in three respective probabilities that are used in the stochastic model. The three scenarios corresponding to probabilities for week e, $P_s(e,k)$, with $s = 1$, 2 and 3 for each DC zone k are presented as follows:

- $P_1(e,k) = \Pr\Big(w(e,k) \leq A(k)\Big)$
- $P_2(e,k) = \Pr\Big(A(k) < w(e,k) \leq B(k)\Big)$ and
- $P_3(e,k) = \Pr\Big(B(k) < w(e,k)\Big)$.

The sum of all the three probabilities in each DC zone for each week must be a unit, i.e. $P_1(e,k) + P_2(e,k) + P_3(e,k) = 1$.

By these probabilities and equation 5.20, the stochastic model with consideration of the rainfall effect in each week is now presented as follows:

$$E[M_{kl}\big(w(e,k)\big)] = T_{kl}\big[P_1(e,k) + (\alpha+1)P_2(e,k) + (\beta+1)P_3(e,k)\big]. \tag{5.21}$$

Therefore, by including equation 5.21, the objective function (5.11) can now be re-written as:

$$\begin{aligned} \underset{X_{jk},Y_{kl},Z_k}{\text{Min}} \quad \lambda\Bigg(\sum_j\sum_k C_{jk}X_{jk} \; + \; \sum_k\sum_l T_{kl}Y_{kl}\Big[P_1(e,k) \; + \; (\alpha+1)P_2(e,k) \\ + \; (\beta+1)P_3(e,k)\Big]\Bigg) \; + \; \sum_k F_kZ_k \end{aligned} \tag{5.22}$$

The resulting expected objective function; (5.22), similar to equation (5.7), is then solved subject to constraints (5.12) to (5.19).

Here we have considered rainfall as the stochastic data that will affect the distance covered in transportation of maize crop from DCs to CPs. The consideration of rainfall data for the calculation of distance travelled in our model is similar to the example problem on farming studied by Birge [11]. In this problem, three weather scenarios are used to influence the crop yields. The crop yields will depend on whether the weather is good, average or bad [11]. The good, average and bad weather form the three possible scenarios of weather realizations.

These types of stochastic data usually influence the other data in the model using the estimate parameters. This is due to the fact that the given stochastic data is not directly linked to the model parameters compared to the case of new-vendor problem [11, 17, 68]. With such circumstances, our research problem being a real life problem is limited to other possible stochastic programming methods. These methods have different statistical distributions such as uniform, exponential, log-normal, Poisson and Wei-bull where random parameters can be treated [17]. For the same reason, the sample average approximation (SAA) approach is also not relevant to our problem.

5.4.1 Data for the stochastic model

Stochastic optimization considers the amount of rainfall in a given week as the stochastic data. These are the weekly amount (total) of rainfall from the Tanzania Meteorological Agency (TMA) regional stations within the DC zones. The data is over the period of 2007 - 2010 and is as presented in Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12. In each year we use all data from all meteorological stations within the given DC zone. This is for the purpose of having more samples of weekly rainfall within a DC zone. We have used the data in the listed tables above for the computation of probability values, $P_1(e,k)$, $P_2(e,k)$ and $P_3(e,k)$ (see Tables 5.4 and 5.5). These probabilities are calculated using data over 17 weeks for each respective DC zone.

The computations are done by first finding the total number of weekly data values in a given interval. We then divide that value by the total number of all data values found in that week in respective DC zones. For example, if the first interval has three data values in week one, and the total number of all data values in that week is twelve, then $P_1(e,k) = 3/12$ or 0.25. The other values of $P_2(e,k)$ and $P_3(e,k)$ are computed in a similar way for that week such that $P_1(e,k) + P_2(e,k) + P_3(e,k) = 1$. These probabilities together with deterministic data stated in section 4.2.1, Chapter 4, are used for the optimization of objective function (5.22) subject to equations (5.12) to (5.19).

Table 5.4: *The weekly based DC zones rainfall probabilities.*

$e\#$	$P_s(e,k), [e,t\downarrow,k\rightarrow]$	**DC Zone** (DC_k)							
		DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
1	$P_1(1,k)$	0.632	0.909	0.333	0.125	0.625	0.667	0.750	0.750
	$P_2(1,k)$	0.368	0.000	0.667	0.875	0.375	0.000	0.250	0.250
	$P_3(1,k)$	0.000	0.091	0.000	0.000	0.000	0.333	0.000	0.000
2	$P_1(2,k)$	0.579	0.636	0.500	0.375	0.625	0.667	0.500	0.750
	$P_2(2,k)$	0.421	0.364	0.417	0.625	0.375	0.333	0.500	0.250
	$P_3(2,k)$	0.000	0.000	0.083	0.000	0.000	0.000	0.000	0.000
3	$P_1(3,k)$	0.895	0.818	0.583	0.375	0.375	0.667	0.750	0.750
	$P_2(3,k)$	0.105	0.182	0.417	0.625	0.625	0.333	0.250	0.250
	$P_3(3,k)$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	$P_1(4,k)$	0.684	0.818	0.583	0.250	0.500	1.000	0.500	1.000
	$P_2(4,k)$	0.316	0.182	0.417	0.750	0.313	0.000	0.500	0.000
	$P_3(4,k)$	0.000	0.000	0.000	0.000	0.188	0.000	0.000	0.000
5	$P_1(5,k)$	0.579	0.455	0.167	0.250	0.563	0.333	0.750	1.000
	$P_2(5,k)$	0.368	0.545	0.750	0.625	0.438	0.667	0.250	0.000
	$P_3(5,k)$	0.053	0.000	0.083	0.125	0.000	0.000	0.000	0.000
6	$P_1(6,k)$	0.421	0.545	0.333	0.375	0.500	0.333	0.750	0.750
	$P_2(6,k)$	0.526	0.455	0.667	0.500	0.438	0.667	0.250	0.250
	$P_3(6,k)$	0.053	0.000	0.000	0.125	0.063	0.000	0.000	0.000
7	$P_1(7,k)$	0.526	0.364	0.583	0.375	0.375	0.333	0.250	0.500
	$P_2(7,k)$	0.368	0.545	0.333	0.625	0.563	0.333	0.750	0.500
	$P_3(7,k)$	0.105	0.091	0.083	0.000	0.063	0.333	0.000	0.000
8	$P_1(8,k)$	0.789	0.636	0.583	0.500	0.500	1.000	0.500	0.750
	$P_2(8,k)$	0.158	0.364	0.417	0.500	0.438	0.000	0.500	0.250
	$P_3(8,k)$	0.053	0.000	0.000	0.000	0.063	0.000	0.000	0.000

Table 5.5: *The weekly based DC zones rainfall probabilities.*

$e\#$	$P_s(e,k), [e, t \downarrow, k \rightarrow]$	**DC Zone** (DC_k)							
		DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
9	$P_1(9,k)$	0.579	0.727	0.417	0.375	0.375	0.667	0.750	0.500
	$P_2(9,k)$	0.421	0.273	0.417	0.625	0.625	0.333	0.250	0.500
	$P_3(9,k)$	0.000	0.000	0.167	0.000	0.000	0.000	0.000	0.000
10	$P_1(10,k)$	0.632	0.727	0.583	0.500	0.500	0.667	0.500	0.750
	$P_2(10,k)$	0.368	0.182	0.417	0.500	0.500	0.000	0.500	0.250
	$P_3(10,k)$	0.000	0.091	0.000	0.000	0.000	0.333	0.000	0.000
11	$P_1(11,k)$	0.737	0.455	0.333	0.375	0.438	0.000	0.250	0.750
	$P_2(11,k)$	0.263	0.545	0.667	0.375	0.500	1.000	0.750	0.250
	$P_3(11,k)$	0.000	0.000	0.000	0.250	0.063	0.000	0.000	0.000
12	$P_1(12,k)$	0.316	0.455	0.333	0.625	0.500	0.667	0.500	0.250
	$P_2(12,k)$	0.684	0.455	0.417	0.375	0.438	0.333	0.500	0.750
	$P_3(12,k)$	0.000	0.091	0.250	0.000	0.063	0.000	0.000	0.000
13	$P_1(13,k)$	0.263	0.273	0.083	0.500	0.313	0.333	0.250	0.000
	$P_2(13,k)$	0.737	0.455	0.833	0.500	0.688	0.667	0.250	1.000
	$P_3(13,k)$	0.000	0.273	0.083	0.000	0.000	0.000	0.500	0.000
14	$P_1(14,k)$	0.263	0.273	0.667	0.750	0.750	1.000	0.750	0.250
	$P_2(14,k)$	0.632	0.727	0.333	0.125	0.250	0.000	0.250	0.750
	$P_3(14,k)$	0.105	0.000	0.000	0.125	0.000	0.000	0.000	0.000
15	$P_1(15,k)$	0.316	0.000	0.667	0.875	0.313	0.333	0.000	0.000
	$P_2(15,k)$	0.421	0.909	0.250	0.125	0.563	0.667	1.000	0.250
	$P_3(15,k)$	0.263	0.091	0.083	0.000	0.125	0.000	0.000	0.750
16	$P_1(16,k)$	0.316	0.273	0.750	0.875	0.500	1.000	0.250	0.000
	$P_2(16,k)$	0.684	0.727	0.250	0.125	0.500	0.000	0.750	1.000
	$P_3(16,k)$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	$P_1(17,k)$	0.158	0.182	0.917	1.000	0.750	0.667	0.500	0.000
	$P_2(17,k)$	0.789	0.727	0.083	0.000	0.188	0.333	0.500	1.000
	$P_3(17,k)$	0.053	0.091	0.000	0.000	0.063	0.000	0.000	0.000

5.4.2 Results for the stochastic model using existing distribution network

The computational experiments carried out in this section are similar to those in section 4.2.2, Chapter 4, but with probabilities as additional inputs. In the numerical experiments, we are determining the cost increase based on stochastic rainfall data at the e^{th} week. Although the transportation is assumed to be carried out at the first week of a four months period, we have also studied and observed the cost increase for all 17 weeks separately in order to study the effect due to rainfall for each week. The stochastic computations carried out in this chapter, in general, are single-stage decisions based on the "here-and-now" solution (see section 2.3) using probability distributions. Apart from the cost increase, the location and allocation of facilities, and their capacities are to be affected. We consider the computational results in cases; Case 1 and 2, as we have have done for the deterministic model, section 4.2.2 of Chapter 4.

Case 1 and computational results under stochastic model

The data used here is the same as explained in section 4.2.2 for Case 1. The new additional data is taken from Tables 5.4 and 5.5. The two types of capacities to be used are true capacity, $\hat{V}_k$, and actual capacity, $\bar{V}_k$.

First we consider the true capacities, $R_k = \{\hat{V}_k\}$, where the five DCs, $DC_1, ..., DC_5$, are used. We solve the equation (5.22) with the listed constraints (5.12) - (5.19).

The results are generated for each week as shown in Table 5.6. In Table 5.6 we also present the corresponding deterministic results for comparison. In this table, Column 1 presents the week number. Column 2 shows the costs of the stochastic model, and Column 3 presents the corresponding costs of the deterministic model given in section 4.2.2, Chapter 4. The differences between the stochastic and deterministic costs are shown in Column 4. This is denoted as VSS (value of stochastic solution), as stated in section 2.3. The weekly percentage cost increases between the two solutions are presented in Column 5. The last column presents the number of DCs selected, denoted by $|K^s|$, after we have solved the stochastic model.

Table 5.6: *Total cost for true capacity in Case 1 using stochastic model as compared to the corresponding deterministic model.*

$e\#$	**Stochastic cost**	**Deterministic cost**	**VSS**	**cost increase (%)**	$\vert K^s\vert$
1	17,102,556.23	15,570,885.08	1,531,671.15	9.84	5
2	17,231,097.32	15,570,885.08	1,660,212.24	10.66	5
3	16,563,688.39	15,570,885.08	992,803.31	**6.38**	5
4	16,868,110.12	15,570,885.08	1,297,225.04	8.33	5
5	17,751,062.15	15,570,885.08	2,180,177.07	14.00	5
6	17,758,349.19	15,570,885.08	2,187,464.11	14.05	5
7	17,573,708.89	15,570,885.08	2,002,823.81	12.86	5
8	16,872,388.96	15,570,885.08	1,301,503.88	8.36	5
9	17,344,297.56	15,570,885.08	1,773,412.48	11.39	5
10	17,007,900.19	15,570,885.08	1,437,015.11	9.23	5
11	17,389,487.88	15,570,885.08	1,818,602.80	11.68	5
12	17,899,971.83	15,570,885.08	2,329,086.75	14.96	5
13	18,474,471.21	15,570,885.08	2,903,586.13	**18.65**	5
14	17,649,037.81	15,570,885.08	2,078,152.73	13.35	5
15	17,850,299.21	15,570,885.08	2,279,414.13	14.64	5
16	17,416,775.78	15,570,885.08	1,845,890.70	11.85	5
17	17,338,942.36	15,570,885.08	1,768,057.28	11.35	5
Average	**17,419,011.33**	**15,570,885.08**	**1,848,126.25**	**11.87**	**5**

The main focus in Table 5.6 is Column 5 where the percentage cost increases due to rainfall at week e are shown. The cost increase ranges from 6.38% (week 3) to 18.65% (week 13) for the 17 weeks with an average increase of 11.87%. In all the 17 runs, all the five DCs are selected as shown in the last column of Table 5.6.

A comparison of results for the first week obtained using the stochastic and the deterministic model is presented in Table 5.7. The notations used in Table 5.7 are the same as those used in the deterministic case, which is in Chapter 4. The results for week 1 are important for comparison with the deterministic results summarized in Table 4.2. This is due to the fact that a four months demand is assumed to be transported in the first week of the four months period as discussed in the deterministic part, Chapter 4. The overall percentage cost increase as shown in Column 5, Table 5.6 for the first week is 9.84%.

Table 5.7: *Comparison of summarized results of stochastic and deterministic model for week 1.*

DC_k	**Results for week 1**			**Summary results from Table 4.2**		
	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1	31	42,801	PC_1; PC_2	28	39,361
DC_2	PC_1	18	39,000	PC_1	18	39,000
DC_3	PC_1; PC_2	27	39,000	PC_1	31	39,000
DC_4	PC_2	9	9,843	PC_2	11	13,283
DC_5	PC_2	11	14,500	PC_2	10	14,500
Total		**96**	**145,144**		**98**	**145,144**

In Table 5.7 we study the location and allocation due to the effects of rainfall in the first week as compared to the deterministic results in Table 4.2.

With respect to DCs to PCs allocations, only PC_1 and PC_2 are supplying to all the five selected DCs. DC_3 is supplied by both PC_1 and PC_2 which is different from the deterministic case where DC_1 is supplied by PC_1 and PC_2 (see Table 5.7). This shows the effect of stochastic rainfall for DCs to PCs allocations.

A comparison of $|L_k|$ and $\sum_{l=1}^{|L_k|} Y_{kl}$ values shows that they are different for DC_1 and DC_4. This accounts for re-allocations of CPs to DCs due to rainfall effects. Furthermore, an analysis on the effect of rainfall is now considered for the lowest and highest cost increase weeks.

Table 5.8 presents a comparison of the lowest and highest cost increase weeks with the corresponding results of the deterministic model, Table 4.2.

Table 5.8: *Comparison of summarized results for the lowest and highest cost weeks with deterministic results.*

DC_k	**Results for week 3**			**Results for week 13**			**Summary results from Table 4.2**		
	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1; PC_2	34	42,801	PC_1;PC_2	27	36,642	PC_1; PC_2	28	39,361
DC_2	PC_1	18	39,000	PC_1	18	39,000	PC_1	18	39,000
DC_3	PC_1	22	39,000	PC_1	26	39,000	PC_1	31	39,000
DC_4	PC_2	9	9,843	PC_2	16	16,002	PC_2	11	13,283
DC_5	PC_2	13	14,500	PC_2	9	14,500	PC_2	10	14,500
Total		**96**	**145,144**		**96**	**145,144**		**98**	**145,144**

Table 5.8 gives more details of the results corresponding to the lowest (week 3) and highest (week 13) and the corresponding results for the deterministic solution, Case 1, in Table 4.2.

Sub-columns under PC_j^s in Table 5.8 show that the results of week 3 and 13 are the same as in Table 4.2. There are some differences in the number of CPs served by DCs as shown in sub-columns under $|L_k|$. The exception is only for DC_2 where the number of CPs ($|L_k|$) served is 18 in all three cases. DC_3 and DC_4 in particular, have high differences in the number of

CPs served by the corresponding DCs. For example, in DC_3 there are few CPs served in week 13 as compared to that in deterministic solution. In week 13, DC_4 served 16 CPs while in deterministic results it served only 11 CPs. This situation shows that DC_4 can be used during the rainy season in week 13 as compared with other DC zones. This is because DC_4 has more frequent rainfall in the first interval, (see the corresponding probability $P_1(13, k)$) as compared to other DC zones as shown in Table 5.5. Thus due to high rainfall in other DC zones, more CPs are served by DC_4 as compared to the deterministic results.

For the transportation decisions, there are also some minor differences observed in the total amount transported by each DC to their respective CPs as shown in columns under $\sum_{l=1}^{|L_k|} Y_{kl}$, Table 5.8. The differences in amount transported to CPs are shown in DC_1 and DC_4 while other DCs are having the same amounts transported to CPs.

Generally, the results show that in every week there are some changes in the location, allocation and transportation decisions as compared to the deterministic results.

As it has been done in the Case 1, the deterministic model, for the stochastic model we have also re-run the program using the actual capacity, $\bar{V}_k$. The results of this re-run are summarized in Table 5.9. The other inputs to the model apart from $\bar{V}_k$ remain the same.

The results presented in Table 5.9 show that the average cost increase for all 17 weeks is 11.19% which is not much different when the true capacity was used (see Table 5.6). The lowest and highest cost increases are 7.38% and 16.43% respectively. All the five DCs are selected as expected since the total optimized DCs' capacity is the same as the total CPs' demand.

Table 5.9: *Total cost for actual capacity in Case 1 using stochastic model as compared to the corresponding deterministic model.*

$e\#$	**Stochastic cost**	**Deterministic cost**	**VSS**	**cost increase (%)**	$\lvert K^s \rvert$
1	14,272,420.91	13,224,626.75	1,047,794.16	7.92	5
2	14,424,712.12	13,224,626.75	1,200,085.37	9.07	5
3	14,200,634.71	13,224,626.75	976,007.96	**7.38**	5
4	14,346,584.77	13,224,626.75	1,121,958.02	8.48	5
5	14,712,039.13	13,224,626.75	1,487,412.38	11.25	5
6	14,824,199.80	13,224,626.75	1,599,573.05	12.10	5
7	14,908,537.88	13,224,626.75	1,683,911.13	12.73	5
8	14,319,679.64	13,224,626.75	1,095,052.89	8.28	5
9	14,626,095.63	13,224,626.75	1,401,468.88	10.60	5
10	14,404,188.41	13,224,626.75	1,179,561.66	8.92	5
11	14,615,840.67	13,224,626.75	1,391,213.92	10.52	5
12	14,974,256.52	13,224,626.75	1,749,629.77	13.23	5
13	15,397,856.60	13,224,626.75	2,173,229.85	**16.43**	5
14	14,787,240.85	13,224,626.75	1,562,614.10	11.82	5
15	15,377,673.29	13,224,626.75	2,153,046.54	16.28	5
16	14,909,415.14	13,224,626.75	1,684,788.39	12.74	5
17	14,868,497.26	13,224,626.75	1,643,870.51	12.43	5
Average	**14,704,110.20**	**13,224,626.75**	**1,479,483.45**	**11.19**	**5**

The results for the first week are compared with those of the deterministic model in Table 5.10. The results presented in this table are self-explanatory similar to the results presented in Table 5.7. However, generally there are no significant differences that can be observed between the values found in the sub-columns under the same label, e.g. $|L_k|$.

Table 5.10: *Comparison of summarized results of stochastic and deterministic model for week 1.*

DC_k	**Results for week 1**			**Summary results from Table 4.5**		
	PC_j^s	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$	PC_j^s	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$
DC_1	PC_1	27	33,190	PC_1	26	33,190
DC_2	PC_1	17	38,532	PC_1	18	38,532
DC_3	PC_1	13	24,650	PC_1	13	24,650
DC_4	PC_1; PC_2	9	9,843	PC_1; PC_2	9	9,843
DC_5	PC_2	30	38,929	PC_2	29	38,929
Total		**96**	**145,144**		**95**	**145,144**

The more detailed results for the lowest and highest cost increase weeks are presented in Table 5.11, where again we have used the weeks corresponding to lowest and highest percentage cost increase (week 3 and 13).

Table 5.11 show results as comparable with those of the deterministic model of Table 4.5. As it can be seen from sub-columns of Table 5.11, there are no significant differences indicated. This is quite different from the results when the true capacities were used. This is mostly due to the fact that the total DCs' capacity is the same as the total CPs' demand, e.g. 144,145 tons. On the other hand, the total capacity of all DCs in the true capacity is 178,500 tons where total demand is 144,145 tons. This means that the DCs' capacity is larger than the demand and that the re-allocations are flexible. For the actual capacity, the flexibility is

Table 5.11: *Comparison of summarized results for the lowest and highest cost weeks with deterministic results.*

DC_k	**Results for week 3**			**Results for week 13**			**Summary results from Table 4.5**		
	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1	27	33,190	PC_1	26	33,190	PC_1	26	33,190
DC_2	PC_1	17	38,532	PC_1	18	38,532	PC_1	18	38,532
DC_3	PC_1	13	24,650	PC_1	13	24,650	PC_1	13	24,650
DC_4	PC_1; PC_2	9	9,843	PC_1; PC_2	9	9,843	PC_1; PC_2	9	9,843
DC_5	PC_2	30	38,929	PC_2	29	38,929	PC_2	29	38,929
Total		**96**	**145,144**		**95**	**145,144**		**95**	**145,144**

negligible.

Case 2 and computational results under stochastic model

As before, the multiple capacities are used as decision variables in this case. Thus the index r value is now used in Z_k^r, V_k^r and F_k^r. It is a similar approach as has been done in Case 2 in section 4.2.2, Chapter 4. The difference is that the stochastic data are used in the model. Clearly, in this case the objective function is re-written as:

$$\min_{X_{jk}, Y_{kl}, Z_k^r} \quad \lambda\Bigg(\sum_j \sum_k C_{jk} X_{jk} \;+\; \sum_k \sum_l T_{kl} Y_{kl} \Big[P_1(e,k) \;+\; (\alpha+1) P_2(e,k) + (\beta+1) P_3(e,k)\Big]\Bigg) \;+\; \sum_k \sum_r F_k^r Z_k^r \tag{5.23}$$

subject to (5.12), (5.15), (5.16) (5.17) & (5.19) (5.24)

$$\sum_j X_{jk} = \sum_r V_k^r Z_k^r, \forall k \tag{5.25}$$

$$\sum_r Z_k^r \leq 1, \forall k, \tag{5.26}$$

$$\sum_l Y_{kl} \leq \sum_r V_k^r Z_k^r, \forall k \tag{5.27}$$

$$Z_k^r \in \{0,1\}, \forall r, k. \tag{5.28}$$

The explanations for the above model are similar to those in the deterministic model of Case 2 in Section 4.2.2, Chapter 4.

The optimization in this case is carried out using the same inputs data as the ones used in Case 2 in the deterministic case with the only addition being the data in Tables 5.4 and 5.5. Results obtained for equations (5.23) - (5.28) show clear differences when compared with Case 2 in the deterministic case in Section 4.2.2.

Table 5.12: *Total cost for multiple capacities in Case 2 using stochastic model compared to the corresponding deterministic model.*

$e\#$	**Stochastic cost**	**Deterministic cost**	**VSS**	**cost increase (%)**	$\|K^s\|$	$\sum_{k=1}^{\|K^s\|} V_k^r$
1	14,096,951.53	12,660,522.80	1,436,428.73	11.35	5	145,247
2	14,158,620.32	12,660,522.80	1,498,097.52	11.83	5	145,712
3	13,880,908.81	12,660,522.80	1,220,386.01	9.64	5	145,247
4	14,011,318.37	12,660,522.80	1,350,795.57	10.67	5	145,247
5	14,567,500.95	12,660,522.80	1,906,978.15	15.06	5	145,712
6	14,550,492.64	12,660,522.80	1,889,969.84	14.93	5	145,247
7	14,482,101.31	12,660,522.80	1,821,578.51	14.39	5	145,215
8	14,489,388.35	12,660,522.80	1,828,865.55	14.45	5	145,215
9	14,317,562.84	12,660,522.80	1,657,040.04	13.09	5	145,247
10	14,040,098.33	12,660,522.80	1,379,575.53	10.90	5	145,247
11	14,414,109.13	12,660,522.80	1,753,586.33	13.85	5	145,712
12	14,623,164.72	12,660,522.80	1,962,641.92	15.50	5	145,217
13	15,123,921.37	12,660,522.80	2,463,398.57	**19.46**	5	145,429
14	14,122,471.22	12,660,522.80	1,461,948.42	11.55	5	145,144
15	14,606,144.17	12,660,522.80	1,945,621.37	15.37	5	145,144
16	14,164,641.90	12,660,522.80	1,504,119.10	11.88	5	145,144
17	13,689,755.32	12,660,522.80	1,029,232.52	**8.13**	4	145,144
Average	**14,314,067.72**	**12,660,522.80**	**1,653,544.92**	**13.06**	**5**	**145,310**

The last column in Table 5.12 shows the total capacities of all DCs which are selected for each week.

The percentage cost increase for week e for multiple capacities model as shown in Table 5.12, Column 5 ranges from 8.13% in week 17 to 19.46% for week 13. Week 13 is still the highest cost increase week as in Case 1 of stochastic model, while the lowest cost increase week is week 17. This is from the fact that the highest cost increase is caused by high probability values in $P_2(e,k)$ and $P_3(e,k)$. In week 13, all five DC zones are mostly dominated by high probability values of $P_2(13,k)$ and $P_3(13,k)$ as shown in Table 5.5 compared to the values for other weeks.

The average cost increase for all 17 weeks is 13.06% as indicated in the last row of Column 5. This percentage cost increase is as compared to deterministic cost which is also presented in Column 3. The percentage cost increase is slightly higher compared to the previous case, Case 1, stochastic model, using $\hat{V}_k$ and $\bar{V}_k$. However, this cost must be compared with the Case 2 of the deterministic model and not with Case 1 of the stochastic model. The higher cost is probably due to the fact that in computational results, for each week, the five DCs are being mostly selected compared to the four DCs in the deterministic case (see Column 6 in Table 5.12). This leads to high transportation costs from PCs to DCs since all five DCs are used instead of four DCs as in the deterministic counterpart. If we compare the results of the stochastic model, Case 2 has an average cost of \$14,314,067.72 (see Table 5.12) which is lower than Case 1 with an average cost of \$17,419,011.33 for $\hat{V}_k$ (see Table 5.6) and \$14,704,110.20 for $\bar{V}_k$ (see Table 5.9). This comparison shows that the use of V_k^r variable improves the cost for the stochastic model.

When compared to the deterministic model the number of DCs selected as presented in Column 6, Table 5.12, are the same except week 17. This also clearly portrays the effect of rainfall since the four selected DCs in week 17 are also the lowest cost increase compared to all the other weeks. As shown in the last column of the table, the total capacities of selected DCs, $\sum_{k=1}^{|K^s|} V_k^r$, range from lowest value of 145,144 and the highest value of 145,712 tons.

The summary results for the first week are detailed in Table 5.13 compared to deterministic results, Table 4.7.

Table 5.13: *Comparison of summarized results of stochastic and deterministic model for week 1.*

DC_k	**Results for week 1**				**Summary results from Table 4.7**			
	PC_j^s	V_k^r	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	V_k^r	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1; PC_2	$V_1^{11}(25,144)$	21	25,144	PC_1	$V_1^3(25,000)$	20	25,000
DC_2	PC_1	$V_2^2(38,532)$	19	38,532	-	-	-	-
DC_3	PC_1	$V_3^{14}(39,144)$	21	39,041	PC_1	$V_3^3(71,000)$	39	71,000
DC_4	PC_2	$V_4^6(13,283)$	11	13,283	PC_1; PC_2	$V_4^{13}(16,000)$	13	16,000
DC_5	PC_2	$V_5^{13}(29,144)$	24	29,144	PC_2	$V_5^3(33,144)$	24	33,144
Total		**(145,247)**	**96**	**145,144**		**(145,144)**	**96**	**145,144**

NOTE: '-' This means a corresponding DC is not selected by the program.

We compare the summarized results in Table 5.13 by considering the sub-columns PC_j^s, V_k^r, $|L_k|$ and $\sum_{l=1}^{|L_k|} Y_{kl}$ under **Results for week 1** and **Summary from Table 4.7**. In the two main columns, the major difference is the number of DCs which are selected. For week 1 five DCs are selected while in the deterministic case only four DCs are selected. Due to this fact, the clear differences shown between the sub-columns of the same labels are self-explanatory as the effect of stochastic rainfall in week 1.

Table 5.14 gives more details of some results for the highest and the lowest cost increase together with the deterministic results from Table 4.7 for comparison.

Table 5.14 shows that, for week 17, there is almost no difference of results compared to the values of the same labels in Table 4.7. Moreover, for week 13, the highest cost week differences of the results are not significant.

Table 5.14: *Comparison of summarized results for the lowest and highest cost weeks with deterministic results.*

DC_k	Results for week 17			Results for week 13			Summary results from Table 4.7		
	PC_j^s	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$	PC_j^s	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$	PC_j^s	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} Y_{kl}$
DC_1	PC_1	21	25,000	PC_1	21	25,000	PC_1	20	25,000
DC_2	-	-	-	PC_1	10	26,500	-	-	-
DC_3	PC_1	37	71,000	PC_1	23	39,000	PC_1	39	71,000
DC_4	PC_1; PC_2	14	16,000	PC_1; PC_2	13	15,715	PC_1; PC_2	13	16,000
DC_5	PC_2	24	33,144	PC_2	30	38,929	PC_2	24	33,144
Total		**96**	**145,144**		**97**	**145,144**		**96**	**145,144**

Generally, the existing distribution system had not been considering the stochastic effect due to rainfall as per collected field data. However, there have been complaints reported by a Longido CP in 2009 on cost increase due to poor roads for its seven wards of maize crop distribution out of the nine wards (Appendix D). The complaints were reported due to the conditions of unpaved roads caused by rainfall. The poor road conditions resulted in the increase of transportation cost in Longido CP by an average of 96.3%. This also motivated us to consider the stochastic effect in the modelling for our study.

5.4.3 Results for the stochastic model using eight DCs

We now perform a numerical study of stochastic model using the eight DCs, as we have done in the deterministic case in Chapter 4. We use the same model, equations (5.23) - (5.28), as in Case 2.

The inputs used are the same as those in Case 2 in subsection 5.4.2, but with additional data for the new three DCs. We have carried out optimization in three phases in each week as we have done in the deterministic part (see subsection 4.2.3).

The results obtained in the three phases for each week are summarized as follows:

- Phase 1 is where six DCs are considered of which five DCs are selected in each week except in week 10 where all the six DCs are selected. In the deterministic case, only five DCs were selected. The lowest weekly cost increase is 7.52% in week 8 and the highest is 18.45% in week 13. The average cost increase for all the 17 weeks is 12.47% as compared to the deterministic case.

- Phase 2 and 3 are when the seven and eight DCs are considered respectively. In both phases we obtained the same results in all weeks except for week five. Phase 2 has an average cost increase of 11.38% and Phase 3 the average cost increase is 11.32%. These cost increases are with respect to the corresponding costs of the deterministic model found in subsection 4.2.3.

In Table 5.15 we have summarized the results obtained for the third phase when the eight DCs were used.

Table 5.15 has the same notations as used in Table 5.12. From the results shown in the last row in Column 5, we see that the average cost increase is 11.32% which is lower than that of Case 2, Table 5.12. For the extended network of eight DCs, the cost on stochastic model is $13,697,054.49, which is the lowest compared to the cost obtained for existing network of five DCs using the stochastic model for Cases 1 and 2. In eight DCs, the lowest cost increase is 6.94% in week 8, the highest is 18.43% in week 13 as shown in Table 5.15.

Column 6 in Table 5.15 shows the number of DCs selected in each week. As it can be seen, there are five, six and seven selected DCs out of the eight DCs considered. The selection of five DCs in week 17 is a unique case caused by high probability values of $P_2(17, k)$ and $P_3(17, k)$ that are due to high rainfall in DC_1, DC_2 and DC_8 as shown in Table 5.5. The three listed DCs are not selected in week 17. However, in the deterministic case only six DCs were selected (see Table 4.8 in subsection 4.2.3). Again this is a clear effect of the stochastic

Table 5.15: *Total cost for eight DCs using stochastic model compared to the corresponding deterministic model.*

$e\#$	**Stochastic cost**	**Deterministic cost**	**VSS**	**cost increase (%)**	$\|K^s\|$	$\sum_{k=1}^{\|K^s\|} V_k^r$
1	13,703,487.19	12,303,719.06	1,399,768.13	11.38	7	145,770
2	13,653,035.26	12,303,719.06	1,349,316.20	10.97	6	145,215
3	13,317,228.94	12,303,719.06	1,013,509.88	8.24	6	145,261
4	13,297,044.78	12,303,719.06	993,325.72	8.07	6	145,215
5	13,949,049.54	12,303,719.06	1,645,330.48	13.37	7	145,216
6	13,998,674.17	12,303,719.06	1,694,955.11	13.78	7	145,770
7	14,013,894.84	12,303,719.06	1,710,175.78	13.90	7	145,770
8	13,157,856.94	12,303,719.06	854,137.88	**6.94**	6	145,215
9	13,699,742.76	12,303,719.06	1,396,023.70	11.35	6	145,215
10	13,587,326.52	12,303,719.06	1,283,607.46	10.43	7	145,770
11	14,031,275.41	12,303,719.06	1,727,556.35	14.04	7	145,770
12	13,944,540.05	12,303,719.06	1,640,820.99	13.34	6	145,215
13	14,570,881.06	12,303,719.06	2,267,162.00	**18.43**	7	145,221
14	13,289,200.19	12,303,719.06	985,481.13	8.01	6	145,215
15	14,068,900.51	12,303,719.06	1,765,181.45	14.35	6	145,144
16	13,314,118.17	12,303,719.06	1,010,399.11	8.21	6	145,500
17	13,253,670.02	12,303,719.06	949,950.96	7.72	5	145,644
Average	**13,697,054.49**	**12,303,719.06**	**1,393,335.43**	**11.32**	**6**	**145,419**

rainfall as addressed in this study.

The results in the last column, $\sum_{k=1}^{|K^s|} V_k^r$, of Table 5.15 present the total optimal capacity of the selected DCs. These capacities range from 145,144 tons to 145,770 tons across the 17 weeks. The different capacities observed from the stochastic model, are due to stochastic rainfall effect compared to the deterministic model where the optimal total DCs' capacity is 145,144 tons (see Table 4.8 in subsection 4.2.3).

We now summarize the results for week 1 compared to deterministic case, Table 4.8 in Table 5.16. The results presented in Table 5.16 are compared in a similar way as we have explained in Table 5.13. Similar comparisons are also presented in Table 5.17. Table 5.17 presents the comparison of the results of the lowest and highest cost weeks with the deterministic results, Table 4.8.

Table 5.16: *Comparison of summarized results for eight DCs of stochastic and deterministic model for week 1.*

DC_k	**Results for week 1**				**Summary results from Table 4.8**			
	PC_j^s	V_k^r	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	V_k^r	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1	$V_1^3(25,000)$	21	25,000	PC_1	$V_1^{11}(25,144)$	21	25,144
DC_2	PC_1	$V_2^{11}(26,000)$	14	26,000	-	-	-	-
DC_3	PC_1	$V3,6(39,000)$	22	38,374	PC_1	$V_3^5(45,000)$	25	45,000
DC_4	PC_1; PC_2	$V_4^6(13,283)$	11	13,283	PC_1; PC_2	$V_4^{13}(16,000)$	13	16,000
DC_5	PC_2	$V_5^1(14,500)$	11	14,500	PC_2	$V_5^1(14,500)$	15	14,500
DC_6	PC_1	$V_6^{13}(9,843)$	4	9,843	PC_1	$V_6^2(28,500)$	14	28,500
DC_7	PC_2	$V_7^3(18,144)$	15	18,144	PC_2	$V_7^9(16,000)$	10	16,000
DC_8	-	-	-	-	-	-	-	-
Total		**(145,770)**	**98**	**145,144**		**(145,144)**	**98**	**145,144**

The results in Table 5.17 have some significant differences in the values which are in the sub-columns under week 13 compared to Table 4.8. This is from the fact that in week 13, seven DCs are selected compared to six DCs selected in Table 4.8. However, in week 8, as

Table 5.17: *Comparison of summarized results for the lowest and highest cost weeks using eight DCs with the deterministic results.*

DC_k	**Results for week 8**			**Results for week 13**			**Summary results Table 4.8**		
	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$	PC_j^s	$\|L_k\|$	$\sum_{l=1}^{\|L_k\|} Y_{kl}$
DC_1	PC_1	21	25,144	PC_1	21	25,144	PC_1	21	25,144
DC_2	-	-	-	PC_1	14	26,500	-	-	-
DC_3	PC_1	21	39,073	PC_1	13	24,573	PC_1	25	45,000
DC_4	PC_1; PC_2	11	13,283	PC_2	11	13,283	PC_1; PC_2	13	16,000
DC_5	PC_2	14	14,500	PC_2	12	14,500	PC_2	15	14,500
DC_6	PC_1	15	35,000	PC_1; PC_2	13	25,000	PC_1	14	28,500
DC_7	PC_2	15	18,144	PC_2	13	16,144	PC_2	10	16,000
DC_8	-	-	-	-	-	-	-	-	-
Total		**97**	**145,144**		**97**	**145,144**		**98**	**145,144**

compared to Table 4.8, there are some differences clearly shown in DC_3, DC_4, DC_6 and DC_7 for values under $|L_k|$ and $\sum_{l=1}^{|L_k|} Y_{kl}$.

From the comparisons of results above, it is clear that the stochastic effect due to rainfall is an important factor to be considered for the transportation planning in food security issues in Tanzania. The results revealed by this study are of great importance for the restructuring of the transportation network for food security.

5.5 Results for the stochastic model using combined 17 weeks

We have observed from the previous section that, on a weekly basis, in a period of 17 weeks, there is an increase in the cost due to stochastic aspect of our model compared to that of the deterministic model. The cost increase was observed for each run (that is, for each week). In this section we are considering the model where all 17 weeks are combined and the demand, d_l, is to be met for each week. This section is similar to that of the deterministic case in section 4.3. We are using decision variable $\bar{Y}_{kl}$ as the weekly amount in tons flow from DC_k to CP_l in week e. This amount will be same for each week and the total demand, D_l, will be met after the 17 weeks. In this case, a weekly demand to be met at CP_l is d_l, given by $\sum_{k=1}^{|K|} \bar{Y}_{kl} = d_l$. The model is used in both the existing distribution network and the extended network. We study the overall cost increase when all 17 weeks are optimized together under the stochastic effect. Results obtained are compared with those of the deterministic model found in sections 4.2 and 4.3.

We first consider the existing distribution network model for single capacity of the DCs. The resulting combined model for single capacity is presented below:

$$\begin{aligned} \underset{X_{jk},\bar{Y}_{kl},Z_k}{\text{Min}} \quad \lambda \Bigg(\sum_j \sum_k C_{jk} X_{jk} \; + \; \sum_k \sum_l \sum_e T_{kl} \bar{Y}_{kl} \Big[P_1(e,k) \; + \; (\alpha+1) P_2(e,k) \\ + (\beta+1) P_3(e,k) \Big] \Bigg) \; + \; \sum_k F_k Z_k \end{aligned} \tag{5.29}$$

$$\text{subject to} \qquad (5.12), (5.13), (5.16) \; \& \; (5.18) \tag{5.30}$$

$$|E| \sum_l \bar{Y}_{kl} \leq V_k Z_k, \forall k, \tag{5.31}$$

$$|E| \sum_k \bar{Y}_{kl} = D_l, \forall l, \tag{5.32}$$

$$\bar{Y}_{kl} \geq 0, \forall k, l. \tag{5.33}$$

The explanations of the model:

- The objective function in equation (5.29) with stochastic component minimizes the total distribution cost and it is similar to equation (5.22) but here we model the combined 17 weeks.

- Constraints (5.30) are as used in the previous model.

- Constraints (5.31) refer to the amount supplied, $\bar{Y}_{kl}$, for each week in $|E|$ weeks by DC_k to all CP_l, $l \in L$, not exceeding V_k. The weekly amount, $\bar{Y}_{kl}$, transported is the same for each week.

- Constraints (5.32) represent the weekly amount, $\bar{Y}_{kl}$, that need to be transported in week e for $|E|$ weeks from all DC_k, $k \in K$, to the CP_l, which must meet the demand, D_l.

- Constraints (5.33) represent the non-negativity restrictions.

5.5.1 Results for the existing distribution network

As we have done in the individual weeks, the existing maize crop distribution system is now being evaluated using the combined 17 weeks model. The computational experiments are carried out using the same cases as used previously.

Computational results for Case 1

The computational experiments in this section are carried out using the stochastic model (5.29) with the constraints (5.30) - (5.33). The data used are the same as those used on weekly basis. The respective data used from several tables are only from DC_1 to DC_5 in this regard. We are considering the Case 1 with the true capacity, $\hat{V}_k$. Next, we show the results using actual capacity, $\bar{V}_k$.

Table 5.18 presents the results of true capacity for 17 weeks model with column labels being the same as in Table 5.8, except the sub-columns under $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$. The results under $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$, denote the amount of maize crop, $\bar{Y}_{kl}$, to be transported from a DC to its respective CPs for each week over 17 weeks. All five DCs are selected and all customers are served. The specific amount $\bar{Y}_{kl}$ to be transported weekly to each CP from DCs are detailed in Table A.1.

Table 5.18: *Comparison of results for Case 1 for the combined 17 weeks - true capacity.*

DC_k	PC_j^s	Stochastic results			Deterministic results, Table 4.9	
		$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert E\rvert \sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1, PC_2	28	2,315.35	39,361	28	2,315.35
DC_2	PC_1	18	2,294.12	39,000	18	2,294.12
DC_3	PC_1	27	2,294.12	39,000	29	2,294.12
DC_4	PC_2	11	781.35	13,283	11	781.35
DC_5	PC_2	12	852.94	14,500	10	852.94
Total		**96**	**8,537.88**	**145,144**	**96**	**8,537.88**

The values found in Table 5.18 under $|L_k|$ and $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ are comparable to the deterministic case found in Table 4.9 as summarized within Table 5.18. The $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ values in both tables are the same. However, $|L_k|$ values are different for only DC_3 and DC_5 but the difference is not highly significant (see Table 5.18). The total cost obtained for the stochastic model using true capacity is \$17,490,817.51. This cost is 10.98% higher than the cost for the deterministic model found in subsection 4.3.1. The increase is not much different from the average cost increase of 11.87% for the individual weeks as presented in Table 5.6. This cost increase is mostly caused by distance increase due to the effects of rainfall on roads.

In Case 1, we re-run the program using the actual capacity, $\bar{V}_k$, and results are shown in Table 5.19. The other inputs data to the model apart from $\bar{V}_k$ remain the same as used in the case of true capacity.

The results in Table 5.19 are self-explanatory as it have been explained in the case of true capacity. The amount of maize crop transported from each DC to each CP is shown in Table A.2. The values found in Tables 5.19 and 4.9 (actual capacity column in section 4.3) under $|L_k|$ and $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ are almost the same. The total cost in this computational results is \$14,706,927.63. Thus the percentage cost increase in this solution compared to deterministic case for actual capacity in subsection 4.3.1 is 10.08%.

Table 5.19: *Comparison of results for Case 1 for the combined 17 weeks - actual capacity.*

DC_k	PC_j^s	Stochastic results			Deterministic results, Table 4.9	
		$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert E\rvert \sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1	26	1,952.35	33,190	26	1952.352941
DC_2	PC_1	17	2,266.59	38,532	18	2266.588235
DC_3	PC_1	13	1,450.00	24,650	13	1,450.00
DC_4	PC_1 ; PC_2	9	579.00	9,843	9	579.00
DC_5	PC_2	30	2,289.94	38,929	29	2289.941176
Total		**95**	**8,537.88**	**145,144**	**95**	**8,537.88**

Computational results for Case 2

In this case, the computational experiments are carried out using the multiple capacities under the stochastic model are presented below:

$$\min_{X_{jk},\bar{Y}_{kl},Z_k^r} \lambda\Bigg(\sum_j\sum_k C_{jk}X_{jk} + \sum_k\sum_l\sum_e T_{kl}\bar{Y}_{kl}\Big[P_1(e,k) + (\alpha+1)P_2(e,k) + (\beta+1)P_3(e,k)\Big]\Bigg) + \sum_k\sum_r F_k^r Z_k^r \tag{5.34}$$

subject to $(5.12), (5.16), (5.25), (5.26), (5.28), (5.32)\ \&\ (5.33),$ (5.35)

$$|E|\sum_l \bar{Y}_{kl} \leq \sum_r V_k^r Z_k^r, \forall k. \tag{5.36}$$

The objective function of the stochastic model now considers the multiple capacities as addressed through Z_k^r, V_k^r and F_k^r. The constraints are the same except equation (5.36) which is a newly modified constraint for restriction on the DCs' multiple capacities.

The 17 weeks model in this case uses the same data as in Case 2 for individual weeks. Table 5.20 shows the results where column and sub-column labels are same as defined for Case 1

Table 5.20: *Comparison of results for Case 2 for the combined 17 weeks.*

	Stochastic results				Deterministic results, Table 4.10			
DC_k	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1	$V_1^7(25,144)$	22	1,596.71	PC_1	$V_1^3(25,000)$	20	1,470.59
DC_2	PC_1	$V_2^5(26,500)$	12	1,558.82	-	-	-	-
DC_3	PC_1	$V_3^{13}(45,144)$	27	2,651.35	PC_1	$V_3^3(71,000)$	38	4,176.47
DC_4	PC_1; PC_2	$V_4^6(13,283)$	11	781.35	PC_1; PC_2	$V_4^{13}(16,000)$	13	941.18
DC_5	PC_2	$V_5^3(33,144)$	25	1,949.65	PC_2	$V_5^3(33,144)$	24	1,949.65
Total		**(145,215)**	**97**	**8537.88**		**(145,144)**	**95**	**8,537.88**

above. The exceptions are the sub-columns under V_k^r that accounts for multiple capacities. These results are different from the corresponding deterministic results, Table 4.10, in terms of the number of DCs selected. All five DCs are selected for the stochastic case while only four DCs are selected in the deterministic case. So $|L_k|$, $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ and V_k^r values in Tables 5.20 and 4.10 are clearly different. Table A.3 shows the specific amount of maize crop transported from DCs to each CP for this case.

The total cost obtained from this study is \$14,360,877.40 with the percentage of cost increase of 11.84% as compared to the corresponding cost of the deterministic model.

5.5.2 Results for the stochastic model using eight DCs

In this extended network where new DCs are involved, the same stochastic model, i.e. equation (5.34) and the constraints (5.35) to (5.36) are used. We use the same input data as used in Case 2 of subsection 5.5.1. However, there are some additional input data corresponding to the three new DCs as it was done in deterministic case, section 4.2.3. The three phases are considered in these computational experiments.

In Phase 1 we run the program using six DCs. The computational results for Phase 1 have a cost increase of 11.73% as compared to the deterministic case where all six DCs are selected.

In phases 2 and 3, where seven and eight DCs are considered respectively, the cost increase of 10.57% was observed in both cases. A total cost observed in both of these two phases is \$13,758,193.63. Table 5.21 details the results of Phase 3 where six out of eight DCs are selected.

Table 5.21: *Comparison of results using eight DCs for the combined 17 weeks.*

	Stochastic results				Deterministic results, Table 4.11			
DC_k	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$	PC_j^s	V_k^r	$\lvert L_k\rvert$	$\sum_{l=1}^{\lvert L_k\rvert} \bar{Y}_{kl}$
DC_1	PC_1	$V_1^{11}(25,144)$	21	1,479.06	PC_1	$V_1^{11}(25,144)$	21	1,479.06
DC_2	-	-	-	-	-	-	-	-
DC_3	PC_1	$V_3^{14}(39,144)$	24	2,298.41	PC_1	$V_3^{5}(45,000)$	26	2,647.06
DC_4	PC_1 ; PC_2	$V_4^{6}(13,283)$	11	781.35	PC_1 ; PC_2	$V_4^{13}(16,000)$	13	941.18
DC_5	PC_2	$V_5^{1}(14,500)$	11	852.94	PC_2	$V_5^{1}(14,500)$	14	852.94
DC_6	PC_1	$V_6^{5}(35,000)$	17	2,058.82	PC_1	$V_6^{2}(28,500)$	14	1,676.47
DC_7	PC_2	$V_7^{3}(18,144)$	13	1,067.29	PC_2	$V_7^{9}(16,000)$	10	941.1764706
DC_8	-	-	-	-	-	-	-	-
Total		**(145,215)**	**97**	**8,537.88**		**(145,144)**	**98**	**8,537.88**

The computational results in Table 5.21 are very much similar to the deterministic case as summarized in Table 4.11. This is from the fact that the same number and the same DCs are selected as the results shown in columns under stochastic and deterministic case. However, the values under $|L_k|$ and $\sum_{l=1}^{|L_k|} \bar{Y}_{kl}$ for both Tables 5.21 and 4.11 are different except only for DC_1. Similarly the values under V_k^r (indicated in brackets) are also significantly different for DC_3, DC_4, DC_6 and DC_7. These are clearly a reflection on the allocations due to stochastic rainfall. Table A.4 shows in details the amount of maize crop transported from DCs to each CP.

In further comparison with the deterministic case, the values under the PC_j^s are the same in both cases, while the V_k^r values are different except for DC_1 and DC_5 as shown in respective sub-columns in Table 5.21. These are re-allocations resulting from the stochastic rainfall effect with a cost increase of 10.57% for the eight considered DCs.

Table 5.22 gives the summary of the 17 weeks results for all types of computational experiments conducted. Some labels used in the columns of Table 5.22 are explained below the table.

Table 5.22: *Summary table for computational results and some comparisons.*

Type of Opt.	$\lvert K^s \rvert$	Stochastic cost	Deterministic cost	VSS	X(%)	Y(%)	Z(%)
C1($\hat{V_k}$)	5	17,490,817.51	15,570,885.08	1,919,932.43	10.98	11.87	0.86
C1($\bar{V_k}$)	5	14,706,927.63	13,224,626.75	1,482,300.88	10.08	11.19	1.11
C2 (V_k^r)	5	14,360,877.40	12,660,522.80	1,700,354.60	11.84	13.06	1.22
6 DCs	6	13,988,157.14	12,346,976.95	1,641,180.19	11.73	12.45	0.72
7 DCs	6	13,758,193.63	12,303,719.06	1,454,474.57	10.57	11.39	0.82
8 DCs	6	13,758,193.63	12,303,719.06	1,454,474.57	10.57	11.35	0.78
Average		**14,677,194.49**	**13,068,408.28**	**1,608,786.21**	**10.96**	**11.88**	**0.92**

NOTE: Opt. = Optimization, C1 = Case 1, C2 = Case 2,

X = Cost increase for stochastic model using combined 17 weeks compared to the corresponding deterministic model,

Y = An average cost increase for stochastic model using individual week compared to the corresponding deterministic model,

Z = Difference between the results in columns **X(%)** and **Y(%)**, i.e. $(Y - X)\%$.

The summarized results in Table 5.22, give the general overview of cost increase due to stochastic rainfall effect for a number of cases. The cost increase is above 10% of the corresponding cost of the deterministic model. This is clearly shown in Table 5.22 under columns $X(\%)$ and $Y(\%)$. Since these costs are in thousands of US dollar, thus the costs are important to be considered. This also calls for the attention in reviewing the existing distribution network in order to ensure its smooth operation with reasonable costs.

5.6 An alternative model for combined 17 weeks

The combined 17 weeks model studied in section 5.5 can be presented in another form when the three probabilities are computed from entire data set of 17 weeks' rainfall for each DC zone. In section 5.5, we used three intervals in each week for calculations of the three probabilities for each DC zone. This section considers the same intervals in calculations of the three probabilities using entire data set of 17 weeks instead of each week for each DC zone.

For the computation of the three probabilities, we consider $P_s(k)$ instead of $P_s(e,k)$, where $s = 1, 2$ and 3, corresponding to three intervals. Thus, $\sum_{s=1}^{3} P_s(k) = 1$ for each DC zone k. Table 5.23 presents the probabilities in each DC zone k to be used in the present model.

Table 5.23: *The probability values for all three scenarios over 17 weeks in each DC zone k.*

P_s	**DC zone (DC_k)**							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
P_1	0.511	0.503	0.495	0.500	0.500	0.608	0.500	0.515
P_2	0.449	0.449	0.456	0.463	0.460	0.333	0.471	0.441
P_3	0.040	0.048	0.049	0.037	0.040	0.059	0.029	0.044

5.6.1 The mathematical model and results

The model in this section is an alternative model but similar to the one used in section 5.5 where the probabilities in Table 5.23 have been calculated using rainfall data over 17 week period.

The model to be optimized is given by:

$$\underset{X_{jk},Y_{kl},Z_k}{\text{Min}} \quad \lambda\Bigg(\sum_j \sum_k C_{jk}X_{jk} \; + \; \sum_k \sum_l T_{kl}Y_{kl}\Big[P_1(k) \; + \; (\alpha+1)P_2(k) \\ + (\beta+1)P_3(k)\Big]\Bigg) \; + \; \sum_k F_k Z_k \tag{5.37}$$

$$\text{subject to} \qquad (5.30), (5.31), (5.32) \; \& \; (5.33). \tag{5.38}$$

For multiple capacities per DC the model becomes:

$$\underset{X_{jk},Y_{kl},Z_k^r}{\text{Min}} \quad \lambda\Bigg(\sum_j \sum_k C_{jk}X_{jk} \; + \; \sum_k \sum_l T_{kl}Y_{kl}\Big[P_1(k) \; + \; (\alpha+1)P_2(k) \\ + (\beta+1)P_3(k)\Big]\Bigg) \; + \; \sum_k \sum_r F_k^r Z_k^r \tag{5.39}$$

$$\text{subject to} \qquad (5.35) \; \& \; (5.36). \tag{5.40}$$

Table 5.24 shows the computational results in both single and multiple capacity models. Results in Table 5.24 shows insignificant differences, while the data under $|K^s|$ differ by one only in the row under *6 DCs* (V_k^r), the remaining results are almost the same.

The main reason to the observed results is that, we used the same rainfall data (Tables A.5,A.6, A.7, A.8, A.9, A.10, A.11 and A.12) with the same intervals (values of $A(k)$ and $B(k)$ in Table 5.3) in each DC zone for calculation of the three probabilities using 17-week period instead of each week. This means that the probabilities in the combined 17 weeks is similar to the finding of averages of the probabilities in each week for all 17 weeks for each interval.

Table 5.24: *Comparison of stochastic model results for Sections 5.5 and 5.6.*

Type of Opt	**Section 5.5 results**		**Section 5.6 results**		**Cost differences**	
	$\lvert K^s \rvert$	**Stochastic cost**	$\lvert K^s \rvert$	**Stochastic cost**	**Numerical**	**Percentage**
C1($\hat{V}_k$)	5	17,490,817.51	5	17,489,886.66	930.85	0.01
C1($\bar{V}_k$)	5	14,706,927.63	5	14,705,302.35	1,625.28	0.01
C2 (V_k^r)	5	14,360,877.40	5	14,359,424.01	1,453.39	0.01
6 DCs (V_k^r)	**6**	13,988,157.14	**5**	13,987,511.59	645.56	0.00
7 DCs (V_k^r)	6	13,758,193.63	6	13,758,046.43	147.20	0.00
8 DCs (V_k^r)	6	13,758,193.63	6	13,758,046.43	147.20	0.00
Average		**14,677,194.49**		**14,676,369.58**	**824.91**	**0.01**

5.7 Results for the projected demand using extended network

In Tanzania, the 2012 national population census revealed the annual population growth to be 2.7% [83]. Hence there will be an increase in demand of the maize crop. We have therefore studied the performance of the extended network based on the projected demands in the next five and ten years. We have denoted the projected demand by $\hat{D}_l$. This is calculated from D_l by considering a percentage increase for annual demand (denoted by $D_l(\uparrow)$ in Table 5.25) in each corresponding number of years. In particular, we have considered the annual demand increase of 5%, 10% and 12% as indicated in Table 5.25. Apart from the new demand, the remaining inputs used for optimization are the same as those used in section 5.6 for eight DCs. For this experiment we have used the mathematical model for the extended network presented with the equations (5.39) - (5.40). The results are summarized in Table 5.25 where the notations used in the columns are the same as those found in the text.

The results in Table 5.25 indicate the sustainability of the extended network for the next five and ten years where up to 12% annual demand increase is possible. This is from the fact that the current total capacity for eight DCs is 337,500 tons while the maximum observed total capacity to be utilized is 319,317 tons. This is for 12% annual demand increase in the

Table 5.25: *Summary results for the increased demand*

Years	$\sum_{l=1}^{\lvert L\rvert} \hat{D}_l$	D_l (↑)	$\lvert K^s\rvert$	$\sum_{k=1}^{\lvert K^s\rvert} V_k^r$	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
5	181,430	5%	7	181,571	25,000	-	39,000	18,144	29,000	39,000	18,144	13,283
	217,716	10%	8	217,783	25,000	26,000	45,000	24,000	33,000	25,000	26,500	13,283
	232,230	12%	7	232,288	28,500	-	45,144	24,000	39,000	53,000	26,500	16,144
10	217,716	5%	8	217,783	25,000	26,000	45,000	24,000	33,000	25,000	26,500	13,283
	290,288	10%	7	290,573	39,361	-	59,000	34,000	38,929	63,000	43,000	13,283
	319,317	12%	8	319,361	39,361	26,000	63,000	34,000	45,000	53,000	43,000	16,000

next ten years (see last row in Table 5.25 under $\sum_{k=1}^{|K^s|} V_k^r$). The number of DCs to be used in projected demand $\hat{D}_l$, are seven and eight (see column under $|K^s|$ in Table 5.25). Notice that under the current demand D_l, only six DCs were found to be optimal.

The last eight columns under DC_1 to DC_8 in Table 5.25, indicate the capacity for each selected DC. DC_3 and DC_6 mostly appear to have higher selected capacities than others while DC_8 has the lowest selected capacity. This is due to the number of CPs together with their demands being higher for DC_3 and DC_6. These two DCs are located in semi-arid areas where there is always deficit of maize crop harvest every year.

The results obtained with the above experiment clearly suggest that the government's plan to build three new DCs with suggested maximum capacities is appropriate, given the increased demands.

Chapter 6

Conclusions and future research

6.1 Conclusions

The capacitated two-level facility location problem (FLP) has been studied in this thesis. The study involves a model that integrates three layers namely: production centers (PCs), distribution centers (DCs) and customer points (CPs).

Using the mathematical model, a distribution network is established with minimum cost for transportation of maize crop from PCs to CPs through DCs. We have studied both a deterministic and a stochastic version of our model using a case study in Tanzania. The consideration of the deterministic model in this thesis is mainly for comparison with the results of the stochastic model. In both cases, we have studied two types of distribution networks, the existing distribution network and an extended distribution network. The existing distribution network is when five DCs are used while in the extended distribution network, the same five DCs are used together with the three new proposed DCs. In these two networks, the general goal is to satisfy the customers' demand with minimum overall distribution cost. We have considered four PCs, eight DCs and 93 CPs. These are the ingredients of the studied network.

The following are the summary results that have been revealed in the existing distribution network for the deterministic model as detailed in Chapter 4:

(a) The manually operated network was found not to be optimal. This is due to the observed overall cost saving that results from reallocation of PCs, DCs and CPs compared to the manually operated network. The details are presented in section 4.2.2, Chapter 4.

(b) Through optimization, an improved network was established, resulting in an average cost saving of \$564 thousand, compared to the manually operated network. The model predicted 4.27% of cost reduction from the cost of manually operated network. The improved results show that only four DCs should be used out of the five DCs considered.

When considering the sustainability of the network over a period of time (e.g. five or ten years to come) with maximum annual demands being satisfied, we have also studied and analysed the extended network using eight DCs. This is based on high production capacities in PCs and future increased demands. The results for this extended network are stated below:

- By using eight DCs, an improvement in terms of cost reduction was achieved compared to the existing network.

- The results for eight DCs have reduced the cost obtained in the existing network in part (b) above by 3%. This is equivalent to a saving of \$357 thousand. When we compared to the cost of the manually operated existing network, the extended network had reduced the cost by 7.27% (3% + 4.27%). This is a significant saving which has been achieved through the extended network. In this experiment, only six DCs are selected out of eight DCs where two of the six selected DCs are the newly proposed DCs.

The stochastic model presented in Chapter 5 is an extension of the deterministic model by considering the effect of rainfall in the transportation network. In the computational experiments for the stochastic model, we have observed an overall network cost increase as compared to the cost of the corresponding deterministic model. Furthermore, the analysis on location-allocations for PCs, DCs and CPs, also have been addressed in Chapter 5. We have carried out these computations in the existing network and the extended network. The computational results for the stochastic model are as follows:

(i) In the existing network, an average cost increase of 13.06% was observed compared to the corresponding cost of the deterministic model.

(ii) In the case of the extended network using eight DCs, the cost increase for the stochastic model is 11.32% as compared to the corresponding cost of the deterministic model. This cost increase obtained for the extended network, is lower than that of the existing network (13.06%) as presented in (i) above. This also clearly indicates the potential of using extended network for cost reduction.

Generally, the cost increase due to stochastic rainfall is an important factor to be considered prior to transportation planning. This is due to the fact that the condition of road networks, in Tanzania, can be affected by rainfall (see Longido case in Appendix D). The Tanzanian government is encouraged to consider this factor as suggested by this study.

The results obtained show that optimization as a decision tool in logistic problems is important. It can be used by all stakeholders and practitioners in their planning. The results of extended network also give more potential for future planning (e.g. expansion of PCs' and DCs' capacities), and that this should be done using optimization as one of the decision tools. The Tanzanian government is encouraged to use the results from this study for reviewing its existing maize crop distribution network.

We have also studied the structure of the optimized extended network using increased annual demand of maize crop over five and ten year horizons. Results show that in both horizons, the proposed extended network is sustainable under 12% annual increase in demand over a period of 10 years.

6.2 Contributions

In the current literature, the two-level FLP does not address the stochasticity due to rainfall effect, in particular in the context of a real life problem. In addition, to the best of our knowledge, this is the first real life case study that has been carried out in the context of Africa. The contributions of our study in the literature are as follows:

- The mathematical modelling of the real life problem;
- The study of the effectiveness of the current network used;
- The viability of the current network;
- The extension of the network to deal with increased demand.

6.3 Future research

There are possible directions that this research could lead to the following:

- The modelling carried out in this study can be done in other similar applications particularly in the context of Africa.
- The two-level FLP studied here can be extended to VRP, supply chain and LRP.
- The model can be extended by the use of different transportation modes such as railways. The railways are a cost effective mode of transportation as compared to transportation by vehicles. A combination of two different modes, such as vehicles and trains, can also be considered in the future modelling.
- The mathematical model can be extended to include the cost of carbon emissions. In this case vehicles with different carbon emission rates can be decision variables.

Appendix A

General information for collected data and tables

The list of data used in this research and their sources are stated below.

- Tanzania National Roads Agency (TANROADS): This is an authority that deals with road management in Tanzania. They managed National Roads Network (NRN) which are classified into Trunk Roads (TR) and Regional Roads (RR). Through TANROADS, I obtained road distances between regions as updated in March 2009. Distances in thousand of kilometers (km), shown in Tables B.1, B.7, B.8, B.9 and B.10, were sourced from this authority. The original data is presented in Figure C.3.

- Ministry of Agriculture, Food Security and Cooperatives (MAFSC): This is the ministry that responsible for all agricultural matters including data for all crops and production forecasts. Maize crop production capacity and surplus was obtained from 'Volume 1: The 2010/11 Final Food Crop Production Forecast for 2011/12 Food Security EXECUTIVE SUMMARY'(http://www.kilimo.go.tz/publications). The used PCs' capacity are based on 2011/12 production year and are sourced from website of this ministry. The production capacity for each PC is shown in Table B.4. The values were obtained through the computations presented in Table B.3.

- National Food Reserve Agency (NFRA): This is an established autonomous agency under MAFSC that specifically deals with food reserve (buying food crops for storage). The main functions are defined as to (i) procure and store emergency food stock that should suffice to address a food disaster for at least three (3) months period, (ii) Stock re-cycling, and (iii) stock release that would stabilize food prices in the market. All the DCs are managed by NFRA. The unused DCs or some capacities within DCs by NFRA can be hired by private companies under public private partnership (PPP) policy of the country. The private companies used these DCs to store their grain crops for the business purposes within and outside the country. Data on DCs' existing capacities, transportation cost (Tanzania shillings per km per ton) and DCs' annual fixed cost are collected in NFRA as shown in Figures C.1, C.4 and C.5.

- Prime Minister Office (Disaster Department): The disaster management department in the Prime Minister's office (PMO) deals with all disaster cases in the country. Food shortage is one of the disaster that is managed by this department. The management of maize crop from DCs to CPs is under this department. In this department, districts' (customers) demand quantities of maize crop (2004-2010) were obtained. Some distances between DCs and CPs (93 districts) are also sourced here. Customers' demand are as shown in the Table A.13. The regional distances (from TANROADS) and some given distances from DCs to CPs are used to compute the other DCs to CPs distances. The task was also done by using Tanzania map showing regions and their districts. The map is in the appendix as presented in Figure C.6. The DC to CP distances in kilometers are shown in Tables B.7, B.8, B.9 and B.10. In general data for optimization are presented in Tables B.1, A.13, B.2, B.3, B.4, B.7, B.8, B.9 and B.10. The tables are referred in the text accordingly as per computations requirement.

Table A.1: *Computational results: CP_l to DC_k allocation and d_l for combined 17 weeks Case 1, true capacity ($\hat{V}_k$).*

CP_l & d_l ($K = DC_3$)		CP_l & d_l ($K = DC_1$)		CP_l & d_l ($K = DC_1$)		CP_l & d_l ($K = DC_5$)	
Babati	83.53	Bagamoyo	160.06	Same	152.29	Biharamulo	53.06
Bahi	73.47	Handeni	192.18	Simanjiro	200.76	BukobaR	16.94
Bariadi	3.71	Kibaha	84.18			Geita	22.53
Chamwino	112.47	Kilindi	69.53			Ilemela	5.35
DodomaR	191.71	Kilosa	66.94			**Kwimba**	**25.35**
DodomaU	38.18	Kilwa	43.06			Magu	329.00
Hanang	**106.88**	Kisarawe	107.76	$CP_l \& d_l (K = DC_2)$		Meatu	246.00
Igunga	68.94	Korogwe	37.94	Arumeru	117.94	Misungwi	72.59
Iramba	137.53	LindiR	44.76	ArushaU	73.41	Muleba	21.71
Kahama	50.41	Liwale	40.76	Bunda	213.94	Nyamagana	4.24
Kishapu	93.18	Lushoto	76.35	Hai	25.35	Sengerema	11.76
Kiteto	51.35	Mafia	1.88	**Hanang**	**1.59**	Ukerewe	44.41
Kondoa	108.65	Masasi	139.65	Karatu	133.94		
Kongwa	194.53	Mkinga	81.18	Longido	264.88	$CP_l \& d_l (K = DC_4)$	
Kwimba	**96.41**	Mkuranga	46.94	Mbulu	72.82	Chunya	60.59
Manyoni	227.71	MorogoroR	98.06	Monduli	255.59	IringaR	233.76
Maswa	133.76	**Mpwapwa**	**158.35**	MoshiR	59.24	Kilolo	18.88
Mpwapwa	**17.71**	MtwaraR	39.29	Musoma	58.53	Kilombero	17.65
Nzega	135.41	Muheza	11.76	MusomaR	191.00	Ludewa	8.82
ShinyangaR	37.76	Mvomero	84.94	Ngorongoro	378.00	Makete	2.41
ShinyangaU	5.88	Mwanga	53.94	Rombo	215.47	Mbarali	100.29
Sikonge	29.76	Nachingwea	70.94	Rorya	129.18	Mbozi	5.88
SingidaR	180.88	Nanyumbu	49.06	Serengeti	29.94	Mufindi	45.18
SingidaU	8.82	Pangani	54.94	Siha	19.59	Njombe	103.18
TaboraR	4.00	Ruangwa	41.24	Tarime	53.71	Ulanga	184.71
TaboraU	10.71	Rufiji	106.59				
Uyui	90.76						

Table A.2: *Computational results: CP_l to DC_k allocation and d_l for combined 17 weeks Case 1, actual capacity ($\bar{V}_k$).*

CP_l & d_l ($K = DC_1$)		CP_l & d_l ($K = DC_5$)		CP_l & d_l ($K = DC_5$)		CP_l & d_l ($K = DC_3$)	
Bagamoyo	160.06	Bariadi	3.71	TaboraU	10.71	Babati	83.53
Handeni	192.18	Biharamulo	53.06	Tarime	53.71	Bahi	73.47
Kibaha	84.18	BukobaR	16.94	Ukerewe	44.41	Chamwino	112.47
Kilindi	69.53	Bunda	213.94	Uyui	90.76	DodomaR	191.71
Kilombero	17.65	Geita	22.53			DodomaU	38.18
Kilosa	66.94	Igunga	68.94	$CP_l \& d_l (K = DC_2)$		**Hanang**	**2.65**
Kilwa	43.06	Ilemela	5.35	Arumeru	117.94	Kiteto	51.35
Kisarawe	107.76	Iramba	137.53	ArushaU	73.41	Kondoa	108.65
Korogwe	37.94	Kahama	50.41	Hai	25.35	Kongwa	194.53
LindiR	44.76	Kishapu	93.18	**Hanang**	**105.82**	Manyoni	227.71
Liwale	40.76	Kwimba	121.76	Karatu	133.94	Mpwapwa	176.06
Lushoto	76.35	Magu	329.00	Longido	264.88	SingidaR	180.88
Mafia	1.88	Maswa	133.76	Mbulu	72.82	SingidaU	8.82
Masasi	139.65	Meatu	246.00	Monduli	255.59		
Mkinga	81.18	Misungwi	72.59	MoshiR	59.24	$CP_l \& d_l (K = DC_4)$	
Mkuranga	46.94	Muleba	21.71	Mwanga	53.94	Chunya	60.59
MorogoroR	98.06	Musoma	58.53	Ngorongoro	378.00	IringaR	233.76
MtwaraR	39.29	MusomaR	191.00	Rombo	215.47	Kilolo	18.88
Muheza	11.76	Nyamagana	4.24	**Rorya**	**107.59**	Ludewa	8.82
Mvomero	84.94	Nzega	135.41	Same	152.29	Makete	2.41
Nachingwea	70.94	**Rorya**	**21.59**	Serengeti	29.94	Mbarali	100.29
Nanyumbu	49.06	Sengerema	11.76	Siha	19.59	Mbozi	5.88
Pangani	54.94	ShinyangaR	37.76	Simanjiro	200.76	Mufindi	45.18
Ruangwa	41.24	ShinyangaU	5.88			Njombe	103.18
Rufiji	106.59	Sikonge	29.76				
Ulanga	184.71	TaboraR	4.00				

Table A.3: *Computational results: CP_l to DC_k allocation and d_l for combined 17 weeks in Case 2.*

CP_l & d_l $(K = DC_3)$		CP_l & d_l $(K = DC_5)$		CP_l & d_l $(K = DC_2)$		CP_l & d_l $(K = DC_1)$	
Babati	83.53	Bariadi	3.71	Arumeru	117.94	Bagamoyo	160.06
Bahi	73.47	Biharamulo	53.06	ArushaU	73.41	Handeni	192.18
Chamwino	112.47	BukobaR	16.94	Hai	25.35	Kibaha	84.18
DodomaR	191.71	Bunda	213.94	Longido	264.88	Kilindi	69.53
DodomaU	38.18	Geita	22.53	Monduli	255.59	Kilwa	43.06
Hanang	108.47	Ilemela	5.35	MoshiR	59.24	Kisarawe	107.76
Igunga	68.94	Kahama	50.41	Ngorongoro	378.00	Korogwe	37.94
Iramba	137.53	Kishapu	93.18	Rombo	215.47	LindiR	44.76
Karatu	133.94	Kwimba	121.76	**Rorya**	**63.76**	Liwale	40.76
Kilosa	66.94	Magu	329.00	**Same**	**55.65**	Lushoto	76.35
Kiteto	51.35	Maswa	133.76	Serengeti	29.94	Mafia	1.88
Kondoa	108.65	Meatu	246.00	Siha	19.59	Masasi	139.65
Kongwa	194.53	Misungwi	72.59			Mkinga	81.18
Manyoni	227.71	Muleba	21.71	CP_l & d_l $(K = DC_4$		Mkuranga	46.94
Mbulu	72.82	Musoma	58.53	Chunya	60.59	MtwaraR	39.29
MorogoroR	98.06	MusomaR	191.00	IringaR	233.76	Muheza	11.76
Mpwapwa	176.06	Nyamagana	4.24	Kilolo	18.88	Nachingwea	70.94
Mvomero	84.94	**Rorya**	**65.41**	Kilombero	17.65	Nanyumbu	49.06
Mwanga	53.94	Sengerema	11.76	Ludewa	8.82	Pangani	54.94
Nzega	135.41	ShinyangaR	37.76	Makete	2.41	Ruangwa	41.24
Sikonge	**27.53**	ShinyangaU	5.88	Mbarali	100.29	Rufiji	106.59
Simanjiro	200.76	**Sikonge**	**2.24**	Mbozi	5.88	**Same**	**96.65**
SingidaR	180.88	Tarime	53.71	Mufindi	45.18		
SingidaU	8.82	Ukerewe	44.41	Njombe	103.18		
TaboraR	4.00	Uyui	90.76	Ulanga	184.71		
TaboraU	10.71						

Table A.4: *Computational results: CP_l to DC_k allocation and d_l for combined 17 weeks using eight DCs.*

CP_l & d_l ($K = DC_6$)		CP_l & d_l ($K = DC_6$)		CP_l & d_l ($K = DC_3$)		CP_l & d_l ($K = DC_4$)	
Arumeru	117.94	Nyamagana	4.24	**Babati**	**39.24**	Chunya	60.59
ArushaU	73.41	**Rorya**	**75.29**	Bahi	73.47	IringaR	233.76
Babati	**44.29**	Sengerema	11.76	Chamwino	112.47	Kilolo	18.88
Hai	25.35	Ukerewe	44.41	DodomaR	191.71	Kilombero	17.65
Hanang	108.47			DodomaU	38.18	Ludewa	8.82
Karatu	133.94	CP_l & d_l ($K = DC_1$)		**Handeni**	**21.00**	Makete	2.41
Longido	264.88	Bagamoyo	160.06	Igunga	68.94	Mbarali	100.29
Mbulu	72.82	**Handeni**	**171.18**	Iramba	137.53	Mbozi	5.88
Monduli	255.59	Kibaha	84.18	Kilosa	66.94	Mufindi	45.18
MoshiR	59.24	Kilindi	69.53	Kiteto	51.35	Njombe	103.18
Ngorongoro	378.00	Kilwa	43.06	Kondoa	108.65	Ulanga	184.71
Rombo	215.47	Kisarawe	107.76	Kongwa	194.53		
Rorya	**53.88**	Korogwe	37.94	Manyoni	227.71	CP_l & d_l ($K = DC_5$)	
Same	152.29	LindiR	44.76	MorogoroR	98.06	Bariadi	3.71
Serengeti	29.94	Liwale	40.76	Mpwapwa	176.06	Biharamulo	53.06
Siha	19.59	Lushoto	76.35	Mvomero	84.94	Kahama	50.41
Tarime	53.71	Mafia	1.88	Mwanga	53.94	Kishapu	93.18
CP_l & d_l ($K = DC_7$)		Masasi	139.65	Nzega	135.41	Kwimba	121.76
BukobaR	16.94	Mkinga	81.18	**Sikonge**	**13.12**	Maswa	133.76
Bunda	213.94	Mkuranga	46.94	Simanjiro	200.76	Meatu	246.00
Geita	22.53	MtwaraR	39.29	SingidaR	180.88	ShinyangaR	37.76
Ilemela	5.35	Muheza	11.76	SingidaU	8.82	ShinyangaU	5.88
Magu	329.00	Nachingwea	70.94	TaboraR	4.00	**Sikonge**	**16.65**
Misungwi	72.59	Nanyumbu	49.06	TaboraU	10.71	Uyui	90.76
Muleba	21.71	Pangani	54.94				
Musoma	58.53	Ruangwa	41.24				
MusomaR	191.00	Rufiji	106.59				

Table A.5: DC_1: *DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	4.9	0.0	1.8	0.0	1.8	0.0	0.0	29.2	10.2	39.5	61.8	1.7	144.9	4.2	89.8	31.4	8.4
2008	0.0	3.7	11.5	37.1	0.0	11.0	45.1	0.0	3.7	23.1	0.0	43.4	91.2	129.8	65.4	51.5	56.9
2009	0.0	0.5	0.0	13.9	13.8	0.1	29.6	5.4	16.8	30.5	33.3	1.6	38.0	74.9	16.6	18.7	129.9
2010	9.7	4.3	0.0	0.0	3.9	12.9	0.0	3.6	64.4	51.5	0.0	62.6	91.0	32.1	10.2	41.8	239.1
2007	18.0	1.0	0.2	0.0	19.3	12.2	0.0	9.0	16.9	15.6	28.4	27.4	64.9	24.9	61.0	11.5	47.1
2008	0.0	16.5	10.8	69.0	0.0	35.2	7.6	0.0	4.7	70.3	1.2	96.1	99.7	138.3	73.5	55.4	71.9
2009	0.2	0.0	0.0	28.9	1.0	0.4	63.2	4.5	32.3	36.3	0.5	1.3	65.8	33.9	1.1	24.2	54.6
2010	12.2	28.0	0.0	0.0	1.6	4.8	1.2	2.6	55.6	12.3	0.0	32.9	14.3	55.6	24.8	25.8	140.7
2007	35.0	5.8	0.0	3.8	143.6	12.1	5.4	21.5	53.5	3.3	12.7	20.6	54.5	15.0	69.0	58.3	0.0
2008	0.0	67.8	37.4	41.3	79.5	96.7	50.6	0.0	3.3	2.6	60.6	79.1	0.0	40.7	120.7	21.9	29.9
2010	78.6	20.2	0.0	36.5	0.0	0.0	107.1	14.9	2.0	0.0	39.0	63.8	61.1	128.3	44.3	2.5	24.8
2007	45.0	37.6	0.0	0.0	42.1	40.2	0.1	34.0	3.3	10.6	77.8	17.4	44.6	31.8	0.5	31.2	71.9
2008	0.0	1.5	0.3	13.5	25.3	28.7	9.6	17.2	8.5	0.8	13.8	57.7	85.2	52.3	150.0	42.6	46.4
2009	0.0	0.0	0.0	11.8	40.7	28.7	9.6	17.2	12.8	13.7	14.7	0.0	54.1	31.8	0.5	31.2	71.9
2010	47.4	39.9	0.0	0.0	0.0	55.1	15.3	10.2	34.8	9.7	0.2	24.7	22.0	39.1	16.6	77.9	63.5
2007	11.1	0.7	0.0	4.4	69.9	71.1	60.3	5.9	74.7	28.1	25.6	27.2	35.2	10.6	95.2	46.1	25.1
2008	73.7	37.7	11.5	47.7	41.1	61.3	47.9	113.8	52.5	71.4	11.2	65.5	0.0	9.1	94.1	12.2	40.6
2009	0.0	0.7	10.7	3.0	13.7	159.2	36.6	90.7	32.2	52.3	0.8	36.0	88.2	15.7	0.0	26.5	19.3
2010	32.2	49.4	0.0	86.5	0.1	22.8	171.3	91.4	63.7	36.0	3.0	92.4	32.8	32.9	32.9	32.9	32.9
2007	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	2.2	8.2	4.7	29.3	0.0	139.4	41.2	10.3
2008	0.0	0.0	46.2	1.7	0.0	2.1	40.2	0.0	8.7	1.8	0.3	26.1	53.5	66.0	14.2	7.1	39.3
2009	0.0	0.0	1.4	1.3	1.0	0.0	47.4	9.6	0.5	0.0	0.7	0.2	22.1	45.8	139.7	16.8	25.2
2010	56.1	70.5	0.0	0.0	0.2	33.0	0.0	0.0	8.5	25.8	0.5	50.2	46.4	75.6	113.2	65.7	43.1
Max	78.6	70.5	46.2	86.5	143.6	159.2	171.3	113.8	74.7	71.4	77.8	96.1	144.9	138.3	150.0	77.9	239.1
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.0
Average	18.5	16.8	5.7	17.4	21.7	29.9	32.5	20.9	24.5	23.4	17.1	36.2	53.9	47.3	59.7	33.7	56.2

Table A.6: *DC_2: DC zone - weekly rainfall in mm.*

Year	**Week**																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	8.2	6.5	3.9	14.2	38.5	6.1	4.9	2.9	13.0	10.2	9.9	13.5	122.2	6.3	40.0	40.5	18.0
2008	0.0	18.9	2.0	4.4	0.0	47.7	28.0	2.0	6.3	9.8	5.5	73.3	132.6	40.8	86.8	17.1	132.7
2009	0.0	0.0	26.7	1.0	19.3	15.3	15.3	15.3	8.9	0.0	18.1	0.0	11.7	31.0	73.4	1.2	15.1
2010	12.4	63.4	10.3	0.0	25.1	23.6	22.5	29.9	7.6	7.5	35.1	30.9	75.8	94.5	33.5	111.9	25.5
2007	9.2	0.0	0.0	4.2	53.6	3.6	0.3	0.0	0.0	0.0	7.0	8.3	20.9	1.9	46.9	90.0	6.0
2008	0.0	0.0	7.9	36.2	0.0	1.0	39.6	0.0	14.6	1.0	40.9	150.5	267.4	21.0	84.8	47.1	85.0
2009	0.0	0.0	0.0	19.9	9.6	0.0	23.0	23.7	17.1	3.6	0.0	0.0	14.5	29.4	93.3	0.2	115.2
2010	0.0	15.0	0.0	0.0	0.5	0.0	5.3	0.6	0.0	2.5	8.8	32.2	111.1	89.7	194.3	115.9	14.4
2007	128.4	74.3	3.5	2.6	39.5	39.0	60.4	15.9	8.4	118.4	90.0	20.7	0.5	34.1	34.1	34.1	34.1
2008	0.0	8.3	41.0	0.5	15.0	98.2	118.0	1.8	60.1	17.7	65.8	45.1	68.2	9.9	43.2	23.4	49.5
2009	2.4	0.0	1.5	6.5	57.1	2.3	3.9	7.3	24.3	25.4	62.7	0.0	94.3	23.9	104.2	0.0	18.7
Max	128.4	74.3	41	36.2	57.1	98.2	118	29.9	60.1	118.4	90	150.5	267.4	94.5	194.3	115.9	132.7
Min	0	0	0	0	0	0	0.3	0	0	0	0	0	0.5	1.9	33.5	0	6
Average	14.6	16.9	8.8	8.1	23.5	21.5	29.2	9.0	14.6	17.8	31.3	34.0	83.6	34.8	75.9	43.8	46.7

Table A.7: *DC_3: DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	84.3	55.8	83.1	30.7	97.3	61.1	74.9	5.5	105.8	35.8	0.0	30.0	54.4	0.0	2.9	1.5	0.0
2008	1.7	0.0	6.8	36.0	42.4	11.8	97.1	8.2	20.7	3.8	40.0	61.4	60.3	3.7	3.0	2.6	0.0
2009	29.1	0.0	0.0	12.9	69.8	37.7	2.1	34.4	31.7	0.0	23.7	1.4	54.9	85.6	12.0	0.0	0.2
2010	38.8	44.9	0.0	20.3	66.5	19.0	4.2	30.8	15.2	1.0	0.0	8.2	17.0	1.5	0.0	2.1	0.1
2007	73.2	113.8	40.6	12.1	36.8	51.1	45.3	0.0	5.2	17.8	19.7	13.5	0.0	1.0	47.4	4.7	0.0
2008	4.0	4.9	21.8	34.5	79.1	29.1	47.0	9.2	1.5	5.2	13.7	95.0	100.4	0.5	0.2	3.0	2.4
2009	59.5	65.6	10.4	46.0	34.5	32.0	0.4	10.4	61.7	41.9	66.3	5.2	34.2	44.3	5.2	0.0	0.0
2010	44.5	24.9	12.8	12.1	31.0	7.0	10.4	77.2	12.3	22.4	2.0	15.0	17.4	3.1	0.0	0.0	0.2
Max	84.3	113.8	83.1	46.0	97.3	61.1	97.1	77.2	105.8	41.9	66.3	95.0	100.4	85.6	47.4	4.7	2.4
Min	1.7	0.0	0.0	12.1	31.0	7.0	0.4	0.0	1.5	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0
Average	41.9	38.7	21.9	25.6	57.2	31.1	35.2	22.0	31.8	16.0	20.7	28.7	42.3	17.5	8.8	1.7	0.4

Table A.8: *DC_4: DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	15.1	31.9	31.3	58.2	30.7	9.1	27.1	2.3	10.3	24.7	104.5	6.3	16.9	8.0	7.4	0.0	0.0
2008	48.5	11.4	40.3	55.7	9.0	98.3	82.6	19.0	5.8	10.8	16.8	60.9	46.3	13.9	42.8	0.0	1.7
2009	30.0	6.4	10.2	0.8	113.6	45.7	1.6	24.5	30.7	19.2	62.8	22.2	16.6	99.1	0.0	0.0	10.2
2010	33.2	48.0	0.0	27.3	0.9	18.8	13.9	67.6	37.1	12.1	10.2	10.9	7.8	4.4	0.0	10.8	4.1
2007	35.8	65.3	80.0	26.6	63.8	24.1	55.1	1.5	40.1	46.4	48.3	2.0	33.3	10.1	7.6	34.5	17.9
2008	60.5	36.6	29.4	59.8	45.0	68.9	65.0	19.5	26.0	19.8	18.7	68.4	36.1	45.0	17.1	13.3	1.3
2009	87.5	8.2	73.3	23.4	80.3	89.3	34.1	31.8	9.3	48.8	103.1	13.6	0.5	24.0	0.8	0.0	0.5
2010	42.2	50.1	1.4	47.6	45.3	18.2	20.1	47.1	50.1	39.6	61.4	59.2	31.8	19.0	8.7	1.6	8.5
Max	87.5	65.3	80.0	59.8	113.6	98.3	82.6	67.6	50.1	48.8	104.5	68.4	46.3	99.1	42.8	34.5	17.9
Min	15.1	6.4	0.0	0.8	0.9	9.1	1.6	1.5	5.8	10.8	10.2	2.0	0.5	4.4	0.0	0.0	0.0
Average	44.1	32.2	33.2	37.4	48.6	46.5	37.4	26.7	26.2	27.7	53.2	30.4	23.7	27.9	10.5	7.5	5.5

Table A.9: *DC_5: DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	23.8	51.7	19.3	7.7	8.7	22.4	36.1	3.2	25.7	49.7	57.6	9.3	0.8	0.0	47.8	31.7	3.7
2008	16.0	7.8	37.5	26.4	38.2	40.7	28.6	32.3	108.1	11.2	22.3	44.7	54.6	4.6	30.2	84.1	0.0
2009	23.5	9.1	48.5	86.1	24.2	25.9	17.5	32.9	34.5	7.0	35.9	3.5	66.1	52.6	8.0	14.0	0.9
2010	12.4	1.7	1.0	10.2	36.6	6.4	23.3	46.9	53.3	11.9	0.9	28.4	52.7	7.3	26.2	32.2	3.8
2007	43.9	1.0	8.3	4.5	46.6	11.6	16.3	20.8	3.8	8.6	27.8	38.0	17.4	0.0	73.7	8.4	7.8
2008	5.5	3.2	18.3	0.0	0.0	42.9	11.1	3.0	5.6	12.5	41.7	132.4	36.2	0.0	42.5	28.8	0.6
2009	4.0	0.0	5.1	11.9	7.7	19.7	1.5	0.0	7.9	8.6	4.3	18.2	27.7	36.3	4.4	45.3	3.0
2010	33.8	35.6	17.5	3.7	31.1	13.1	5.4	49.7	138.9	15.9	14.4	142.5	19.8	30.5	104.1	35.5	28.1
2007	56.1	16.7	72.8	24.9	24.9	76.2	20.0	8.6	25.6	54.6	14.6	36.4	61.3	0.0	176.7	120.4	50.3
2008	2.1	60.2	94.0	156.8	0.4	126.5	17.3	7.0	36.3	102.6	24.1	46.1	78.5	0.0	103.5	95.0	5.2
2009	38.6	42.4	69.3	138.9	9.3	93.1	12.0	77.3	36.1	45.6	168.3	84.7	54.5	39.9	179.3	118.9	72.4
2010	14.5	12.9	43.8	60.0	13.3	57.4	147.1	144.4	71.1	13.8	25.9	55.0	96.1	119.0	20.5	8.9	201.4
2007	24.4	35.7	84.3	0.0	35.7	4.6	55.4	43.8	57.7	58.7	31.3	22.9	43.0	0.0	84.1	77.0	25.3
2008	1.4	24.4	13.3	34.3	7.0	13.0	37.3	3.1	24.7	9.1	59.1	61.2	5.8	0.0	44.1	18.1	6.2
2009	12.5	3.1	13.9	86.5	14.5	54.8	0.8	20.4	10.9	4.9	37.3	3.6	107.1	92.2	93.2	25.0	9.9
2010	73.9	45.5	0.0	6.1	11.7	14.3	100.4	71.8	22.8	45.1	0.0	85.4	106.7	3.5	35.4	35.3	32.6
2007	92.4	18.0	34.7	43.5	89.3	41.1	76.6	15.8	8.9	61.4	6.2	6.5	0.0	0.0	8.0	22.2	0.0
2008	20.4	41.6	52.5	21.3	46.2	4.6	64.9	21.1	32.6	26.4	80.9	16.9	46.4	0.9	78.5	13.1	1.7
2009	33.3	25.7	35.9	155.0	33.7	67.2	37.6	44.6	82.5	1.5	73.6	0.7	25.3	27.2	72.4	0.3	3.7
2010	84.0	8.4	0.6	26.9	53.1	12.8	34.7	12.6	58.3	45.3	45.6	125.7	18.7	0.7	4.6	26.7	9.3
Max	92.4	60.2	94.0	156.8	89.3	126.5	147.1	144.4	138.9	102.6	168.3	142.5	107.1	119.0	179.3	120.4	201.4
Min	1.4	0.0	0.0	0.0	0.0	4.6	0.8	0.0	3.8	1.5	0.0	0.7	0.0	0.0	4.4	0.3	0.0
Average	30.8	22.2	33.5	45.2	26.6	37.4	37.2	33.0	42.3	29.7	38.6	48.1	45.9	20.7	61.9	42.0	23.3

Table A.10: DC_6: *DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	0	0	1.5	0.5	15	2.3	3.9	1.8	8.4	17.7	62.7	0	0.5	34.1	34.1	34.1	34.1
2008	2.4	8.3	3.5	2.6	39.5	39	60.4	7.3	24.3	25.4	65.8	20.7	68.2	23.9	43.2	23.4	49.5
2009	128.4	74.3	41	6.5	57.1	98.2	118	15.9	60.1	118.4	90	45.1	94.3	9.9	104.2	0	18.7
Max	128.4	74.3	41.0	6.5	57.1	98.2	118.0	15.9	60.1	118.4	90.0	45.1	94.3	34.1	104.2	34.1	49.5
Min	0.0	0.0	1.5	0.5	15.0	2.3	3.9	1.8	8.4	17.7	62.7	0.0	0.5	9.9	34.1	0.0	18.7
Average	43.6	27.5	15.3	3.2	37.2	46.5	60.8	8.3	30.9	53.8	72.8	21.9	54.3	22.6	60.5	19.2	34.1

Table A.11: DC_7: *DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	1.4	3.1	0.0	0.0	7.0	4.6	0.8	3.1	10.9	4.9	0.0	3.6	5.8	0.0	35.4	18.1	6.2
2008	12.5	24.4	13.3	6.1	11.7	13.0	37.3	20.4	22.8	9.1	31.3	22.9	43.0	0.0	44.1	25.0	9.9
2009	24.4	35.7	13.9	34.3	14.5	14.3	55.4	43.8	24.7	45.1	37.3	61.2	106.7	3.5	84.1	35.3	25.3
2010	73.9	45.5	84.3	86.5	35.7	54.8	100.4	71.8	57.7	58.7	59.1	85.4	107.1	92.2	93.2	77.0	32.6
Max	73.9	45.5	84.3	86.5	35.7	54.8	100.4	71.8	57.7	58.7	59.1	85.4	107.1	92.2	93.2	77.0	32.6
Min	1.4	3.1	0.0	0.0	7.0	4.6	0.8	3.1	10.9	4.9	0.0	3.6	5.8	0.0	35.4	18.1	6.2
Average	28.1	27.2	27.9	31.7	17.2	21.7	48.5	34.8	29.0	29.4	31.9	43.3	65.6	23.9	64.2	38.8	18.5

Table A.12: DC_8: *DC zone - weekly rainfall in mm.*

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
2007	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.3	0.2	22.1	0.0	14.2	7.1	10.3
2008	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.8	0.5	4.7	29.3	45.8	113.2	16.8	25.2
2009	0.4	0.0	1.4	1.3	0.2	2.1	40.2	0.0	8.5	2.2	0.7	26.1	46.4	66.0	139.4	41.2	39.3
2010	56.1	70.5	46.2	1.7	1.0	33.0	47.4	9.6	8.7	25.8	8.2	50.2	53.5	75.6	139.7	65.7	43.1
Max	56.1	70.5	46.2	1.7	1.0	33.0	47.4	9.6	8.7	25.8	8.2	50.2	53.5	75.6	139.7	65.7	43.1
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.3	0.2	22.1	0.0	14.2	7.1	10.3
Average	14.1	17.6	11.9	0.7	0.3	8.8	21.9	2.4	4.5	7.5	2.4	20.3	37.8	46.8	101.6	32.7	29.5

Table A.13: *CPs, (CP_l, $l \in L$) and their annual respective demands obtained from the field, D_l (tons).*

$l \in L$	D_l	$l \in L$	D_l	$l \in L$	D_l	$l \in L$	D_l
Arumeru	2,005	Kilolo	321	Meatu	4,182	Ruangwa	701
ArushaU	1,248	Kilombero	300	Misungwi	1,234	Rufiji	1,812
Babati	1,420	Kilosa	1,138	Mkinga	1,380	Same	2,589
Bagamoyo	2,721	Kilwa	732	Mkuranga	798	Sengerema	200
Bahi	1,249	Kisarawe	1,832	Monduli	4,345	Serengeti	509
Bariadi	63	Kishapu	1,584	MorogoroR	1,667	ShinyangaR	642
Biharamulo	902	Kiteto	873	MoshiR	1,007	ShinyangaU	100
BukobaR	288	Kondoa	1,847	Mpwapwa	2,993	Siha	333
Bunda	3,637	Kongwa	3,307	MtwaraR	668	Sikonge	506
Chamwino	1,912	Korogwe	645	Mufindi	768	Simanjiro	3,413
Chunya	1,030	Kwimba	2,070	Muheza	200	SingidaR	3,075
DodomaR	3,259	Lindi-R	761	Muleba	369	SingidaU	150
DodomaU	649	Liwale	693	Musoma	995	TaboraR	68
Geita	383	Longido	4,503	MusomaR	3,247	TaboraU	182
Hai	431	Ludewa	150	Mvomero	1,444	Tarime	913
Hanang	1,844	Lushoto	1,298	Mwanga	917	Ukerewe	755
Handeni	3,267	Mafia	32	Nachingwea	1,206	Ulanga	3,140
Igunga	1,172	Magu	5,593	Nanyumbu	834	Uyui	1,543
Ilemela	91	Makete	41	Ngorongoro	6,426		
Iramba	2,338	Manyoni	3,871	Njombe	1,754		
IringaR	3,974	Masasi	2,374	Nyamagana	72		
Kahama	857	Maswa	2,274	Nzega	2,302		
Karatu	2,277	Mbarali	1,705	Pangani	934		
Kibaha	1,431	Mbozi	100	Rombo	3,663		
Kilindi	1,182	Mbulu	1,238	Rorya	2,196		

Table A.14: The demand within 2004 - 2010 in each year in given CP

S/N	**District**	**Year and demand (D_l) in tons**					
		2004	**2005**	**2006**	**2009**	**2010**	**Max D_l value**
1	Arumeru	1023	819	520	2005	833	**2005**
2	Arusha-U				1248	454	**1248**
3	Babati	1150		379	1420	667	**1420**
4	Bagamoyo	2721		1194	1509	1320	**2721**
5	Bahi				1249	896	**1249**
6	Bariadi	63					**63**
7	Biharamulo			902			**902**
8	Bukoba-R			288			**288**
9	Bunda	3637	832	851	553		**3637**
10	Chamwino				1837	1912	**1912**
11	Chunya	1030			259		**1030**
12	Dodoma-R	2207	1090	3259			**3259**
13	Dodoma-U	100	322	422	600	649	**649**
14	Geita			383			**383**
15	Hai		193	316	431	387	**431**
16	Hanang	488		111	1844	761	**1844**
17	Handeni	1429			3267	556	**3267**
18	Igunga	1172	1119				**1172**
19	Ilemela			91			**91**
20	Iramba	2338	526		582		**2338**
21	Iringa-R	3974	251	731	1238	321	**3974**
22	Kahama				857		**857**
23	Karatu	724	725	1770	2277	681	**2277**

Table A.15: The demand within 2004 - 2010 in each year in given CP

S/N	**District**	**Year and demand (D_l) in tons**					
		2004	**2005**	**2006**	**2009**	**2010**	**Max D_l value**
24	Kibaha	1431		109	348		**1431**
25	Kilindi	1182		300	883		**1182**
26	Kilolo	184	284	321	70		**321**
27	Kilombero			300			**300**
28	Kilosa	500		0	1138	482	**1138**
29	Kilwa	413	394	621	732		**732**
30	Kisarawe	1832		52	21		**1832**
31	Kishapu	1584			526	1070	**1584**
32	Kiteto	693		148	873	845	**873**
33	Kondoa	1847	60	1212	737	517	**1847**
34	Kongwa	200		2311	3307	2507	**3307**
35	Korogwe	605		67	645	581	**645**
36	Kwimba	2070	1123		969	89	**2070**
37	Lindi-R	200	626	622	761	234	**761**
38	Liwale	150	138	130	693	131	**693**
39	Longido				4503	1419	**4503**
40	Ludewa			150			**150**
41	Lushoto	627			1298	950	**1298**
42	Mafia			32			**32**
43	Magu	5593	1241		1127		**5593**
44	Makete			41			**41**
45	Manyoni	3871	1133		1112	533	**3871**
46	Masasi	1914	941		2374	26	**2374**
47	Maswa	2274	324		553	475	**2274**

Table A.16: The demand within 2004 - 2010 in each year in given CP

S/N	**District**	**Year and demand (D_l) in tons**					
		2004	**2005**	**2006**	**2009**	**2010**	**Max D_l value**
48	Mbarali	1705			674		**1705**
49	Mbozi		100				**100**
50	Mbulu	100		591	1238	274	**1238**
51	Meatu	4182	1898		296	1318	**4182**
52	Misungwi	1234	765		954		**1234**
53	Mkinga				1380	134	**1380**
54	Mkuranga	798					**798**
55	Monduli	2031	1085	1429	4345	1280	**4345**
56	Morogoro-R	1667			772	443	**1667**
57	Moshi-R		394	1007	605	642	**1007**
58	Mpwapwa	2157	236	673	2993	1189	**2993**
59	Mtwara-R				668		**668**
60	Mufindi	768	201	123			**768**
61	Muheza	200		71			**200**
62	Muleba			369			**369**
63	Musoma			995			**995**
64	Musoma-R	3146	525	552	3247		**3247**
65	Mvomero	1444			1089	616	**1444**
66	Mwanga	917	126	179	814	434	**917**
67	Nachingwea	500		226	1206		**1206**
68	Nanyumbu				695	834	**834**
69	Ngorongoro		499	820	6426	3024	**6426**
70	Njombe	1754	366	587			**1754**
71	Nyamagana			72			**72**

Table A.17: The demand within 2004 - 2010 in each year in given CP

S/N	**District**	**Year and demand (D_l) in tons**					
		2004	**2005**	**2006**	**2009**	**2010**	**Max D_l value**
72	Nzega	2302				262	**2302**
73	Pangani	934			706		**934**
74	Rombo			874	3663		**3663**
75	Rorya				2196		**2196**
76	Ruangwa	336	241	211	701	89	**701**
77	Rufiji	1812		298		599	**1812**
78	Same	1387	1139	1598	2589	1548	**2589**
79	Sengerema	200					**200**
80	Serengeti			509			**509**
81	Shinyanga-R	50			568	642	**642**
82	Shinyanga -U	100			76	91	**100**
83	Siha				125	333	**333**
84	Sikonge	192	506				**506**
85	Simanjiro	1519	504	1024	3413	2239	**3413**
86	Singida -R	3075	310				**3075**
87	Singida U	150					**150**
88	Tabora -R	68					**68**
89	Tabora-U		182				**182**
90	Tarime		381	913			**913**
91	Ukerewe			547	755		**755**
92	Ulanga	3140					**3140**
93	Uyui	1543					**1543**
	Total annual	**94,649**	**27,614**	**37,319**	**92,067**	**41,317**	**145,144**

Appendix B

Research data

Table B.1: *PCs and DCs: Road distances (C_{jk}) (kilometers).*

PC_j	DC_k							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
PC_1	492	689	264	120	802	521	965	629
PC_2	822	1020	594	210	761	766	924	959
PC_3	1150	1348	922	538	790	1094	953	1287
PC_4	947	1144	719	335	1257	976	1420	1084

Table B.2: *DCs' true or initial capacities in tons ($\hat{V}_k$).*

DC_k	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
Capacity($\hat{V}_k$)	52,000	39,000	39,000	34,000	14,500	53,000	53,000	53,000

Table B.3: *PCs' capacity (2011-2012 production) computations summary table.*

PC_j	**1**	**2**	**3**	**4**	**5**	**6**	**7**
PC_1	426,945	359,157	67,788	84.12	118,383	**99,586.8**	**100**
PC_2	810,425	628,418	182,007	77.54	323,615	**250,936.8**	**251**
PC_3	515,492	330,822	184,670	64.18	218,915	**140,490.8**	**140**
PC_4	297,290	225,470	71,820	75.84	53,630	**40,673.9**	**41**
Total	**2,050,152**	**1,543,867**	**506,285**	**305.68207**	**714,543**	**531,688.4**	**532**

NOTE:

1: Total cereals production (2011-2012), **2**: Total maize crop production, **3**: Other total cereals production, **4**: Maize crop% in total cereal production **5**: Total cereal surplus, **6**: Total maize crop surplus, **7**: Total maize crop surplus in thousand.

Table B.4: *PCs' Capacities, S_j.*

PC_j	**Capacity, S_j (tons)**
PC_1	100,000
PC_2	251,000
PC_3	140,000
PC_4	41,000
Total	532,000

Table B.5: *The existing non-optimized (manually operated) CPs to DCs allocations.*

DC	**Region**	**CP**	**DC**	**Region**	**CP**
Arusha	Arusha	Karatu	Shinyaga	Mara	Bunda
		Arusha U			Musoma U
		Arumeru			Serengeti
		Longido			Rorya
		Monduli			Tarime
					Musoma R
Arusha	Kilimanjaro	Mwanga	Shinyaga	Tabora	Uyui
		Siha			Tabora U
		Hai			Igunga
		Moshi R			Nzega
		Rombo			Tabora R
		Same			Sikonge
Arusha	Manyara	Hanang	Dar	Coast	Kibaha
		Ngorongoro			Mafia
		Babati			Rufiji
		Simanjiro			Kisarawe
		Mbulu			Mkuranga
					Bagamoyo
Shinyanga	Shinyanga	Meatu	Dar	Tanga	Kilindi
		Maswa			Muheza
		Kahama			Handeni
		Bariadi			Pangani
		Shinyanga U			Mkinga
		Kishapu			Lushoto
		Shinyanga R			Korogwe

Table B.6: *The existing non-optimized (manually operated) CPs to DCs allocations.*

DC	**Region**	**CP**	**DC**	**Region**	**CP**
Shinyanga	Mwanza	Misungwi	Dodoma	Singida	Manyoni
		Geita			Singida R
		Ukerewe			Singida U
		Nyamagana			Iramba
		Ilemela	Dodoma	Dodoma	Kondoa
		Sengerema			Bahi
		Magu			Chamwino
		Kwimba			Kongwa
Shinyanga	Kagera	Bukoba R			Dodoma R
		Muleba			Dodoma U
		Biharamulo			Mpwapwa
			Dodoma	Manyara	Kiteto
Makambako	Iringa	Mufindi	Dar	Morogoro	Mvomero
		Njombe			Kilombero
		Ludewa			Morogoro R
		Makete			Kilosa
					Ulanga
		Iringa R	Dar	Mtwara	Masasi
		Kilolo			Mtwara R
Makambako	Mbeya	Mbarali			Nanyumbu
		Chunya	Dar	Lindi	Ruangwa
		Mbozi			Lindi R
					Liwale
					Nachingwea
					Kilwa

Table B.7: *CPs and DCs: Road distances, T_{kl}(kms).*

$CP_l (l \in L)$	DC_k $(k \in K)$							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
Arumeru	666	20	445	829	644	188	807	455
ArushaU	668	22	447	831	646	190	809	457
Babati	814	168	257	641	456	20	619	603
Bagamoyo	63	709	514	675	1,052	751	1,215	291
Bahi	516	490	65	449	473	322	636	653
Bariadi	1,127	762	676	1,082	160	594	230	1,197
Biharamulo	1,402	1,037	951	1,335	413	869	706	1,472
BukobaR	1,567	1,202	1,116	1,500	578	1,478	416	1,637
Bunda	1,409	578	958	1,342	420	428	138	1,479
Chamwino	426	450	25	409	563	282	726	613
Chunya	895	1,012	587	203	1,125	844	1,288	952
DodomaR	461	435	10	394	548	267	711	598
DodomaU	461	435	10	394	548	267	711	598
Geita	1,234	863	783	1,167	245	695	119	1,298
Hai	586	60	485	869	684	228	847	375
Hanang	927	280	370	754	344	112	507	715
Handeni	240	406	474	1,215	1,034	574	1,193	125
Igunga	819	794	368	752	170	286	333	889
Ilemela	1,149	784	698	1,082	160	616	20	1,219
Iramba	836	456	370	754	168	288	331	891
IringaR	492	689	279	135	817	521	980	644
Kahama	1,101	736	598	978	112	568	252	1,171
Karatu	826	180	525	909	724	188	807	615
Kibaha	40	606	411	572	949	779	1,112	314
Kilindi	290	456	524	908	1,080	624	1,243	218

Table B.8: *CPs and DCs: Road distances, T_{kl}(kms).*

$CP_l (l \in L)$	DC_k $(k \in K)$							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
Kilolo	492	889	344	200	882	601	1,045	709
Kilombero	450	879	517	420	1,055	774	1,218	587
Kilosa	400	829	467	628	1,005	724	1,168	537
Kilwa	294	940	745	906	1,283	1,108	1,446	648
Kisarawe	30	676	481	642	1,019	844	1,182	384
Kishapu	1,039	674	588	972	50	516	133	1,109
Kiteto	671	158	179	563	556	151	880	593
Kondoa	682	235	190	574	523	67	686	670
Kongwa	438	499	74	458	612	331	775	514
Korogwe	350	296	584	1,105	920	464	1,083	139
Kwimba	1,109	744	658	1,042	120	576	43	1,179
Lindi-R	459	1,105	910	1,071	1,448	1,273	1,611	813
Liwale	764	1,410	1,215	1,376	1,753	1,578	1,916	1,118
Longido	731	85	510	894	709	253	872	520
Ludewa	840	1,037	612	228	1,153	869	1,313	977
Lushoto	365	311	600	1,120	935	479	1,098	124
Mafia	200	846	651	812	1,189	1,014	1,172	554
Magu	1,339	974	888	1,272	350	806	187	1,409
Makete	772	869	544	160	1,082	801	1,245	909
Manyoni	571	456	120	504	418	273	581	708
Masasi	600	1,246	1,051	1,212	1,589	1,414	1,752	954
Maswa	1,077	712	626	1,110	88	544	163	1,147
Mbarali	686	883	458	74	996	715	1,159	823
Mbozi	899	1,096	671	287	1,209	928	1,372	1,036

Table B.9: *CPs and DCs: Road distances, T_{kl}(kms).*

$CP_l (l \in L)$	DC_k $(k \in K)$							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
Mbulu	891	245	590	974	424	89	587	680
Meatu	1,140	775	689	1,073	151	607	304	1,210
Misungwi	1,169	804	718	1,102	180	636	20	1,239
Mkinga	390	340	634	1,149	964	508	1,127	36
Mkuranga	35	681	486	647	994	849	1,187	389
Monduli	696	50	450	834	649	124	812	485
MorogoroR	196	625	263	424	801	520	956	333
MoshiR	561	85	510	894	704	253	867	270
Mpwapwa	400	545	120	504	658	377	821	688
MtwaraR	575	1,221	1,026	1,187	1,564	1,389	1,727	929
Mufindi	662	759	434	50	972	591	1,135	699
Muheza	330	435	564	1,244	1,059	498	1,222	24
Muleba	1,538	1,173	1,087	1,471	549	1,005	386	1,608
Musoma	1,489	498	1,038	1,422	500	513	218	933
MusomaR	1,489	498	1,038	1,422	500	513	218	933
Mvomero	280	533	171	508	709	428	872	417
Mwanga	496	150	440	959	774	318	937	285
Nachingwea	614	1,260	1,065	1,226	1,603	1,428	1,766	968
Nanyumbu	656	1,302	1,107	1,268	1,645	1,470	1,808	1,010
Ngorongoro	946	300	725	1,109	899	308	1,062	735
Njombe	674	907	482	62	1,020	739	1,183	847
Nyamagana	1,149	787	698	1,082	160	616	10	1,212
Nzega	895	530	444	828	94	362	257	965
Pangani	399	566	633	1,017	1,189	734	1,353	45

Table B.10: *CPs and DCs: Road distances, T_{kl}(kms).*

$CP_l (l \in L)$	DC_k $(k \in K)$							
	DC_1	DC_2	DC_3	DC_4	DC_5	DC_6	DC_7	DC_8
Rombo	656	190	610	999	814	358	977	425
Rorya	1,529	538	1,078	1,462	540	553	258	973
Ruangwa	565	1,211	1,016	1,177	1,554	1,379	1,717	919
Rufiji	160	806	611	772	1,149	974	1,312	514
Same	436	210	630	1,019	934	378	997	225
Sengerema	1,178	813	727	1,111	189	645	26	1,248
Serengeti	1,547	440	1,096	1,480	558	455	170	875
ShinyangaR	1,019	658	568	952	30	486	193	1,089
ShinyangaU	999	638	548	932	10	466	173	1,069
Siha	616	60	485	869	684	228	847	375
Sikonge	1,086	721	635	1,019	252	573	415	1,223
Simanjiro	546	205	361	745	829	373	992	640
SingidaR	696	331	230	614	293	163	456	766
SingidaU	696	331	230	614	293	163	456	766
TaboraR	1,026	661	575	959	192	493	357	1,098
TaboraU	1,026	661	575	959	192	493	357	1,098
Tarime	1,529	540	1,078	1,462	540	543	258	973
Ukerewe	1,499	1,134	1,048	1,432	510	966	347	1,569
Ulanga	600	1,029	667	570	1,205	924	1,368	737
Uyui	1,114	749	663	1,047	280	581	443	1,184

Table B.11: *Case 1 results ($\hat{V}_k$): CP_l to DC_k allocations and D_l for existing network.*

CP_l & D_l ($K = DC_3$)		CP_l & D_l ($K = DC_3$)		CP_l & D_l ($K = DC_1$)		CP_l & D_l ($K = DC_2$)	
Babati	1,420	TaboraR	68	Bagamoyo	2,721	Arumeru	2,005
Bahi	1,249	TaboraU	182	Handeni	3,267	ArushaU	1,248
Bariadi	63	Uyui	1,543	Kibaha	1,431	Bunda	3,637
Biharamulo	902			Kilindi	1,182	Hai	431
BukobaR	288	CP_l & D_l ($K = DC_4$)		Kilosa	1,138	**Hanang**	27
Chamwino	1,912	Chunya	1,030	Kilwa	732	Karatu	2,277
DodomaR	3,259	IringaR	3,974	Kisarawe	1,832	Longido	4,503
DodomaU	649	Kilolo	321	Korogwe	645	Mbulu	1,238
Geita	383	Kilombero	300	LindiR	761	Monduli	4,345
Hanang	1,817	Ludewa	150	Liwale	693	MoshiR	1,007
Igunga	1,172	**Makete**	41	Lushoto	1,298	Musoma	995
Ilemela	91	Mbarali	1,705	Mafia	32	MusomaR	3,247
Iramba	2,338	Mbozi	100	Masasi	2,374	Ngorongoro	6,426
Kahama	857	Mufindi	768	Mkinga	1,380	Rombo	3,663
Kishapu	1,584	Njombe	1,754	Mkuranga	798	Rorya	2,196
Kiteto	873	Ulanga	3,140	MorogoroR	1,667	Serengeti	509
Kondoa	1,847			**Mpwapwa**	2,692	Siha	333
Kongwa	3,307	CP_l & D_l ($K = DC_5$)		MtwaraR	668	Tarime	913
Kwimba	2,070	**Magu**	4,672	Muheza	200		
Magu	921	Maswa	2,274	Mvomero	1,444		
Makete	-	Meatu	4,182	Mwanga	917		
Manyoni	3,871	Misungwi	1,234	Nachingwea	1,206		
Mpwapwa	301	Muleba	369	Nanyumbu	834		
Nzega	2,302	Nyamagana	72	Pangani	934		
Sikonge	506	Sengerema	200	Ruangwa	701		
Simanjiro	-	ShinyangaR	642	Rufiji	1,812		
SingidaR	3,075	ShinyangaU	100	Same	2,589		
SingidaU	150	Ukerewe	755	**Simanjiro**	3,413		

Table B.12: *Case 1 results ($\bar{V}_k$): CP_l to DC_k allocations and D_l for existing network.*

CP_l & D_l ($K = DC_1$)		CP_l & D_l ($K = DC_5$)		CP_l & D_l ($K = DC_5$)		CP_l & D_l ($K = DC_3$)	
Bagamoyo	2,721	Bariadi	63	Tarime	913	Babati	1,420
Handeni	3,267	Biharamulo	902	Ukerewe	755	Bahi	1,249
Kibaha	1,431	BukobaR	288	Uyui	1,543	Chamwino	1,912
Kilindi	1,182	Bunda	3,637			DodomaR	3,259
Kilombero	300	Geita	383			DodomaU	649
Kilosa	1,138	Igunga	1,172	CP_l & D_l ($K = DC_2$)		***Hanang***	45
Kilwa	732	Ilemela	91	Arumeru	2,005	Kiteto	873
Kisarawe	1,832	Iramba	2,338	ArushaU	1,248	Kondoa	1,847
Korogwe	645	Kahama	857	Hai	431	Kongwa	3,307
LindiR	761	Kishapu	1,584	***Hanang***	1,799	Manyoni	3,871
Liwale	693	Kwimba	2,070	Karatu	2,277	Mpwapwa	2,993
Lushoto	1,298	Magu	5,593	Longido	4,503	SingidaR	3,075
Mafia	32	Maswa	2,274	Mbulu	1,238	SingidaU	150
Masasi	2,374	Meatu	4,182	Monduli	4,345		
Mkinga	1,380	Misungwi	1,234	MoshiR	1,007	CP_l & D_l ($K = DC_4$)	
Mkuranga	798	Muleba	369	Musoma	995	Chunya	1,030
MorogoroR	1,667	***MusomaR***	2,413	***MusomaR***	834	IringaR	3,974
MtwaraR	668	Nyamagana	72	Mwanga	917	Kilolo	321
Muheza	200	Nzega	2,302	Ngorongoro	6,426	Ludewa	150
Mvomero	1,444	Rorya	2,196	Rombo	3,663	Makete	41
Nachingwea	1,206	Sengerema	200	Same	2,589	Mbarali	1,705
Nanyumbu	834	ShinyangaR	642	Serengeti	509	Mbozi	100
Pangani	934	ShinyangaU	100	Siha	333	Mufindi	768
Ruangwa	701	Sikonge	506	Simanjiro	3,413	Njombe	1,754
Rufiji	1,812	TaboraR	68				
Ulanga	3,140	TaboraU	182				

Table B.13: *Case 2 results (V_k^r): CP_l to DC_k allocations and D_l for existing network.*

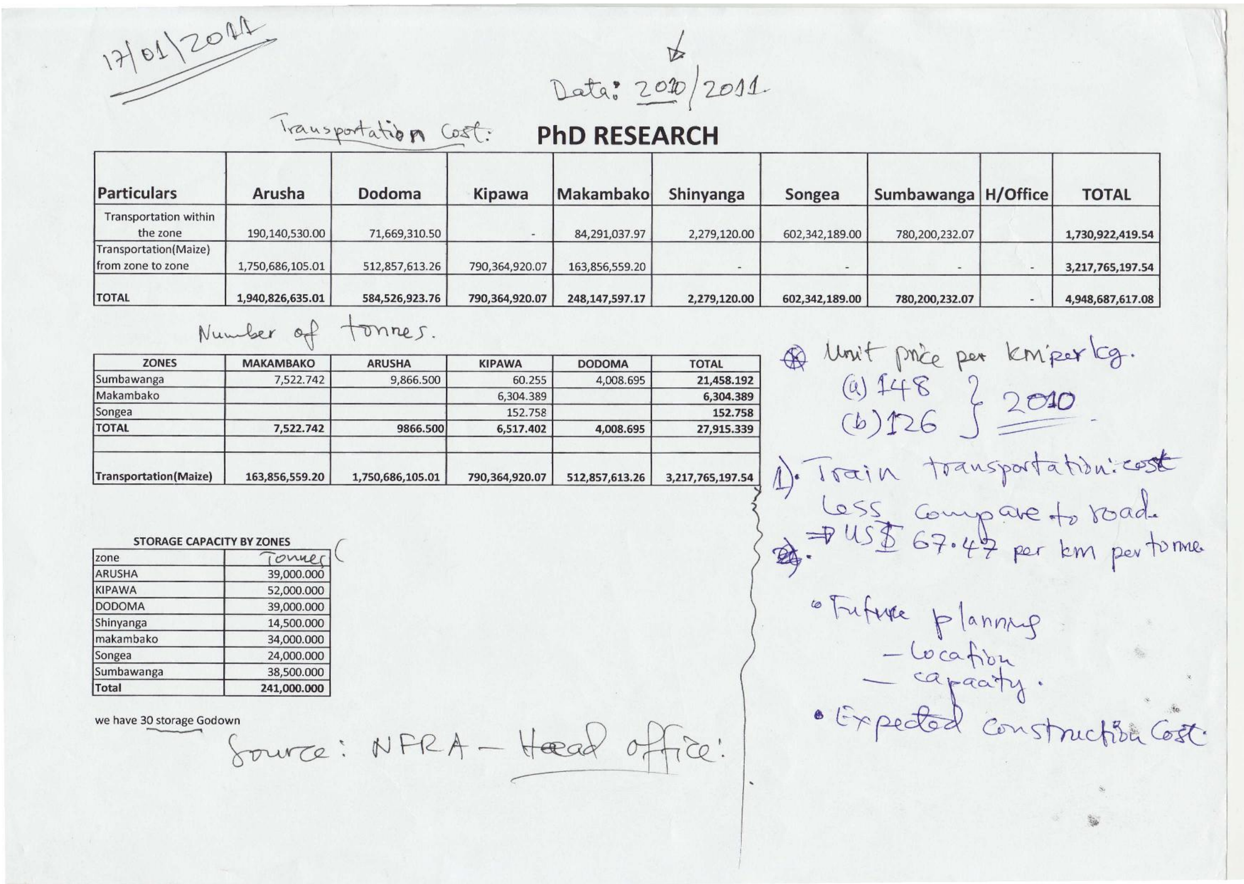
CP_l & D_l ($K = DC_3$)		CP_l & D_l ($K = DC_3$)		CP_l & D_l ($K = DC_5$)		CP_l & D_l ($K = DC_1$)	
Arumeru	2005	Ngorongoro	6426	Bariadi	63	Bagamoyo	2721
ArushaU	1248	Nzega	2302	Biharamulo	902	**Handeni**	**2966**
Babati	1420	Rombo	3663	BukobaR	288	Kibaha	1431
Bahi	1249	Same	2589	Bunda	3637	Kilindi	1182
Chamwino	1912	Siha	333	Geita	383	Kilwa	732
DodomaR	3259	Sikonge	506	Ilemela	91	Kisarawe	1832
DodomaU	649	Simanjiro	3413	**Kahama**	**845**	Korogwe	645
Hai	431	SingidaR	3075	Kishapu	1584	LindiR	761
Hanang	1844	SingidaU	150	Kwimba	2070	Liwale	693
Handeni	**301**	TaboraR	68	Magu	5593	Lushoto	1298
Igunga	1172	TaboraU	182	Maswa	2274	Mafia	32
Iramba	2338	Uyui	1543	Meatu	4182	Masasi	2374
Kahama	**12**			Misungwi	1234	Mkinga	1380
Karatu	2277	CP_l & D_l ($K = DC_4$)		Muleba	369	Mkuranga	798
Kiteto	873	Chunya	1030	Musoma	995	MtwaraR	668
Kondoa	1847	IringaR	3974	MusomaR	3247	Nachingwea	1206
Kongwa	3307	Kilolo	321	Nyamagana	72	Nanyumbu	834
Longido	4503	Kilombero	300	Rorya	2196	Pangani	934
Manyoni	3871	Kilosa	1138	Sengerema	200	Ruangwa	701
Mbulu	1238	Ludewa	150	Serengeti	509	Rufiji	1812
Monduli	4345	Makete	41	ShinyangaR	642		
MorogoroR	**88**	Mbarali	1705	ShinyangaU	100		
MoshiR	1007	Mbozi	100	Tarime	913		
Mpwapwa	2993	**MorogoroR**	**1579**	Ukerewe	755		
Muheza	200	Mufindi	768				
Mvomero	1444	Njombe	1754				
Mwanga	917	Ulanga	3140				

Table B.14: *Optimal results: CP_l to DC_k allocations and D_l for eight DCs.*

CP_l & D_l ($K = DC_5$)		CP_l & D_l ($K = DC_4$)		CP_l & D_l ($K = DC_6$)		CP_l & D_l ($K = DC_3$)	
Bariadi	63	Chunya	1030	Serengeti	509	Babati	1420
Biharamulo	902	IringaR	3974	Siha	333	Bahi	1249
Geita	383	Kilolo	321	Tarime	913	Chamwino	1912
Ilemela	91	Kilombero	300	CP_l & D_l ($K = DC_1$)		DodomaR	3259
Kahama	857	Kilosa	1138	Bagamoyo	2721	DodomaU	649
Kishapu	1584	Ludewa	150	Handeni	3267	Igunga	1172
Kwimba	2070	Makete	41	Kibaha	1431	Iramba	2338
Maswa	2274	Mbarali	1705	**Kilindi**	**825**	**Kilindi**	**357**
Meatu	4182	Mbozi	100	Kilwa	732	Kiteto	873
Misungwi	**1093**	**MorogoroR**	**1579**	Kisarawe	1832	Kondoa	1847
Nyamagana	72	Mufindi	768	Korogwe	645	Kongwa	3307
ShinyangaR	642	Njombe	1754	LindiR	761	Manyoni	3871
ShinyangaU	100	Ulanga	3140	Liwale	693	**MorogoroR**	**88**
Sikonge	**119**	CP_l & D_l ($K = DC_6$)		Lushoto	1298	Mpwapwa	2993
TaboraR	68	Arumeru	2005	Mafia	32	Mvomero	1444
CP_l & D_l ($K = DC_7$)		ArushaU	1248	Masasi	2374	Mwanga	917
BukobaR	288	**Bunda**	**1421**	Mkinga	1380	Nzega	2302
Bunda	**2216**	Hai	431	Mkuranga	798	Rombo	3663
Magu	5593	Hanang	1844	MtwaraR	668	Same	2589
Misungwi	**141**	Karatu	2277	Muheza	200	**Sikonge**	**387**
Muleba	369	Longido	4503	Nachingwea	1206	Simanjiro	3413
Musoma	995	Mbulu	1238	Nanyumbu	834	SingidaR	3075
MusomaR	3247	Monduli	4345	Pangani	934	SingidaU	150
Rorya	2196	MoshiR	1007	Ruangwa	701	TaboraU	182
Sengerema	200	Ngorongoro	6426	Rufiji	1812	Uyui	1543
Ukerewe	755						

Appendix C

Original data documents



17/01/2011

Data: 2010/2011.

Transportation Cost:

PhD RESEARCH

Particulars	Arusha	Dodoma	Kipawa	Makambako	Shinyanga	Songea	Sumbawanga	H/Office	TOTAL
Transportation within the zone	190,140,530.00	71,669,310.50	-	84,291,037.97	2,279,120.00	602,342,189.00	780,200,232.07		**1,730,922,419.54**
Transportation(Maize) from zone to zone	1,750,686,105.01	512,857,613.26	790,364,920.07	163,856,559.20	-	-	-	-	**3,217,765,197.54**
TOTAL	**1,940,826,635.01**	**584,526,923.76**	**790,364,920.07**	**248,147,597.17**	**2,279,120.00**	**602,342,189.00**	**780,200,232.07**	**-**	**4,948,687,617.08**

Number of tonnes.

ZONES	MAKAMBAKO	ARUSHA	KIPAWA	DODOMA	TOTAL
Sumbawanga	7,522.742	9,866.500	60.255	4,008.695	**21,458.192**
Makambako			6,304.389		**6,304.389**
Songea			152.758		**152.758**
TOTAL	**7,522.742**	**9866.500**	**6,517.402**	**4,008.695**	**27,915.339**
Transportation(Maize)	**163,856,559.20**	**1,750,686,105.01**	**790,364,920.07**	**512,857,613.26**	**3,217,765,197.54**

STORAGE CAPACITY BY ZONES

zone	Tonnes
ARUSHA	39,000.000
KIPAWA	52,000.000
DODOMA	39,000.000
Shinyanga	14,500.000
makambako	34,000.000
Songea	24,000.000
Sumbawanga	38,500.000
Total	**241,000.000**

we have 30 storage Godown

Source: NFRA – ~~Head~~ office.

Unit price per km per kg.
(a) 148
(b) 126 } 2010

1). Train transportation: cost less compare to road.
2). ⇒ US$ 67.47 per km per tonne

- Future planning
  - location
  - capacity.
- Expected construction Cost.

Figure C.1: *NFRA - PCs to DCs maize crop transportation, 2010* http://dailynews.co.tz/home/?n=14034 : Tuesday April 23, 2013

Local News

Construction of maize grain storage facility underway

Share on Facebook

From PETI SIYAME in Sumbawanga, **24th October 2010 @ 12:00, Total Comments: 2, Hits: 3513**

THE government is constructing a grain storage facility that can hold more than 200,000 tonnes of maize which the National Reserve Food Authority (NFRA) has recently been instructed to purchase from farmers in the country.

Prime Minister Mizengo Pinda revealed the plans when responding to members of Regional Consultative Committee (RCC) here yesterday who prayed to the government to let more maize buyers in the region instead of the current arrangement of allowing Energy Mill as the sole buyer.

Rukwa Regional Commissioner, Mr Daniel ole Njoolay, told the Premier that the request for more buyers followed a bumper cereal production realized by farmers in the region this season. The region has doubled grain production from less than one million tonnes in 2005 to over 2 million tonnes.

According to the RC farmers have harvested over **700,000 tonnes** of maize while the actual demand stands at **200,000 tonnes** but NFRA has been allocated to purchase **only 60,000 tonnes of maize**.

"That is already a crisis as more than 400,000 tonnes of maize which are still in the hands of farmers are may rot away due to lack of markets and absence of proper storage facilities," he added.

Mr Pinda accepted the request and allowed Saccos and cooperatives as well as local business men to purchase maize from farmers in the region but cautioned farmers not to sell their entire stocks and directed the regional authorities to ensure that farmers kept between10 to15 bags of 100 kg of maize in their house holds.

He further said that initially the government had directed NFRA to increase purchase of maize from farmers from **150,000 tonnes** to **over 400,000 tonnes but after finding out that the storage facilities have the capacity of storing up only 200,000 tonnes** then they decided to convert the remaining **200,000 tonnes of maize to cash which would be used to construct huge storage facility that would be able to pile up over 400,000 tonnes of maize during next season.**

The bumper haverst of different food crops realized by farmers in Rukwa region was due to friendly weather condition and timely applications of agriculture inputs including improved seed, fertilizers and insecticides .

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1

Figure C.2: *News from Government magazine on new DCs to be built*

TANROADS

TANZANIA ROAD DISTANCE CHART IN KM - MARCH 2009

	DAR	ARUSHA	BABATI	BUKOBA	DODOMA	IRINGA	KIBAHA	KIGOMA	LINDI	MBEYA	MOROGORO	MOSHI	MTWARA	MUSOMA	MWANZA	SHINYANGA	SINGIDA	SONGEA	S'WANGA	TABORA	TANGA
DAR		646	814	1433	451	492	35	1539	452	822	192	566	556	1370	1152	989	696	947	1150	1026	354
ARUSHA	646		168	1068	425	689	611	1174	1098	1020	621	80	1202	498	787	624	331	1144	1348	661	435
BABATI	814	168		900	257	521	779	1006	1266	766	516	248	1370	666	619	456	163	976	1094	493	603
BUKOBA	1433	1068	900		982	1246	1398	551	1885	1205	1241	1148	1989	634	416	516	737	1701	1122	638	1503
DODOMA	451	425	257	982		264	416	1088	903	594	259	505	1007	919	701	538	245	719	922	575	588
IRINGA	492	689	521	1246	264		457	1229	944	330	300	769	1048	1183	965	802	509	455	658	839	629
KIBAHA	35	611	779	1398	416	457		1504	487	787	157	531	591	1109	1117	954	661	912	1115	991	319
KIGOMA	1539	1174	1006	551	1088	1229	1504		1991	899	1347	1254	2095	851	633	622	843	1365	571	744	1609
LINDI	452	1098	1266	1885	903	944	487	1991		1068	644	1018	104	1597	1604	1441	1148	602	1396	1478	806
MBEYA	822	1020	766	1205	594	330	787	899	1068		630	1100	1122	1142	924	761	603	466	328	567	959
MOROGORO	192	621	516	1241	259	300	157	1347	644	630		541	748	1178	960	797	504	755	958	834	329
MOSHI	566	80	248	1148	505	769	531	1254	1018	1100	541		1122	578	758	704	411	1224	1428	741	355
MTWARA	556	1202	1370	1989	1007	1048	591	2095	104	1122	748	1122		1701	1708	1545	1252	656	1450	1582	910
MUSOMA	1370	498	666	634	919	1183	1109	851	1597	1142	1178	578	1701		218	381	674	1638	1171	575	933
MWANZA	1152	787	619	416	701	965	1117	633	1604	924	960	758	1708	218		163	456	1420	953	357	1113
SHINYANGA	989	624	456	516	538	802	954	622	1441	761	797	704	1545	381	163		293	1257	790	194	1059
SINGIDA	696	331	163	737	245	509	661	843	1148	603	504	411	1252	674	456	293		964	931	330	766
SONGEA	947	1144	976	1701	719	455	912	1365	602	466	755	1224	656	1638	1420	1257	964		794	1033	1084
S'WANGA	1150	1348	1094	1122	922	658	1115	571	1396	328	958	1428	1450	1171	953	790	931	794		596	1287
TABORA	1026	661	493	638	575	839	991	744	1478	567	834	741	1582	575	357	194	330	1033	596		1096
TANGA	354	435	603	1503	588	629	319	1609	806	959	329	355	910	933	1113	1059	766	1084	1287	1096	

NOTE:

ROUTE	VIA	ROUTE	VIA	ROUTE	VIA
Dar - Musoma	Dodoma - Singida	Babati - Iringa	Dodoma	Kigoma - Morogoro	Singida - Dodoma
Dar - Mwanza	Dodoma - Singida	Babati - Mbeya	Singida - Rungwa	Lindi - Songea	Masasi
Arusha - Dodoma	Babati	Babati - Morogoro	Dodoma	Lindi - Mbeya	Masasi - Songea
Arusha - Iringa	Babati - Dodoma	Babati - Musoma	Arusha - Serengeti	Mbeya - Moshi	Iringa - Dodoma
Arusha - Mbeya	Babati - Dodoma - Iringa	Dodoma - Mbeya	Mtera	Mbeya - Mtwara	Masasi - Songea
Arusha - Musoma	Serengeti	Iringa - Moshi	Dodoma	Moshi - Iringa	Babati - Dodoma
Arusha - Mwanza	Babati - Singida	Iringa - Tabora	Dodoma - Singida	Musoma - S'wanga	Mpanda - Ipole
Arusha - Songea	Babati - Dodoma - Iringa	Kigoma - Iringa	Sumbawanga	Mwanza - Tanga	Serengeti -Arusha
Arusha - S'wanga	Babati - Dodoma - Iringa	Kigoma - Mbeya	Sumbawanga	Shinyanga - Tanga	Singida - Babati - Arusha
				Singida - S'wanga	Rungwa - Mbeya

Figure C.3: *Tanzania roads - Regional distances in km as from TANROADS*

N.F.R.A.

ANNUAL STORAGE COSTS

TAKE THE PRACTICAL SITUATION OF THE STORAGE OF 8000 TONS

OF MAIZE IN GODOWN NO. 1 SONGEA

LAYER DUSTING:

Is done during procurement when stacking grain-filled bags, using pirimiphos methyl dust.

- The dosage rate in 250 grams per ton.
- Total pesticide dust used in 8,000 tons is 2,000 kgs.
- Its price is sh. 10,000/= per kg.
- **Total cost of pesticide used is 2,000 kgs x 10,000/- = Sh. 20,000,000/=**

FUMIGATION:

Is done 5 times in 1 year using Aluminium phosphide tablets.

- The fumigation of 8000 tons once required 121 kgs of Aluminium phosphide tablets.
- Total fumigant used in one year is 121 kgs x 5 = 605 kgs
- **Total fumigant cost is 605 kgs x 65,000/- = Sh. 39,325,000/=**

ROUTINE PESTCIDE SPRAYING:

Routine spraying and spraying during fumigation is done using Organophosphate pesticides and is usually carried out twice monthly, and two times during any fumigation operation:-

- The rate of pesticide use for the whole godown is 10 litres in a single operation
- Quantity of pestcide used for:
    1. Routine spraying is 10 litres x 2 x 12 months = 240 litres
    2. Fumigation spraying is 10 litres x 2 x 5 = 100 lts
- Total Pesticide used is 340 litres
- **So total cost of pesticide used is 340 lts x 36,000/= = Sh. 12,240,000/=**

LABOR COSTS

- During Fumigation:

We need 21 days to carry out a single fumigation operation, and we use 12 casual operators.

Labor cost is: 12 x 4,500/= x 21 days x 5 operations = **Sh. 5,670,000/=**

Figure C.4: *Songea DC annual operation costs - 2012*

- Pesticide Spraying and Warehouse Cleanliness:

We use 4 workers to do routing spraying and sanitation in and around the warehouse

The cost is: Sh.4500/= x 4 x 30days x 12 months = **Sh. 6,480,000/=**

TOTAL STORAGE COSTS FOR 8,000 TONS

Is Sh.	20,000,000/=
	39,000,000/=
	12,000,000/=
	5,670,000/=
+	6,480,000/=
= **Sh.**	**83,150,000/=**

So the cost of preserving 8000 tons of maize for one year is Tsh. $\frac{83,150,000/=}{8,000}$

Which is **Tsh. 10,393.75 per ton**

or Tsh. 10.40 per kg

Prepared by: E.R.Mtango

05th March 2012

Figure C.5: *Songea DC annual operation costs - 2012*

Figure C.6: *Tanzania map showing regions and districts- 2013*

File

UNIVERSITY OF DAR ES SALAAM
COLLEGE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MATHEMATICS

Telegrams: University
Phone: 0655/0784/-840620
EMAIL: emassawe@maths .udsm.ac.tz
emassawe@uccmail.co.tz

P.O.BOX 35062
Dar Es Salaam
TANZANIA

8

24 December, 2010

CHIEF EXECUTIVE OFFICER
NATIONAL FOOD RESERVE AGENCY
P.O.BOX 5384
DAR ES ER SALAAM

RE: Ph.D STUDIES THESIS DATA

The holder of this letter, Mr. Saidi Sima is an academic member of staff at the Department of mathematics. Mr Sima is currently pursuing his Ph.D studies at the University of Witswatersrand, South Africa. Mr. Sima is writing a thesis on "Integrated stochastic routine distribution network design: A two-level location routine problem with application to food crops transportation in Tanzania" using the available data in your esteemed executive agency.

I am therefore kindly requesting you to assist him in any information/data which he may need. Thanking you in advance

Dr. E. S. Massawe
Head, Mathematics Department, UDSM

MATHEMATICS DEPT
UNIVERSITY OF DAR-ES-SALAAM
P.O. Box 35062, DAR-ES-SALAAM

Figure C.7: *Letter for PhD Data collection in Tanzania - 2010/2011*

UNIVERSITY OF DAR ES SALAAM
COLLEGE OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MATHEMATICS

Telegrams: University
Phone: 0655/0784/-840620
EMAIL: emassawe@maths .udsm.ac.tz
emassawe@uccmail.co.tz

P.O.BOX 35062
Dar Es Salaam
TANZANIA

28 January, 2011

To whom it may

RE: Ph.D STUDIES THESIS DATA

The holder of this letter, Mr. Saidi Sima, staff at the Department of mathematics. Mr Sima is currently pursuing his Ph.D studies at the University of Witswatersrand, South Africa.. Mr. Sima is writing a thesis on "Integrated stochastic routine distribution network design: A two-level location routine problem with application to food crops transportation in Tanzania" using the available data in your esteemed executive agency.

I am therefore kindly requesting you to assist him in any information/data which he may need. Thanking you in advance

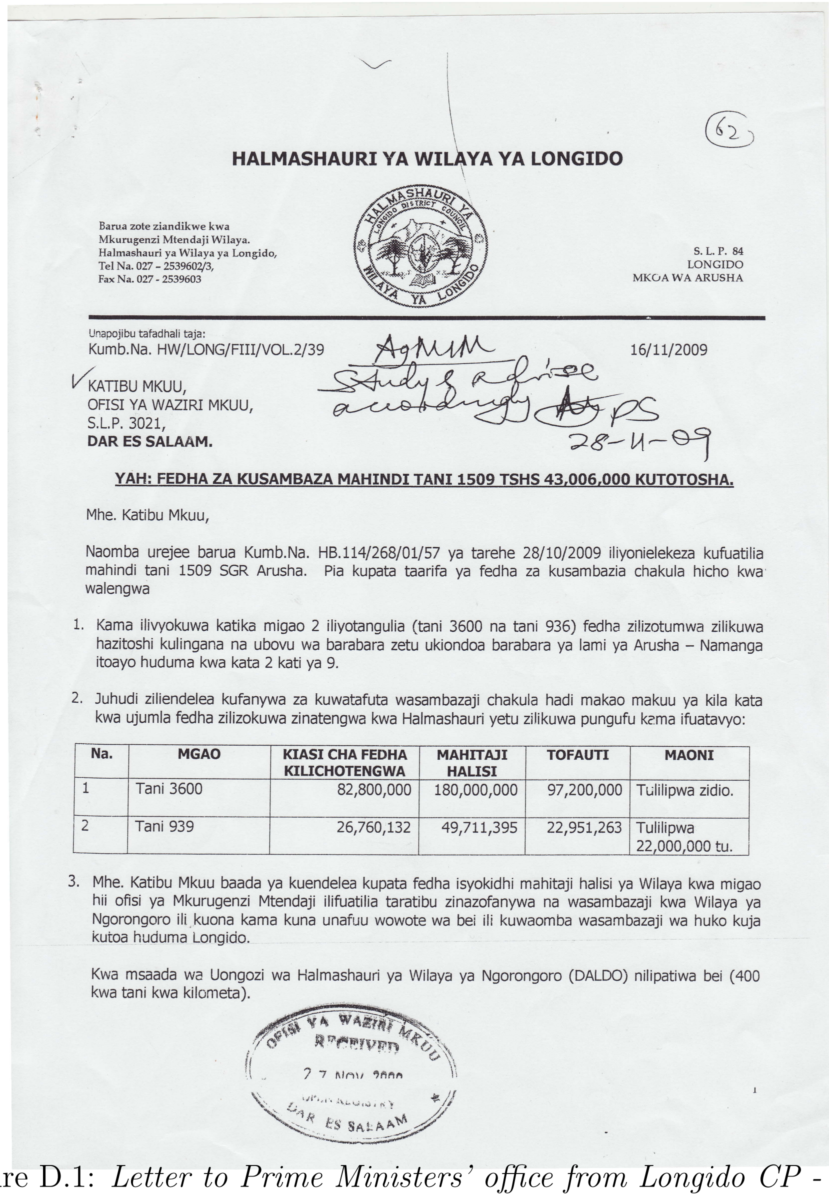
Dr. E. S. Massawe
Head, Mathematics Department, UDSM

MATHEMATICS DEPT.
UNIVERSITY OF DAR-ES-SALAAM
P O Box 35062, DAR-ES-SALAAM

Figure C.8: *Letter for PhD Data collection in Tanzania -2010/2011*

Appendix D

Cost increase due to rainfall



(62)

HALMASHAURI YA WILAYA YA LONGIDO

HALMASHAURI YA WILAYA YA LONGIDO DISTRICT COUNCIL

Barua zote ziandikwe kwa
Mkurugenzi Mtendaji Wilaya.
Halmashauri ya Wilaya ya Longido,
Tel Na. 027 – 2539602/3,
Fax Na. 027 - 2539603

S. L. P. 84
LONGIDO
MKOA WA ARUSHA

Unapojibu tafadhali taja:
Kumb.Na. HW/LONG/FIII/VOL.2/39 AgMM 16/11/2009

Study & advise accordingly At PS 28-11-09

KATIBU MKUU,
OFISI YA WAZIRI MKUU,
S.L.P. 3021,
DAR ES SALAAM.

YAH: FEDHA ZA KUSAMBAZA MAHINDI TANI 1509 TSHS 43,006,000 KUTOTOSHA.

Mhe. Katibu Mkuu,

Naomba urejee barua Kumb.Na. HB.114/268/01/57 ya tarehe 28/10/2009 iliyonielekeza kufuatilia mahindi tani 1509 SGR Arusha. Pia kupata taarifa ya fedha za kusambazia chakula hicho kwa walengwa

1. Kama ilivyokuwa katika migao 2 iliyotangulia (tani 3600 na tani 936) fedha zilizotumwa zilikuwa hazitoshi kulingana na ubovu wa barabara zetu ukiondoa barabara ya lami ya Arusha – Namanga itoayo huduma kwa kata 2 kati ya 9.

2. Juhudi ziliendelea kufanywa za kuwatafuta wasambazaji chakula hadi makao makuu ya kila kata kwa ujumla fedha zilizokuwa zinatengwa kwa Halmashauri yetu zilikuwa pungufu kama ifuatavyo:

Na.	MGAO	KIASI CHA FEDHA KILICHOTENGWA	MAHITAJI HALISI	TOFAUTI	MAONI
1	Tani 3600	82,800,000	180,000,000	97,200,000	Tulilipwa zidio.
2	Tani 939	26,760,132	49,711,395	22,951,263	Tulilipwa 22,000,000 tu.

3. Mhe. Katibu Mkuu baada ya kuendelea kupata fedha isyokidhi mahitaji halisi ya Wilaya kwa migao hii ofisi ya Mkurugenzi Mtendaji ilifuatilia taratibu zinazofanywa na wasambazaji kwa Wilaya ya Ngorongoro ili kuona kama kuna unafuu wowote wa bei ili kuwaomba wasambazaji wa huko kuja kutoa huduma Longido.

Kwa msaada wa Uongozi wa Halmashauri ya Wilaya ya Ngorongoro (DALDO) nilipatiwa bei (400 kwa tani kwa kilometa).

OFISI YA WAZIRI MKUU
RECEIVED
27 NOV 2009
REGISTRY
DAR ES SALAAM

1

Figure D.1: *Letter to Prime Ministers' office from Longido CP - 2009*

Mlinganisho ulionyesha gharama kama ifuatavyo:

a) Uzito tani 939

Na.	KATA	UMBALI TOKA SGR (km)	TANI	GHARAMA USAFIRISHAJI (NGORONGORO)	USAFIRISHAJI LONGIDO RATE/TANI	GHARAMA USAFIRISHAJI LONGIDO	TOFAUTI YA USAFIRI NGORONGORO NA LONGIDO
1	Longido	90 km	92.002	3,312,072	35,000	3,220,770	91,302
2	Namanga	115 km	138.972	6,392,712	40,000	5,558,880	834,432
3	Tingatinga	115 km	65.926	3,032,596	60,000	3,955,560	(-922,964)
4	Ketumbeine	140 km	157.752	8,834,112	50,000	7,887,600	946,512
5	Olmolog	165 km	177.471	11,763,086	55,000	9,760,905	1,952,381
6	Meirugoi	225 km	64.984	5,848,560	60,000	3,899,040	1,949,520
7	Lumbwa	210 km	51.799	4,351,116	60,000	3,107,940	1,243,176
8	Matale	155 km	42.651	2,644,362	50,000	2,132,550	511,812
9	Engarenaibor	125 km	147.423	7,371,150	50,000	7,371,150	0
			Jumla	**53,549,766**		**46,894,395**	**6,655,371**

Jumla ya gharama (Ngorongoro) = 53,549,766 + (upakiaji) 2,817,000 = (jumla) 56,366,766/=

Jumla ya gharama (Longido) = 46,894,395 + (upakiaji) 2,817,000 = (jumla) 49,711,395/=

Fedha iliyotengwa = 26,760,132
Upungufu Longido = 22,951,263/=

4. Mgao mpya (Bado kusambazwa tani 1509 fedha iliyotolewa kusambaza ni Tshs 43,006,000/=. Bado gharama halisi iko juu kwa viwango vya wasambazaji wa Ngorongoro kuja kusambaza mahindi hayo Longido na pia kwa viwango vya sasa vya wasambazaji wa Longido wale wa Ngorongoro watahitaji Tshs 90,498,900/=

Na.	KATA	TANI	UMBALI TOKA SGR (KM)	NGORONGORO KIWANGO USAFIRI 400/TANI/KM	KWA WALE WASAMBAZAJI WA LONGIDO	
					USAFIRISHAJI KIWANGO KWA TANI	GHARAMA
1	Olmolog	285.542	165	18,845,772	55,000	15,704,810
2	Namanga	223.749	115	10,292,454	40,0000	8,949,960
3	Tingatinga	105.203	115	4,839,338	60,000	6,312,180
4	Ketumbeine	254.114	140	14,230,384	50,000	12,705,700
5	Engarenaibor	236.834	125	11,841,700	50,000	11,841,700
6	Lumbwa	82.79	210	6,954,360	60,000	4,967,400
7	Meirugoi	104.831	225	9,434,790	60,000	6,289,860
8	Matale	67.656	155	4,194,672	50,000	3,382,800
9	Longido	148.28	90	5,338,000	35,000	51,89,800
			Jumla ndogo	**85,971,900**	-	**75,344,210**
			Upakiaji	**4,527,000**	-	**4,527,000**
			Jumla kuu	**90,498,900**	-	**79,871,210**

Fedha iliyotengwa na Wizara = 43,006,000/= upungufu Longido = 36,865,210/=

Figure D.2: *Letter to Prime Ministers' office from Longido CP - 2009*

Mhe. Katibu Mkuu nimetoa maelezo marefu kutokana na Mkurugenzi Mtendaji Longido kuathiriwa na zoezi hili la kusambaza mahindi ya njaa kwa awamu ya 5, 6 na sasa ya 7. Kwa vile tu wasafirishaji hawako tayari kufuata viwango vya kusafirisha mahindi vilivyowekwa na Wizara. Mbaya zaidi Halmashauri yangu haina uwezo kimapato kujazia nakisi ya fedha inayotolewa.

Mhe. Katibu Mkuu nilifuatilia pia kujua uzoefu wa wenzetu wa Ngorongoro juu ya usambazaji chakula/mahindi kwa fedha kidogo – majibu ni kuwa wao wana fursa ya mamlaka ya Hifadhai ya Ngorongoro kusadia usambazaji (sisi hatuna fursa hiyo).

Awamu za 1 – 4 ziliandamana na fedha ya kukidhi hali halisi ya usafirishaji.

Naiomba ofisi yako izingatie ushauri uliotolewa na Halmashauri yangu kupitia kamati ya maafa ya Wilaya.

Wako

C. M. Laizer
MKURUGENZI MTENDAJI
HALMASHAURI YA WILAYA YA LONGIDO.

Nakala:

1) Mhe. Mkuu wa Mkoa
S.L.P. 3050,
ARUSHA. (Kwa msaada tena wa kuwasilisha Wizarani hali halisi ya Halmashauri hii)

2) Katibu Tawala Mkoa,
S.L.P. 3050,
ARUSHA.

3) Mkuu wa Wilaya
S.L.P. 2,
LONGIDO

4) Mhe. Michael L. Laizer
Mbunge – Jimbo la Longido

5) Mhe. Mwenyekiti wa Halmashauri
S.L.P. 84,
LONGIDO.

Utekelezaji wa maagizo ya Kamati ya Maafa (W) (3–5)

2 Timu imeenda Loliondo ikijumlisha Internal Auditor na MMM3. Ndipo Mwesembaga kufuatilia. Waliondoka tar 11/12. Taarifa yao inasubiriwa.
15/12

3

Figure D.3: *Letter to Prime Ministers' office from Longido CP - 2009*

Kiambatanisho: 1

MUHTASARI WA MGAO WA CHAKULA KATIKA MIKOA YENYE UPUNGUFU WA CHAKULA NA MAHITAJI,FEBRUARI,2006.

MKOA	WILAYA	IDADI YA WATU WOTE	WENYE UPUNGUFU	MAHITAJI YA CHAKULA (MT)	MGAO WA MAHINDI (MT)	JUMLA YA GHARAMA YA USAFIRISHAJI (TSH.)
1	2	3	4	5	6	7
Arusha	Karatu	245,821	86,748	1,770	1182	46,098,000
	Monduli	207,526	70,058	1,429	954	12,402,000
	Arumeru	571,998	25,475	520	348	2,436,000
	Ngorongoro	159,422	40,193	820	548	34,524,000
JUMLA		**1,184,767**	**222,473**	**4,539**	**3032**	**95,460,000**
Pwani	Kibaha	146,251	4,260	109	73	803,000
	Kisarawe	103,759	2,022	52	35	315,000
	Bagamoyo	244,417	46,827	1194	798	12,448,800
	Mafia	42,669	1260	32	22	946,000
	Rufiji	215,526	11,668	298	296	10,360,000
JUMLA		**752,622**	**66,037**	**1685**	**1224**	**24,872,800**
Dodoma	Dodoma (V)	462,019	159,758	3259	2177	10,885,000
	Kondoa	451,902	59,398	1212	809	33,169,000
	Mpwapwa	277,013	32,985	673	449	12,123,000
	Kongwa	271,854	90,610	2311	1544	27,483,200
	Dodoma (M)	358,746	20,688	422	281	1,405,000
JUMLA		**1,821,534**	**363,441**	**7877**	**5260**	**85,065,200**
Iringa	Iringa	257,190	35,840	731	488	15,420,800
	Kilolo	214,739	15,727	321	215	9,245,000
	Mufindi	296,092	6006	123	82	2,050,000
	Njombe	446,859	28,755	587	392	7,448,000
	Makete	104,075	1,590	41	27	945,000
JUMLA		**1,318,955**	**87,918**	**1803**	**1204**	**35,108,800**

Figure D.4: *Sample of DC to CP Transportation of maize showing a month it took place*

Kiambatisho-2

TAARIFA YA MGAO WA MAHINDI YA MSAADA

MWAKA 2009/2010 hadi Marchi 2010 (Awamu ya 1 & 2)

MKOA	WILAYA	UMBALI TOKA SGR (KM)	CHAKULA CHOTE CHA MSAADA (MT)	CHAKULA CHA KUUZA TSH.50/= (MT)	CHAKULA CHA BURE (MT)	GHARAMA ZA KUSAFIRISHA
Arusha	Arusha DC	22	1248	1123	125	11,980,800.00
	Karatu	180	746	671	75	42,522,000.00
	Longido	85	2448	2203	245	69,768,000.00
	Meru	22	1384	1245	139	13,286,400.00
	Monduli	50	1861	1675	186	33,498,000.00
	Ngorongoro	370	2309	2078	231	263,226,000.00
Jumla			9996	8995	1001	434,281,200.00
Dodoma	Bahi	65	1249	1124	125	28,102,500.00
	Kongwa	74	3307	2976	331	83,336,400.00
	Kondoa	190	737	663	74	44,220,000.00
	Mpwapwa	120	2201	1981	220	85,839,000.00
	Chamwino	25	1837	1653	184	19,288,500.00
	Dodoma (U)	10	600	510	90	3,600,000.00
Jumla			9931	8907	1024	264,386,400.00
Iringa	Iringa (V)	143	232	209	23	10,648,800.00
	Kilolo	200	70	63	7	4,410,000.00
Jumla			302	272	30	15,058,800.00
Kilimanjaro	Same	210	2056	1851	205	135,696,000.00
	Mwanga	150	569	512	57	27,312,000.00
	Rombo	190	621	559	62	37,260,000.00
	Hai	60	431	388	43	9,051,000.00

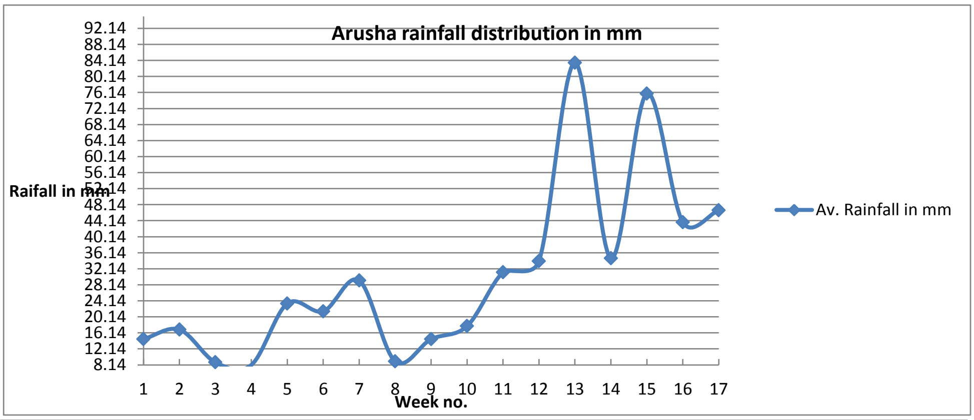
Figure D.5: *Sample of DC to CP Transportation of maize showing a month it took place*

GHARAMA YA USAFIRISHAJI WA MAHINDI YA MSAADA KWA MIKOA ILIOKUMBWA NA UPUNGUFU 20 APRILI, 2009

MKOA	WILAYA	UMBALI TOKA SGR (KM)	MGAO WA MAHINDI AWAMU YA KWANZA	GHARAMA YA USAFIRI (TSH.)	MGAO WA MAHINDI AWAMU YA PILI	GHARAMA YA USAFIRI HADI KATA (TSH.)	MGAO WA MAHINDI AWAMU ZOTE (MT)	GHARAMA YA USAFIRI HADI KATA KWA AWAMU ZOTE (TSH.)	MAHINDI YA KUUZA KWA SH.50/= (MT)	MAHINDI YA BURE (MT)	SEHEMU YA KUCHUKUA	MAPATO YA MAHINDI YATAKAOUZWA (TSH.)
1	2	4		5	6	7	8	9	11	12	13	14
	Longido	200			2,054.5	129,433,500.0	2054.5	129,433,500.0	1,462.6	591.9	ARUSHA	73,130,000.0
	Karatu	180			1,530.3	87,227,100	1,530.3	87,227,100.0	949.0	581.3	ARUSHA	47,450,000.0
Arusha	Monduli	50			2,483.6	44,704,800	2,483.6	44,704,800.0	1,582.8	900.8	ARUSHA	79,140,000.0
	Meru	22	310	2,976,000.00	310.5	2,980,800	620.5	5,956,800.0	145.0	165.5	ARUSHA	7,250,000.0
	Ngorongoro	300			4,116.4	382,825,200	4,116.4	382,825,200.0	2,553.2	1,563.2	ARUSHA	127,660,000.0
JUMLA			310	2,976,000	10,495.3	647,171,400	10,805.3	650,147,400.0	6,692.6	3,802.7		334,630,000.0
Pwani	Kibaha	40			250.9	3,763,500	250.9	3,763,500.0	188.2	62.7	KIPAWA	9,410,000.0
	Bagamoyo	63	186	4,073,400.00	186.4	4,082,160	372.4	8,155,560.0	93.4	93.0	KIPAWA	4,670,000.0
JUMLA			186	4,073,400	437.3	7,845,660	623.3	11,919,060.0	281.6	155.7		14,080,000.0
	Mpwapwa	120			791.8	30,880,200	791.8	30,880,200.0	476.8	315.0	DODOMA	23,840,000.0
JUMLA			-	-	791.8	30,880,200	791.8	30,880,200	476.8	315.0		23,840,000.0
	Iringa	143			1,005.8	46,166,220	1,005.8	46,166,220.0	773.7	232.1	MA'MBAKO	38,685,000.0
JUMLA			-	-	1,005.8	46,166,220	1,005.8	46,166,220	773.7	232.1		38,685,000.0
	Same	210			532.8	35,164,800	532.8	35,164,800.0	506.2	26.6	ARUSHA	25,310,000.0
	Mwanga	150			244.7	11,745,600	244.7	11,745,600.0	232.5	12.2	ARUSHA	11,625,000.0
Kilimanjar	Rombo	190			3,041.2	182,472,000	3,041.2	182,472,000.0	1,886.3	1,154.9	ARUSHA	94,315,000.0
JUMLA			-	-	3,818.7	229,382,400	3,818.7	229,382,400	2,625.0	1,193.7		131,250,000.0
	Ruangwa	565	94	16,215,000.00	173.7	29,963,250	267.7	46,178,250.0	120.1	53.6	KIPAWA	6,005,000.0
	Kilwa	294	124	11,308,800.00	334.0	30,460,800	458.0	41,769,600.0	314.8	19.2	KIPAWA	15,740,000.0
Lindi	Lindi Rural	459			374.7	52,720,290	374.7	52,720,290.0	356.0	18.7	KIPAWA	17,800,000.0
	Nachingwea	614	238	44,553,600.00	574.7	107,583,840	812.7	152,137,440.0	503.7	71.0	KIPAWA	25,185,000.0
	Liwale	764	114	26,470,800.00	313.2	72,725,040	427.2	99,195,840.0	297.6	15.6	KIPAWA	14,880,000.0
JUMLA			570	98,548,200	1,770.3	293,453,220	2,340.3	392,001,420	1,592	178.1		79,610,000
	Kiteto	179	151	8,561,700.00	227.3	12,887,910	378.3	21,449,610.0	151.6	75.7	DODOMA	7,580,000.0
	Simanjiro	205	116	7,482,000.00	1,400.6	90,338,700	1,516.6	97,820,700.0	1,293.6	107.0	ARUSHA	64,680,000.0
Manyara	Hanang	280			270.8	23,559,600	270.8	23,559,600.0	203.1	67.7	ARUSHA	10,155,000.0
	Mbulu	245	183	13,999,500.00	183.6	14,045,400	366.6	28,044,900.0	131.8	51.8	ARUSHA	6,590,000.0
	Babati	167			311.1	16,519,410	311.1	16,519,410.0	233.3	77.8	ARUSHA	11,665,000.0
JUMLA			450	30,043,200	2,393.4	157,351,020	2,843.4	187,394,220	2,013.4	380.0		100,670,000.0
	Rorya	540	388	64,020,000.00	388.0	64,020,000	776.0	128,040,000.0	128.8	259.2		6,440,000.0
	Bunda	420			552.6	71,285,400	552.6	71,285,400.0	525.0	27.6	SH'NGA	26,250,000.0
	Musoma (V)	500	565	86,445,000.00	565.2	86,475,600	1,130.2	172,920,600.0	172.1	393.1	SH'NGA	8,605,000.0
JUMLA			953	150,465,000	1,505.8	221,781,000	2,458.8	372,246,000	825.9	679.9		41,295,000.0

Figure D.6: *Sample of DC to CP Transportation of maize showing a month it took place*

Week	Av. Rainfall in mm
1	14.60
2	16.95
3	8.80
4	8.14
5	23.47
6	21.52
7	29.20
8	9.03
9	14.57
10	17.83
11	31.25
12	34.05
13	83.56
14	34.77
15	75.86
16	43.76
17	46.75



Week	Av. Rainfall in mm
1	18.46
2	16.77
3	5.73
4	17.41
5	21.68
6	29.90
7	32.53
8	20.90
9	24.52
10	23.37
11	17.14
12	36.20
13	53.86
14	47.32
15	59.68
16	33.67
17	56.21

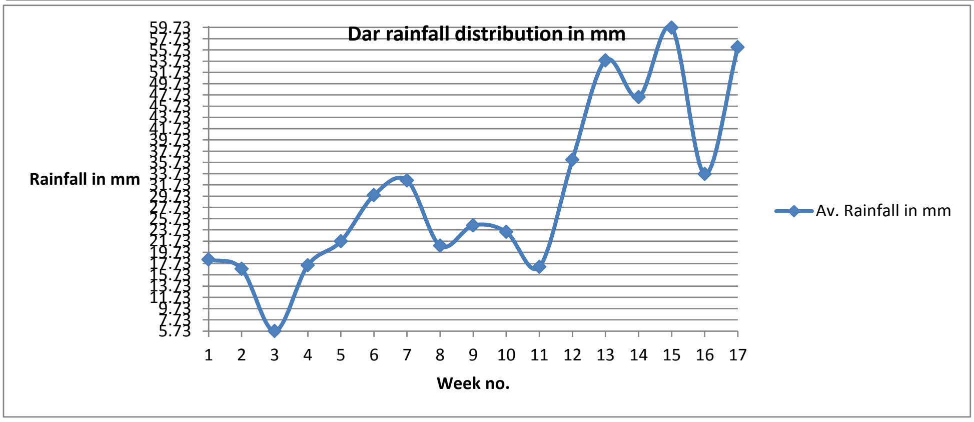
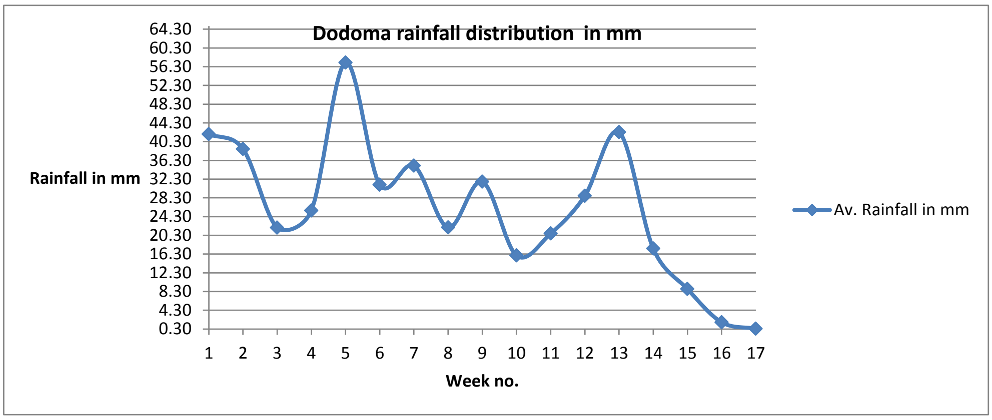


Figure D.7: *Some DC zones rainfall distributions graphs*

Week	Av. Rainfall in mm
1	41.89
2	38.74
3	21.94
4	25.58
5	57.18
6	31.10
7	35.18
8	21.96
9	31.76
10	15.99
11	20.67
12	28.71
13	42.33
14	17.46
15	8.84
16	1.74
17	0.36



Week	Av. Rainfall in mm
1	44.10
2	32.24
3	33.24
4	37.43
5	48.58
6	46.55
7	37.44
8	26.66
9	26.17
10	27.67
11	53.23
12	30.44
13	23.66
14	27.94
15	10.55
16	7.53
17	5.52

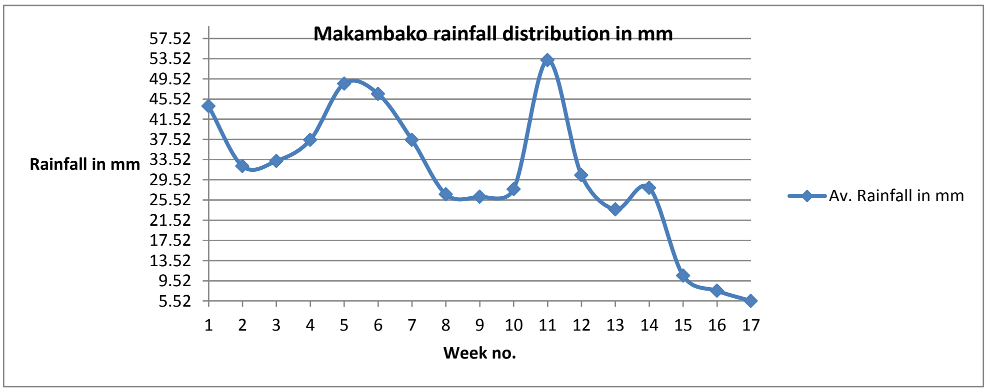


Figure D.8: *Some DC zones rainfall distributions graphs*

Week	Av. Rainfall in mm
1	30.83
2	22.24
3	33.53
4	45.24
5	26.61
6	37.42
7	37.19
8	32.97
9	42.26
10	29.72
11	38.59
12	48.10
13	45.93
14	20.74
15	61.86
16	42.04
17	23.29

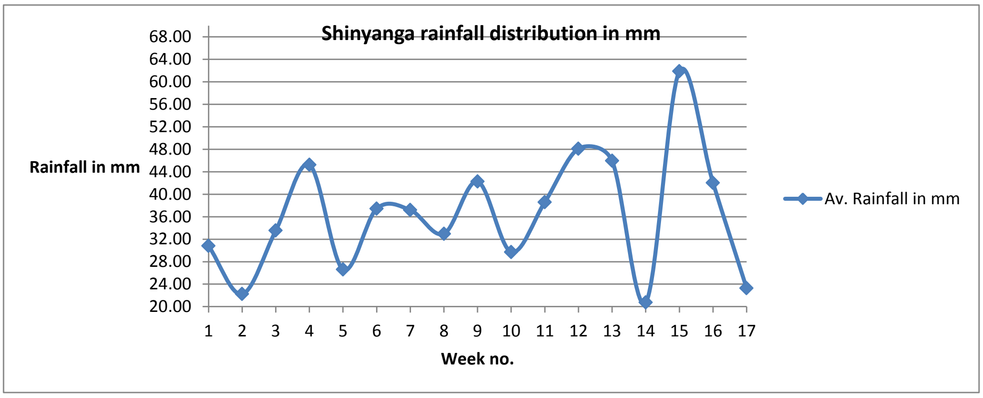


Figure D.9: *Some DC zones rainfall distributions graphs*

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