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Tactical Network Planning for Food Aid Distribution in Kenya

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Abstract. In Sub-Saharan Africa, the annual seasonal patterns cause frequent and regular shocks which make the population more vulnerable to food insecurity. Kenya is affected by periodic droughts at the beginning and at the end of two irregular rainy seasons, which have a profound effect on seasonal food crises. This project aims at providing a mathematical programming based methodology for the design of food aid distribution networks in Kenya. It can also be applied to other developing countries. We present a location model to determine a set of distribution centers, where the food is directly distributed to the beneficiaries, for the region of Garissa in Kenya. Our model takes into account the welfare of all stakeholders involved in the response system: the government of Kenya, the World Food Programme, the Red Cross, and the beneficiaries. We describe how we have combined need assessment and population data to plan food distribution in Garissa. We also show how we have used GIS data on the road network to establish a set of potential distribution centers. In addition to the results obtained by solving our primary model, we present the several sensitivity analyses and variants of the basic covering model.

Keywords: Food aid, network design, location problem, stakeholder welfare.

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1 Introduction

According to the United Nations World Food Programme (2012), hunger and malnutrition pose the largest risks to worldwide health. Many developing countries suffer from food shortages, but Sub-Saharan Africa is the only region in the world that is constantly suffering from widespread chronic food insecurity and persistent threats (Shaw, 2009). Seasonalities have always had an important impact on hunger and poverty in rural Africa. The annual patterns of the two dry and two rainy seasons cause frequent and regular shocks which make people vulnerable to food insecurity and hamper their opportunities to move out of poverty. Relatively little attention has been paid to the implications of seasonalities on food insecurity and rural poverty, despite the fact that they generate short-term hunger and seasonal food crises every year (Devereux, 2012). Because seasonalities are repetitive, rural households and communities have developed coping strategies to buffer their effects, like pastoralist livelihood systems (Young, 1992).

Food aid is an instrument used to reduce insecurity in poor nations. Although food aid has often been criticized (see Bourn and Blench, 1990; Barrett, 2006; Margolies and Hoddinott, 2012), it remains an important component of humanitarian operations. Food aid management entails humanitarian operations evolving within highly complex supply chains. As mentioned by Van Wassenhove (2006) and Christopher and Tatham (2011), logistics is now being recognized to be an integral part of relief operations. In the last decade, humanitarian organizations have started adopting supply chain management methodologies to increase their performance and enhance co-ordination between the actors involved in assistance operations. For example, the World Food Programme (WFP) has made continuous efforts to expand its logistics capacity and to improve the efficiency of its transportation operations, which has enabled it to acquire an acknowledged expertise in moving large amounts of food commodities, often in difficult circumstances, throughout the developing world (see Shaw, 2011).

Haddow and Bullock (2004) have distinguished four phases for disaster management operations of humanitarian organisations: response, recovery, mitigation and preparedness. Figure 1 provides an overview of the cycle of these phases and their meanings. In disaster management, one typically considers that the shocks (disasters) occur before the response phase. These shocks are typically unpredictable and devastating, and they only last a relatively short period of time, like in the case of earthquakes and tsunamis. Our problem is related to preparedness and planning continuous relief operations rather that to the immediate response (see Kovács and Spens, 2007; Çelik et al., 2012, for a distinction between disaster relief and development aid work). For long-term development operations, such as food aid distribution in Sub-Saharan Africa, the context is different because the shocks grow over longer periods and are more predictable, even though emergencies can also occur (the 2011 famine in the Horn of Africa for example). However, the four phases of disaster management are still appropriate and applicable to the context of food security, but they overlap over time. Like the consequences of sudden-onset disasters, long-term development issues also engender human suffering, often coupled with economic damage or poverty, even if the causes cannot usually be attributed to one specific catastrophe.

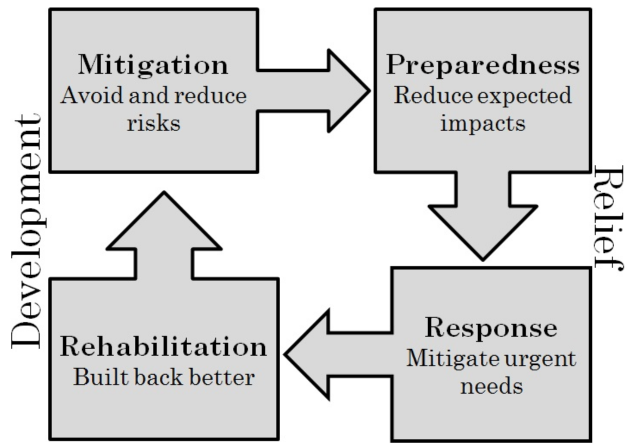


Figure 1: Disaster management lifecycle (Source: Tomasini and Van Wassenhove, 2009).

In this context, where the welfare of the stakeholders is related to economical or accessibility concerns, managing tactical food aid supply chains is a complex task. Humanitarian organisations operate with limited resources which depend primarily on donations. It is therefore of critical importance for these organisations to effectively design their supply chain and transportation plans in order to reach as many affected people as possible during crises. Humanitarian logistics shares several characteristics with its industrial counterpart. Multiple relevant location and transportation problems encountered in the context of food distribution are defined on networks and share a common structure with classical distribution management problems. Indeed, Tzeng et al. (2007) have compared general physical distribution systems for business with relief distribution systems. They have suggested that the points located in non-devastated areas where the commodities are collected act as supply nodes (depots), whereas the devastated areas where relief is provided to victims act as demand nodes (customers). Van Wassenhove (2006) pinpoints the cross-learning potential for both humanitarian and private sectors in emergency food relief operations and the benefits of potential collaborations. This has motivated us to analyze the food aid distribution problem in developing coutries through the use of a mathematical programming based methodology, an approach not commonly used in this context. As mentioned by White et al. (2011) operations research can make important contributions to the improvement of decision making in developing countries although it is of limited use to help reduce poverty. We believe that the results obtained by exploiting such a methodology can provide a valuable perspective for decision makers responsible food relief management.

Our study is motivated by the case of food aid distribution in a region of Kenya (Figure 2), Garissa District and its surroundings, but our contribution is of general applicability for developing countries that are struggling with food insecurity. To our knowledge, this project constitutes the first attempt to develop a support decision system for the design of food aid supply chains. It makes use of real seasonal need assessment data, geographic information systems, and data related to demographics and road infrastructure. Although food aid is often associated with rapid and short-term disaster relief, there are cases in poor and low rainfall areas where food aid is more predictable since it addresses regular and seasonal food insecurity. Maxwell1 and Watkins (2003) have argued that in such cases, it makes sense to invest in the optimization of the distribution network. The Garissa District is one such area and serves as a relevant example for medium-term network optimization.

1.1 Literature review

The surge of natural disasters over the last decade has led to a growing interest in the humanitarian applications of quantitative research in the field of humanitarian logistics. Van Wassenhove and Martinez (2012) show that significant improvements can be achieved by using an operations research methodology to adapt supply chain practices to humanitarian logistics for two applied cases of field vehicle fleet management. Altay and Green (2006) and Simpson and Hancock (2009) have provided exhaustive surveys of operations research-based projects which have contributed to disaster related research in the last decades. Johnson and Smilowitz (2012) have introduced the area of community-based OR, which addresses problems common to humanitarian logistics, such as vulnerable populations, fairness and sustainability objectives. Ergun et al. (2011) have summarized several contributions adressing key problems from the humanitarian and public sectors and have suggested solution approaches.

A number of algorithms have been proposed to deal with location problems related to disaster management issues. Tzeng et al. (2007) have used fuzzy multi-objective programming to create an emergency relief distribution model and have proposed a framework for data collection. They have also tested their methodology on a real case study based on earthquake response in Taiwan. Recently, Naji-Azimia et al. (2012) have modelled the distribution of survival goods to people in disaster areas as a generalization of the covering tour problem and have proposed a heuristic tested

Figure 2: Map of Kenya (Source: Nation Online, 2012).

on randomly generated data. Campbell and Jones (2011) have studied the problem of prepositioning supplies in the context of preparation for disaster by considering risk and inventory levels. They have first solved the problem analytically for one depot and then incorporated their results into a heuristic for a p-median problem.

White et al. (2011) have provided a broad overview of operations research applications in developing countries and have also discussed its relevance for long-term development. We refer the reader to Çelik et al. (2012) for a recent complete tutorial on humanitarian logistics. These authors have highlighted the importance of long-term development issues although most of the operations research-based methodologies developed for the field of humanitarian logistics are related to disaster management problems.

Two projects have been conducted in collaboration with the World Food Programme regarding food aid planning. De Angelis et al. (2007) have proposed a routing and scheduling for emergency air deliveries of food aid in Angola. Alvarenga et al. (2010) have designed a simulation tool to generate an optimal shipment schedule which takes into account transportation lead times, transportation capacities, land transportation storage and handling costs while considering the current state of the supply chain network. This tool first simulates port operations, and then optimizes the truck shipping routes and schedules for food shipments to the main warehouses of a country. However, to our knowledge, none of the projects presented in this literature review directly applies to food aid network planning at the last-mile distribution level.

The problem considered in this paper is related to long-term humanitarian operations and consists in designing a tactical network for food aid distribution. This problem can be modeled as an uncapacitated facility location problem, which has been largely studied by location scientists. Mathematical models and classification schemes for location problems have been reviewed by ReVelle et al. (2008) and Daskin (2008). Melo et al. (2009) have presented applications of facility location models to supply chain network design arising in various industries and have highlighted the current state-of-the-art contributions. Although many sophisticated exact branch-and-bound algorithms have been developed (see Erlenkotter, 1978; Koerkel, 1989), a number of simple heuristics have also been proved to be very successful (see Kratica et al., 2001; Michel and Van Hentenryck, 2004). In this project, we solve the problem with a general purpose mixed integer programming solver. However, the main challenge of the project lies more in modeling the problem, carrying out data collection and processing, and performing analyses for a real case study than on algorithmic development. Data collection and processing is fraught with difficulties in developing countries like Kenya. It was facilitated by the fact that the fourth author runs a consulting company involved in projects related to food aid distribution in Kenya, and the first author made a one-month field trip in August 2012 to gather first-hand information.

2 Problem context and motivation

We now present the context of food aid distribution in Kenya. We describe the humanitarian operations activities associated with the food distribution supply chain, and we explain the roles of the main stakeholders involved in the process.

2.1 Seasonalities and assessment

Rainfalls are highly variable in Kenya; there are two rainy seasons and two intervening dry seasons. The long rain season lasts from March until June, and is followed by a long dry season from June to October. The second rainy season is shorter and lasts from October to December, followed by another dry period from December to March. All parts of the country are subject to periodic droughts at the beginning and at the end of the two rainy seasons, which has a profound effect on settlement patterns and on the Kenyan population affected by nutrition crises. The severity of the droughts has a deep influence on the ability of the affected population to recover from food insecurity, which drives the food aid needs for the following periods. The most vulnerable regions of Kenya are the arid and semi-arid regions in which agro-pastoralism and pastoralism are the dominant livelihood systems (see Bourn and Blench, 1999).

To account for the effects of seasonalties, the Kenya Food Security Steering Group (KFSSG) conducts a need assessment for food aid twice a year, after each rainy season. The KFSSG is a joint group of specialists from the Government of Kenya (GoK), the United Nations (UN), non-governmental organizations (NGOs), and district level teams (see Government of Kenya, 2012a). The assessments consist in determining the number of beneficiaries and the ratio entitlements at the district and division levels across the country. The ratio entitlement corresponds to the percentage of a standard food ration that the beneficiaries are entitled to receive, and is calculated on the basis of their nutritional requirements. This ratio depends on the severity of the seasonal food scarcity. A full ratio entitlement, commonly called a food basket, is made up of 400 g of cereal, 60 g of pulses, 25 g of oil (fortified with vitamine A and D), 50 g of fortified blended food (corn soya blend), 15 g of sugar, and 15 g of iodized salt. To determine the number of beneficiaries and the ratio entitlement, the KFSSG analyzes the available information on the food security situation and other relevant indicators, such as price data, field assessment and livelihood economic contexts. The results of the assessment are valid for a six-month period, i.e. until the following assessment plan is implemented.

The pastoralist populations practice seasonal migrations depending on resource availabilities for their livestock. They allow them to exploit more land in order to suit their food production and survive in arid regions, but the women and the children who remain in pastoralist settlements are often left behind with few resources. Pastoralist households are indeed among the most vulnerable groups in this society. Sanford and Habtu (2000) expose the shortcomings of early warning and response systems in the pastoral areas. The need to develop service delivery models which meet the particular demands of the pastoral communities and the effects of seasonal food scarcity is of critical importance. Managing food aid supply chains in such complex environments is a real challenge for humanitarian organisations. This project aims to provide a methodology for designing and managing tactical food aid distribution networks. Our study takes into account the results of the 2012 short rains assessment for the district of Garissa and its surroundings, a district characterized by semi-arid lands and pastoralist populations.

The district of Garissa is important for food aid in Kenya. Over the period ranging from September 2004 to August 2011, during each six-month period, an average of 83,483 people of this district have received food aid. This corresponds to about 5% of the 1,823,588 people who have received food aid in Kenya, making it the sixth most important district out of the 28 in which aid is distributed, behind Turkana, Wajir, Makueni, Mandera and Kitui. On average, 35% of the district population has been receiving aid. During the most difficult period, this number reached 62%. Only five districts have a higher percentage of the population receiving aid (the district receiving the most is Marsabit, with 60% on average).

Importantly, the district of Garissa has been receiving aid more consistently than the country as a whole. Indeed, the variation in the number of its beneficiaries is lower than it is at the national level: the coefficient of variation in the number of beneficiaries across six-month periods in Garissa is 0.45, and 0.51 at the country level. Only Turkana, Marsabit, Samburu, Mandera, Wajir, Tana River and Kwale, receive aid more consistently. These are all semi-arid regions prone to drought. As suggested by Maxwell1 and Watkins (2003), in Garissa like in these other districts, the relatively stable number of beneficiaries has led to a fixed distribution system which justifies the need for an optimized network.

2.2 Food aid supply chain

Sub-Saharan African in-country food aid supply chains are composed of several main warehouses (MWs) located in strategic regions where primary storage infrastructure is available. The MWs serve mostly as storage facilities and transshipment hubs (Figure 3a). The food is then transported to distribution centers (DCs) from the MWs, where it is informally stored and directly handed out to the beneficiaries. The DCs are temporary depots such as shelters, schools, and community facilities which are often located in remote regions, depending on the population needs (Figure 3b). The beneficiaries must walk to the DCs in order to receive food assistance. For ongoing aid operations, the MWs are usually fixed warehouse infrastructures located in strategic locations in the country, whereas the DCs are temporary depots whose locations may vary over time. These informal warehouses must be located in places accessible to the population. Each MW is used for supplying a specific region in the country, and each DC is supplied from the MW that serves its region. Determining where to locate the DCs in order to reach the vulnerable populations and planning how much food aid should be delivered to these distribution points is of primary importance for supply chain responsiveness and cost effectiveness.

(a) Main warehouse. (b) Distribution center.

Figure 3: Photographs of a MW and of a DC.

2.3 Stakeholder's responsibilities

Several agents are involved in the food aid supply chain in Kenya. Here we explain who are the different stakeholders involved in the supply chain (World Food Programme, Kenya Red Cross Society, Community Relief Committee, and beneficiaries) and what their responsibilities are. We will focus on the supply chain activities at the regional level, i.e. on the logistics operations engaged once the food is stored at the regional MW. There also exist several ethical, social, and economic implications associated with food aid distribution which are neither analyzed nor discussed in this paper since they lie beyond the scope of this project.

2.3.1 The World Food Programme

The WFP is in full charge of the international transportation movements, the transport of food aid from Mombassa port to the MWs, and the transshipments between the MWs. Once the food supplies arrive at an MW, the cooperating lead partner agency manages the transportation operations from the MW to the DCs, as well as the food distribution to the population. Humanitarian organisations usually contract with trucking companies to move cargo across the network, and such secondary transport operations are generally very costly. While not taking the lead for contracting with transporters, the WFP fixes the transportation rates and reimburses the cooperating lead partner agency for transportation costs. The WFP is also engaged in offering guidance on logistics activities, such as storage and handling of commodities, as well as providing training on food aid distribution practices, reporting and warehousing when necessary.

2.3.2 The Kenya Red Cross Society

In the district of Garissa and its surroundings, the Kenya Red Cross Society (KRCS) acts as the cooperating lead partner for food assistance, which implies that it is responsible for the reception and storage of food at the MW. As mentioned above, the KRCS is also mandated to organize secondary transport operations and to distribute commodities provided by the WFP or the GoK to the beneficiaries. The KRCS must maintain records and facilitate monitoring for all commodities received at the MW and distributed at the DCs. The KRCS must also take reasonable measures to ensure that food assistance reaches the beneficiaries within a reasonable delay and in the condition in which it has been received. In order to be qualified for conducting food aid distribution, the KRCS staff receives a training on the community based food aid targeting and distribution system (World Food Programme and Government of Kenya, 2005). The KRCS acts as facilitator and monitor to ensure that the principles established for food aid distribution in Kenya are properly followed during the settlement process following the assessment, and during the monthly food distribution operations. The organization thus continuously assists the community during the different phases of the food aid distribution.

2.3.3 Community Relief Committee

The community members of each DC elect a Community Relief Committee (CRC) comprised of seven to 17 members. After being trained by the KRCS, the CRC becomes mainly in charge of the beneficiary registration and of the food aid distribution. The CRC is thus responsible for the targeting of the beneficiaries, record keeping as well as setting arrangements to call beneficiaries during the monthly distributions, and dealing with absences and complaints. The CRC must make arrangements to provide accessible temporary storage, to receive and handle the food, and to ensure security at the DC. The purpose of the relief committee is to give more responsibilities to the community and enhance information transparency. The CRC acts as a link between the KRCS and the community, including the beneficiaries. This system aims to provide a better understanding of the food distribution mechanisms for the people receiving assistance and to help the beneficiaries make decision for themselves rather than being controlled by agencies remote from their environment. An important component for ensuring better access to information is the participation of women within the relief committee since humanitarian organisations strive to encourage the presence of the women in assistance projects (see World Food Programme and Government of Kenya, 2005).

2.3.4 Beneficiaries

The beneficiaries are the people within the communities who receive food assistance through different aid programmes. Ideally, they should be targeted because they are the most vulnerable people in the community. They must travel and collect their food at their assigned DC on the day of the distribution. As far as possible, the organizations hand-out food aid to women. For the food distribution to be successful, the community should get involved in the process and should participate in the meetings organized by the KRCS and the CRC.

3 Problem formulation

We propose a mathematical programming based methodology to determine where to locate the DCs, how much food to deliver to them and which populations they should serve. The regional food aid distribution network can be formulated on a directed graph $G = (V, A)$, where V is a set of nodes and A is a set of arcs. The set V can be partitioned into $\Big\{\{v_0\}, V_1, V_2\Big\}$, where v_0 is an MW supplying a specific affected region, V_1 is a set of population agglomerations, and V_2 is a set of potential locations for DCs. The number of tonnes of food required by the population located at node $v_i \in V_1$ is equal to q_i. Let us also define W_i as the set of potential DCs located within a coverage radius $\bar{r}$ km of v_i, with $v_i \in V_1$ and $W_i \subseteq V_2$. The route taken by a transporter to go from v_0 to $v_j \in V_2$ is represented by an arc (v_0, v_j), and the path taken by the population v_i to walk up from $v_i \in V_1$ to $v_j \in V_2$, is represented by an arc (v_i, v_j).

3.1 Mathematical model based on social welfare costs

The model must take into account the anticipated food assistance needs and must optimize the social welfare of all the stakeholders involved in the food distribution. We define the following variables:

x_{ij} : the proportion of population at v_i needing a hand-out from a DC at v_j, with $i \in V_1$, and $v_j \in W_i$;

y_j : a binary variable equal to 1 if and only if DC v_j is in operation during the planning horizon, with $v_j \in V_2$.

The tactical food aid network design problem is formulated as follows:

Model 1

$$\text{minimize} \quad \sum_{i \in V_1} \sum_{j \in W_i} \alpha_{ij} \, x_{ij} + \sum_{i \in V_1} \sum_{j \in W_i} \beta_j \, q_i \, x_{ij} + \sum_{j \in V_2} \gamma_j \, y_j$$

subject to

$$\sum_{j \in W_i} x_{ij} = 1 \qquad i \in V_1 \tag{1}$$

$$x_{ij} \leq y_j \qquad i \in V_1, \; j \in W_i \tag{2}$$

$$x_{ij} \geq 0 \qquad i \in V_1, \; j \in W_i \tag{3}$$

$$y_j \in \{0, 1\} \qquad j \in V_2. \tag{4}$$

The objective is to minimize the weighted cost of all the stakeholders involved in the food distribution process at the regional level. The first term of the objective function is the total access cost for the beneficiaries to travel and collect their food at the DCs, the second term is the supply cost paid by the WFP for transporting the food from the MW to the DCs, and the last term accounts for the DC managing and hand-out costs which are under the KRCS responsibility. The coefficient α_{ij} represents the cost borne by the population at v_i needing a hand-out from DC at v_j; the coefficient β_j represents the cost per tonne borne by the WFP to transport food destined to the DC located at v_j; the coefficient γ_j represents the fixed cost of locating a DC at v_j. The determination of these coefficients is explicited in Section 3.2.2. Constraints (1) ensure that the demand of each population is satisfied, while constraints (2) stipulate that the population points can only be served from open DCs. Constraints (3) and (4) are standard non-negativity and integrality constraints. Note that if an optimal solution implies that a population agglomeration of beneficiaries is being served from multiple DCs, then the population must be equidistant to all DCs from which it is partially served. These beneficiaries can thus be arbitrarily assigned entirely to any of these DCs to ensure integrality.

3.2 The case of Garissa and its surrounding

We now explain how the graph G was constructed for the region of Garissa and its surroundings. We describe how the different parameters were determined through the use of geographic information system data. We also explain how the parameters in the objective function were determined, which entails the evaluation of all the corresponding stakeholder welfare costs.

3.2.1 Network

To discretize the population locations on the map, we used gridded population proxies based on satellite data (see Jordan et al., 2010, and Figure 4). The population nodes $v_i \in V_1$ correspond to the centroids of delimited landscape areas of one square kilometer. The potential geographical grid points for the DC potential locations, which constitute the set V_2, are those points close enough to a road (within a distance less than 200 meters) and which are also sufficiently populated to constitute a CRC (their population must be at least 20 people per square kilometer). Indeed, the DCs must be close to the road in order to be accessible by truck, and they must be sufficiently populated so that the security of the DC can be ensured by the surrounding community. For DC potential locations we have also considered points of interests, such as schools, community centers, and health facilities. This information can be retrieved from government data publicly available online and can be manipulated through a GIS (Government of Kenya, 2012b).

In our case, the demand of the system corresponds to the food aid needs. Each population point $v_i \in V_1$ has p_i inhabitants and has a food aid need q_i expressed in tonnes to be satisfied during a six-month planning horizon, which is the result of a specific need assessment. In order to compute the need of each population grid point in Garissa and its surroundings, we have considered that these needs were uniformly distributed among the population across the numbers detailed in the short rain assessment of 2012 for the smallest administrative level given.

We have also used population and Kenyan road network shapefile information to determine the following distances:

- for all $v_i \in V_1$, the distance d^*_{ij} (obtained by mean of PostGIS) from a grid population point v_i to its closest road;
- for all $v_i \in V_1$ and $v_j \in V_2$, the geographical distance d^g_{ij} (obtained by mean of PostGIS) from a population grid points v_i to a potential DC v_j;

- for all $v_j \in V_2$, the road distance d^r_{0j} (obtained by mean of Google API) from the Garissa MW to a potential DC v_j.

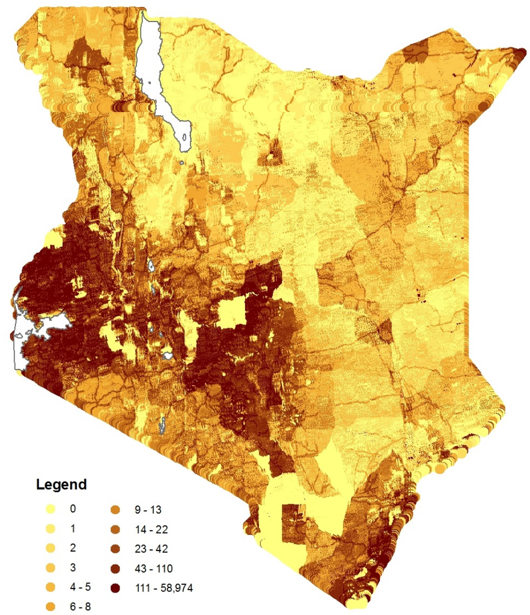


Figure 4: Population data for Kenya (Jordan et al., 2010).

3.2.2 Objective function

In the context of food aid distribution, several costs affect both the beneficiaries and the humanitarian organisations involved. These stakeholders, the beneficiaries, the KRCS and the WFP, have their own responsibilities in the supply chain, which translate into different objectives. In order to determine a global social welfare function, we have evaluated the values of all these responsibilities in terms of Kenya shillings (KSh). For the humanitarian organizations, these are management, transportation, and hand-out costs; for the beneficiaries, these are access costs.

Beneficiary access costs

The beneficiary access costs are opportunity costs measured by evaluating the productive activities sacrificed for collecting food assistance. The access cost is thus a value associated with the time taken by a beneficiary to walk from her location to her assigned DC. We have assumed that the beneficiaries use a least duration path to walk from v_i to v_j at an off-road pace of 4 km/h. The walking time from v_i to v_j is thus equal to the 0.25 h/km, times the geographical distance. To evaluate the value of walking time, we have used the minimum wage rate for unskilled labor

(Minister for Labor, 2012), which is less that two dollars per day. Moreover, the beneficiaries must pay for transportation to bring their food ration back home, which is usually done by paying an individual who operates a trailer attached to a donkey (Figure 5a). Using statistics presented in monitoring reports from WFP, we have determined that the cost of donkey transportation can be approximated by the linear function 20 KSh + 2.5 KSh/km × *distance*. The total access cost α_{ij} per kilometer of a beneficiary located at node v_i and collecting her food ration entitlement at DC v_j is obtained by adding up her opportunity costs and the donkey transportation cost.

WFP supply costs

Humanitarian organisations contract with trucking companies to transport food aid across the network (Figure 5b). For transportation operations between the MW to the DCs, the WFP sets a fixed price per tonne, which depends on the distance between the MW and the delivery location. The WFP offers a constant price per tonne c_0 for the DCs located within a short distance of the MW. For the locations that are further from the MW, the WFP sets constant prices c_1 and c_2 per km-tonne, depending on the distance to the MW. For confidentiality reasons, we are not allowed to reveal the current cost function, but only a generic one. The long-haul transportation costs in KSh per tonne to serve DC v_j from Garissa MW v_0 can be represented by the following step function:

$$\beta_j = \begin{cases} c_0 & \text{if } d^r_{0j} \in [0, \bar{d}_0] \\ c_1\, d^r_{0j} & \text{if } d^r_{0j} \in (\bar{d}_0, \bar{d}_1] \\ c_2\, d^r_{0j} & \text{if } d^r_{0j} > \bar{d}_1. \end{cases}$$

KRCS location and hand-out costs

The KRCS must mobilize staff to ensure that food distribution proceeds according to the established practices of the World Food Programme and Government of Kenya (2005). The CRC training and the beneficiary registration validation require about two days of work for the KRCS facilitators at each DC, which should be considered as a fixed cost for the six-month planning horizon. There are also monthly costs for the food distribution monitoring functions, such as advertising, dispatch and distribution supervision, which require two days of work per month per DC. The KRCS location and hand-out cost at each DC v_j are thus the cost of labor γ_j for ensuring that food distribution is made properly during the planning horizon (Figure 5c).

(a) Donkey transportation. (b) Ground transportation. (c) Monitoring activities.

Figure 5: Photographs of some stakeholder activities.

3.3 Descriptive statistics

We now provide an overview of the data through some relevant descriptive statistics. Table 1 summarizes the population grid point data for the district of Garissa and its surroundings. It shows that for the region of interest, the average population per square kilometer is 9.57 and the average distance from the population centroids to their closest routes is 11.03 km. Most of the population grid points are scarcely populated (the median is equal to 3), which explains why the average distance to the closest route is quite large. The food aid allocation statistics for the 12 covered divisions from Garissa MW are given in the last line of Table 1. This information was required to determine the structure of the food aid network in order to design the response system by means of mathematical programming.

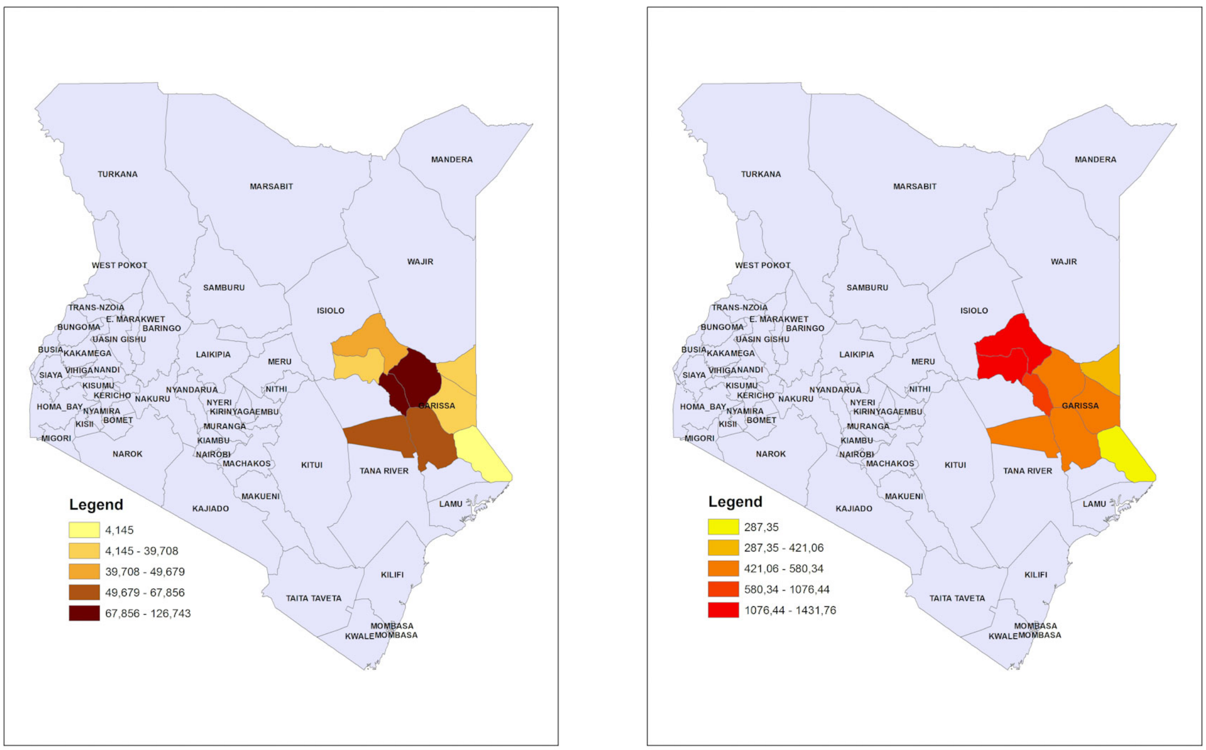
Table 1: Summary of Garissa and its surroundings

Description	n	Mean	Std. Dev.	Median	Min.	Max.
Population per km^2	47,241	9.57	159.32	3	0	13,793
Distance to closest route (km)	47,241	11.03	9.34	8.49	0	50.34
Population per division	12	50,120.2	34,977.8	37,049	3987	121,822
Six-month food need per division (tonnes)	12	521.3	154.73	555.65	287.35	768.24

Table 2 summarizes the relevant information on the food aid distribution network in Garissa. The set V_2 of potential DCs, which consists in the population grid points close to a route and densily populated, contains 1,460 elements. The average travel distance from Garissa MW to these potential DC is 106.32 km. There are 24,453 population grid points (V_1) with at least two inhabitants (Figure 6a). The average estimated food aid allocation per beneficiary in these population points is of 24.38 kg for the six-month period (Figure 6b). The average distance from the population points to their closest potential DC is 11.85 km and the median is 8.71 km, which indicates that there is at least one potential DC located close to most of the population points.

Table 2: Summary of food aid distribution network

Description	n	Mean	Std. Dev.	Median	Min.	Max.
Potential DC nodes (V_2)	1,460					
Road distance to MW (km)	1,460	106.32	71.41	107.16	0.05	268.93
Population nodes (V_1)	24,453					
Six-month food need per beneficiary (kg)	24,453	24.38	24.42	11.36	3.96	115.34
Euclidian distance to closest potential DC (km)	24,453	11.85	10.91	8.71	0	54.48



(a) Population map.

(b) Food allocation map (tonnes).

Figure 6: Population and food aid allocation maps for each division of Garissa District and its surroundings.

3.4 Covering models

The problem can also be modeled by means of a covering formulation. This allows us to determine how many DCs are required to cover all the beneficiaries within a coverage radius $\bar{r}$ or what portion of the population would be covered by fixing the number of DCs to a given value p. We thus define the following variables:

y_j : a binary variable equal to 1 if and only if DC v_j is in operation during the planning horizon, with $v_j \in V_2$;

z_i : a binary variable equal to 1 if and only if population v_j is covered by at least one DC during the planning horizon, with $v_i \in V_1$.

We also define the following parameters:

π_{ij} : a binary parameter equal to 1 if and only if the distance from the population v_i to DC v_j does not exceed $\bar{r}$, with $v_i \in V_1$ and $v_j \in V_2$.

A first problem is to maximize the need coverage with p DCs:

Model 2

$$\text{maximize} \quad \sum_{j \in V_2} p_i \, z_i$$

subject to

$$z_i \leq \sum_{j \in V_2} \pi_{ij} \, y_j \qquad \forall i \in V_1 \tag{5}$$

$$\sum_{j \in V_2} y_j = p \tag{6}$$

$$z_i \in \{0,1\} \qquad \forall i \in V_1 \tag{7}$$

$$y_j \in \{0,1\} \qquad \forall j \in V_2. \tag{8}$$

A second problem of interest is to minimize the number p of DCs to cover all the beneficiaries within a coverage radius $\bar{r}$:

Model 3

$$\text{minimize} \quad p$$

subject to

$$
\begin{aligned}
\sum_{j \in W_i} \pi_{ij}\, y_j &\geq 1 && \forall i \in V_1 && (9)\\
\sum_{j \in V_2} y_j &= p && && (10)\\
y_j &\in \{0,1\} && \forall j \in V_2. && (11)
\end{aligned}
$$

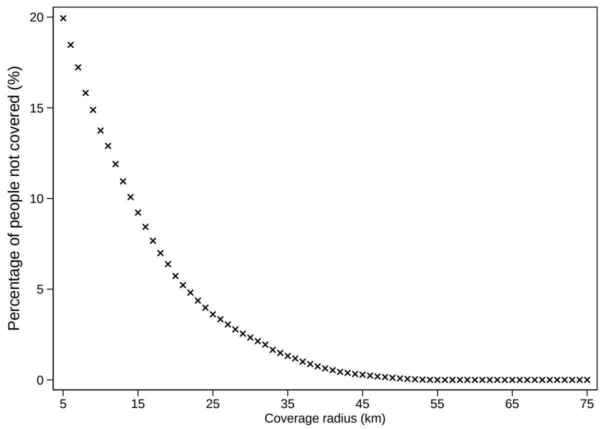
4 Computational results

In this section, we describe the computational results obtained by solving different optimization problems for the case of Garissa and its surroundings. We first provide the results of some sensitivity analyses before illustrating optimal response systems.

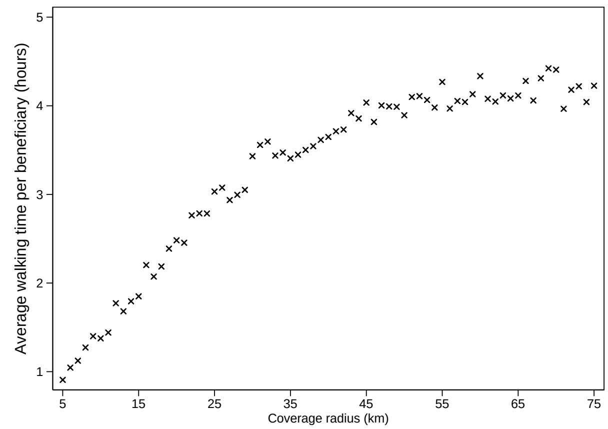
4.1 Sensitivity analyses

The objective of this section is to better understand the impact of the response system structure on the stakeholder welfare. To this end, we have conducted several sensitivity analyses by varying some parameters and solving the problems formulated in Section 3. These were solved by means of CPLEX 12.8.0 and by setting the optimality gap to 2%. We consider that this is a reasonable gap given the precision of the data.

We have first assessed the impact of the coverage radius on the percentage of people covered by the response system. In Model 1, we assume that a population without any DC within a distance $\bar{r}$ is not taken into account in the optimization problem, which implies that this population is not covered by the response system. We have also assessed the results on the average walking time per beneficiary to ensure that the solution did not result in having beneficiaries walking too far when the coverage radius was fixed to a large value. Figure 7 shows the results obtained with Model 1 for different values of $\bar{r}$. We note from Figure 7a that in order to cover all the population, the coverage radius must be set to at least 55 km. Nevertheless, according to the results shown in Figure 7b, the average walking time per beneficiary remains acceptable even when the coverage radius becomes larger, and the increase in average walking time tends to stabilize when it becomes larger than 35 km. This means that even if the coverage radius is large, the optimal solution mostly assigns the populations to their closest DC.



(a) Percentage of the population not covered as a function of the coverage radius.



(b) Average walking time per beneficiary as a function of the coverage radius.

Figure 7: Percentage of the population not covered and average walking time per beneficiary as a function of the coverage radius.

Figure 8 shows the values of the objective function as well as the values of its different terms obtained by solving Model 1 and varying the coverage radius from 5 km to 75 km. For each $\bar{r} \in \{5, 6, ..., 75\}$, the black dots correspond to the value of the objective function (total cost), the grey diamonds correspond to the WFP supply cost, the grey "x" correspond to the beneficiary opportunity cost, and the grey squares correspond to the KRCS hand-out cost. We have observed that the most important part of the total cost is borne by the WFP for transporting the food from the MW to the DCs. This finding is consistent with the affirmation of Trunick (2005) who observed that approximately 80% of disaster relief efforts relate to logistics activities. The beneficiary opportunity costs are also important compared with the KRCS hand-out costs, which constitute the smallest component of the total cost. These results show the importance of transportation costs in the response system, even when the beneficiary opportunity cost is taken into account. This implies that an organization like the WFP has an interest in being actively involved in the DC selection process. We also note that the reduction in supply cost becomes less significant when the coverage radius is larger than 45 km. Considering that the minimum radius needed to cover all the population is 55 km, there is no benefit in solving the problem with a larger covering radius.

In Model 1, the objective function is a weighted sum of the three stakeholder objectives. In order to determine the behaviour of each term, we have solved the problem by minimizing each objective separately, thus yielding three cases: 1) $\alpha_{ij} = 0$ and $\gamma_j = 0$ (Figures 9a, 9b, 9c, and 9d); 2) $\alpha_{ij} = 0$ and $\beta_j = 0$ (Figures 10a, 10b, 10c, and 10d); 3) $\beta_{ij} = 0$ and $\gamma_j = 0$ (Figures 11a, 11b, 11c, and 11d). Case 2 is equivalent to solving Model 3, i.e. minimizing the number of open DCs

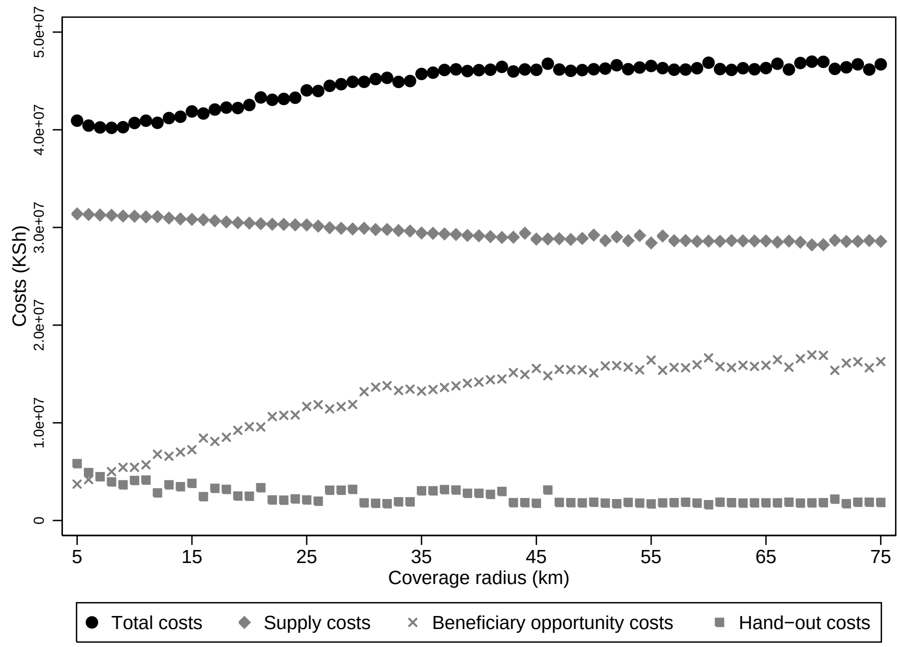
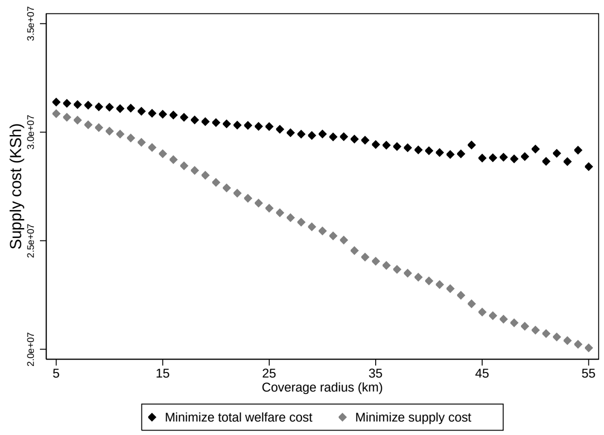


Figure 8: Stakeholder costs as a function of the coverage radius.

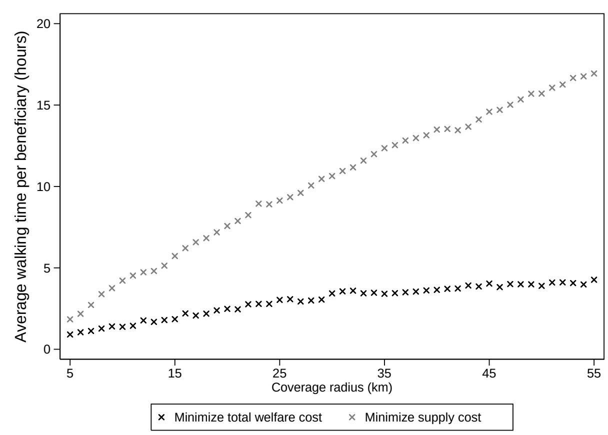
to cover the population with a coverage radius $\bar{r}$. We note that CPLEX could not solve case 2 for $\bar{r} = \{33, 34, 40, ..., 55\}$ because of excessive branching.

Comparing Figures 11c, 9c and 10c, we note that optimizing the total welfare cost, as opposed to a single-objective function, yields larger percentages of increase for the KRCS hand-out cost, the beneficiary opportunity cost and the WFP supply cost, respectively. However, cases 1 and case 2 yield solutions that make the beneficiaries walk significantly more to go and collect their food, as shown in Figures 9d and 10d. The average walking time per beneficiary becomes unacceptable when the covering radius exceeds 15 km, as shown in Figures 9b and 10b. Note that the percentage increase in WFP supply cost remains less than 10% for covering radii smaller than 20 km. Figure 11 illustrates the results obtained when only the beneficiary opportunity cost is considered in the network design.

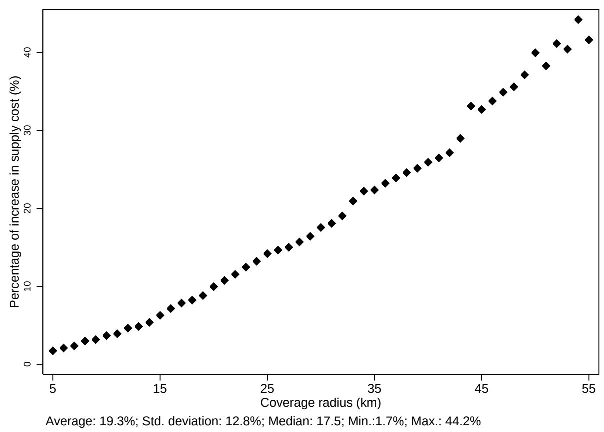
These results show that including the beneficiary opportunity costs into the network optimization does not have a substantial impact on the financial costs incurred by the operational agencies, but increases the accessibility of the beneficiaries. Currently, the opportunity cost of beneficiaries is not sufficiently considered in the academic literature and in the WFP emergency costing models. This seems to conflict with the humanitarian principles which tend to emphasize the welfare of the beneficiaries rather than cost reductions.



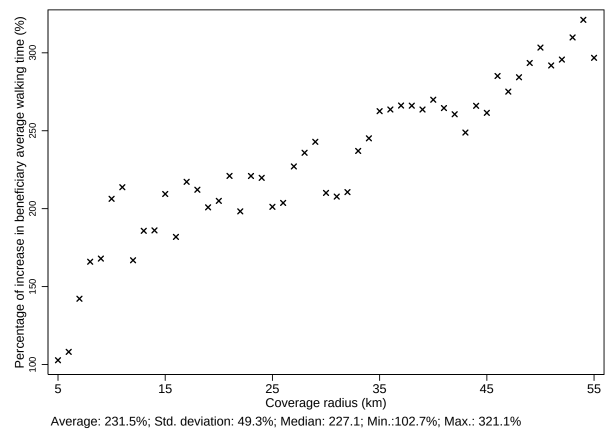
(a) WFP supply costs as a function of the coverage radius.



(b) Average walking time per beneficiary as a function of the coverage radius.



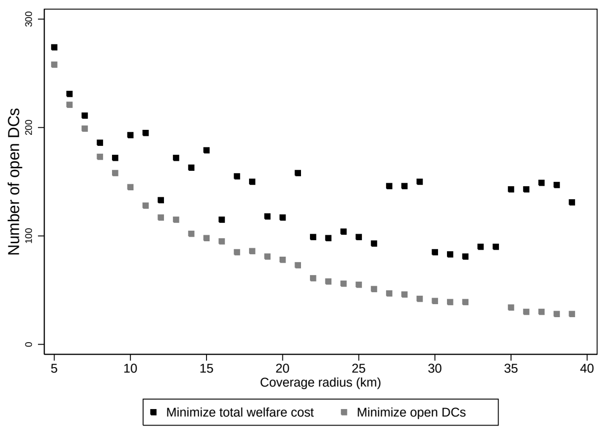
(c) Percentage increase in the WFP supply cost when minimizing total welfare cost (Model 1) as opposed to a single-objective function (case 1), as a function of the coverage radius.



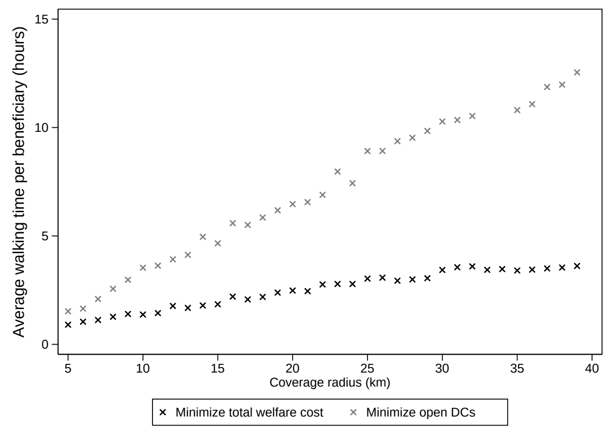
(d) Percentage increase in the average beneficiary walking time when minimizing a single-objective function (case 1) as opposed to the total welfare cost (Model 1), as a function of the coverage radius.

Figure 9: Comparing the results of multi-objective and single objective optimizations (case 1).

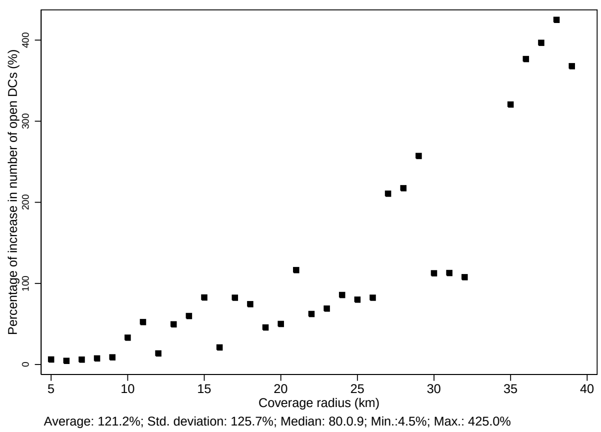
Moreover, to ensure that the beneficiaries are not underestimated in the parameterization of the mathematical model, we have solved Model 1 with various values of the hourly wage rate. In the initial parameterization, we have estimated the beneficiaries' opportunity costs by valuing their time proportionally to the minimum wage rate for unskilled labor ($wage = 22$ KSh/h). We have thus solved Model 1 for each $wage \in \{20, 21, ..., 40\}$ to evaluate the impact of the value given to the beneficiaries' time on the response system. The results yielded by this experiment are illustrated in Figure 12. We note from Figure 12a that the total cost of the response systems is mostly due to the increase in beneficiary opportunity costs, which is mostly explained by the increase of α_{ij}



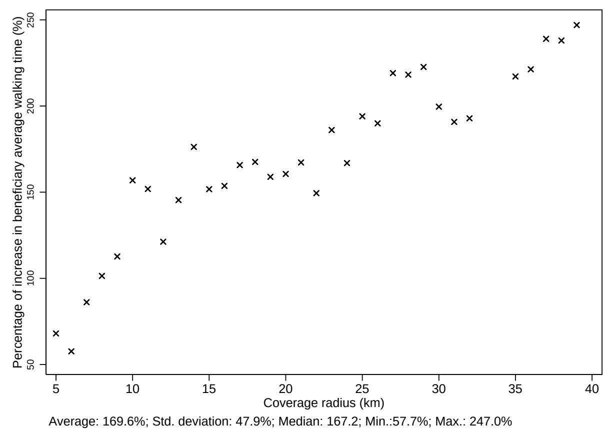
(a) Number of open DCs as a function of the coverage radius.



(b) Average walking time per beneficiary as a function of the coverage radius.



(c) Percentage increase in the KRCS hand-out cost when minimizing total welfare cost (Model 1) as opposed to a single-objective function (case 2), as a function of the coverage radius.

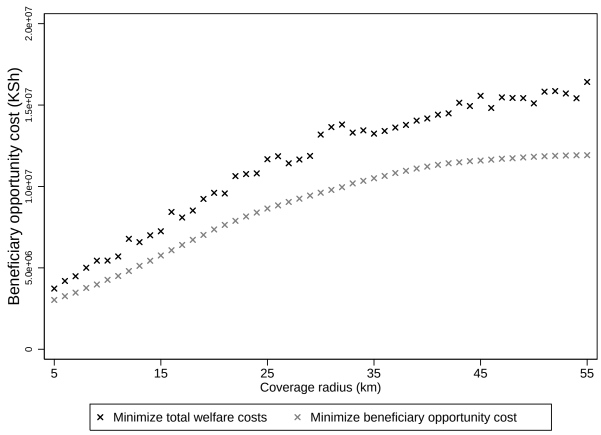


(d) Percentage increase in the average beneficiary walking time when minimizing a single-objective function (case 2) as opposed to the total welfare cost (Model 1), as a function of the coverage radius.

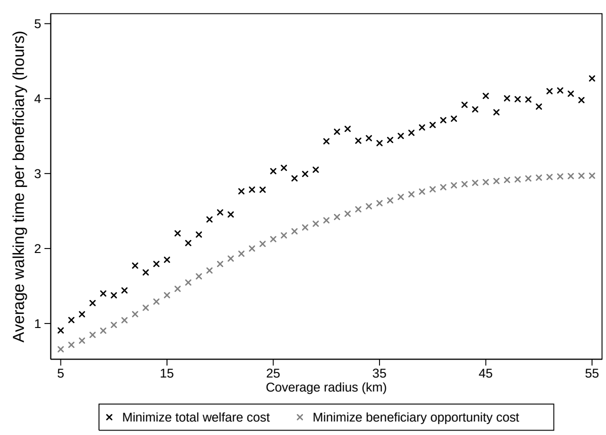
Figure 10: Comparing the results of multi-objective and single objective optimizations (case 2).

since the supply and hand-out costs do not increase significantly when *wage* increases. Figure 12b also shows that the average walking time by the beneficiaries does not drop considerably with *wage*. This validates adoption of the minimum wage rate for unskilled labor as the value for the beneficiary opportunity cost.

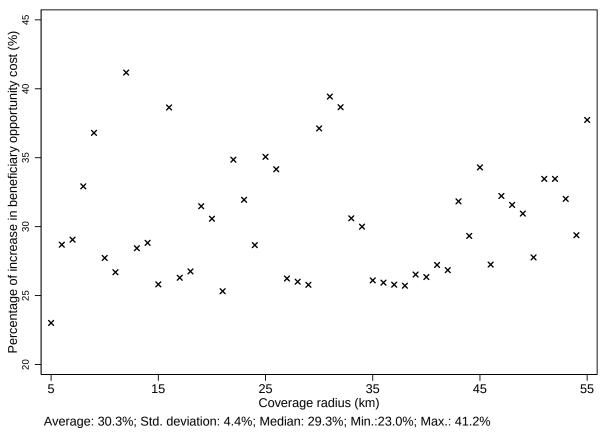
There are currently 156 DCs in Garissa District and its surroundings. In order to compute the maximum number of people that can be covered with 156 DCs, we have solved Model 2 with $p = 156$ and $\bar{r} \in \{5, 6, ..., 55\}$. Figure 13a shows the percentage of the uncovered population obtained by solving Model 2 with $p = 156$ and Figure 13b shows the difference in the number of open DCs



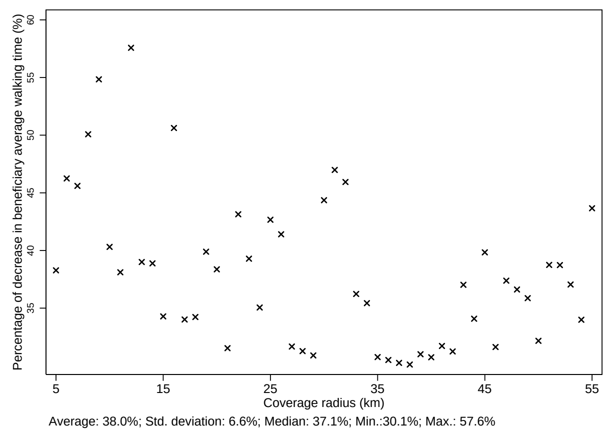
(a) Beneficiary opportunity cost as a function of the coverage radius.



(b) Average walking time per beneficiary as a function of the coverage radius.



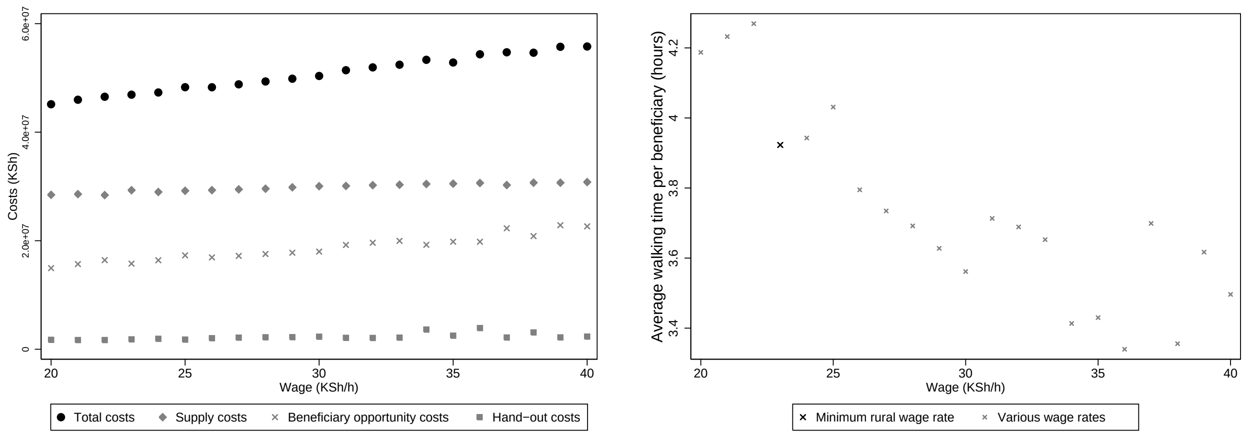
(c) Percentage increase in beneficiary opportunity costs when minimizing total welfare cost (Model 1) as opposed to a single-objective function (case 3), as a function of the coverage radius.



(d) Percentage decrease in the average beneficiary walking time when minimizing a single-objective function (case 3) as opposed to the total welfare cost (Model 1), as a function of the coverage radius.

Figure 11: Comparing the results of multi-objective and single objective optimizations (case 3).

obtained by solving Model 1 with 156 open DCs, as in the current situation. Note that, as shown in Figure 10a, the minimum number of open DCs obtained with Model 3 is 158 for $\bar{r} = 9$ and 145 for $\bar{r} = 10$, which implies that 156 open DCs do not enable to cover all the population living within a radius of less than 10 km from a DC. Figure 13b shows that solving Model 1 is more advantageous for the beneficiaries when a smaller coverage radius is used since Model 1 yields more than 156 open DCs. We therefore believe that the current condition could be improved by considering all the welfare cost in the network design, as we did in Model 1, especially since smaller coverage radii are

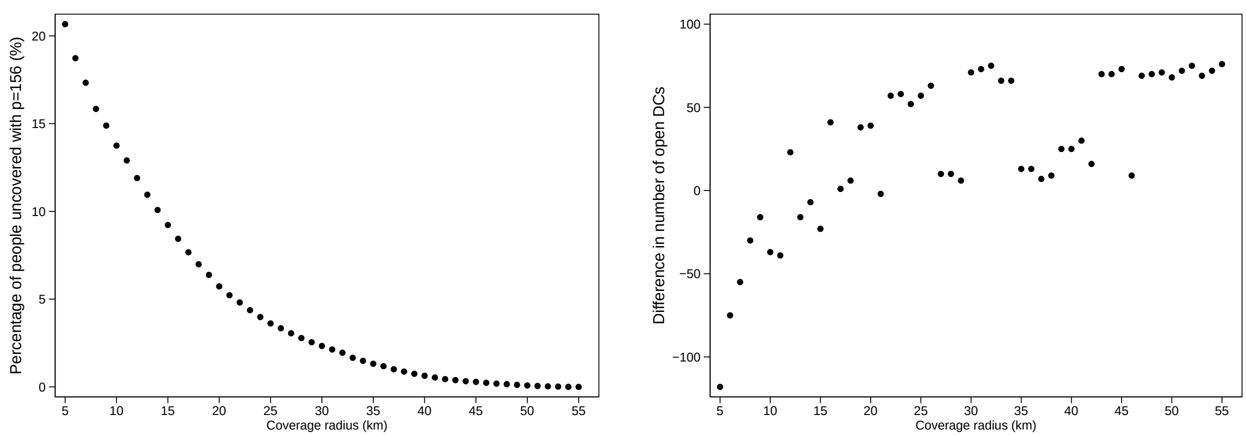


(a) All stakeholders' costs as a function of the coverage radius.

(b) Average walking time per beneficiary as a function of the coverage radius.

Figure 12: Impact of beneficiary time value on the response system ($\bar{r} = 55$ km).

preferable for the beneficiaries and the DC costs are the least important part of the total welfare cost.



(a) Percentage of uncovered population as a function of the coverage radius.

(b) Difference in number of open DCs obtained by solving Model 1 with 156 as a function of the coverage radius.

Figure 13: Results obtained by solving Model 2 with $p = 156$.

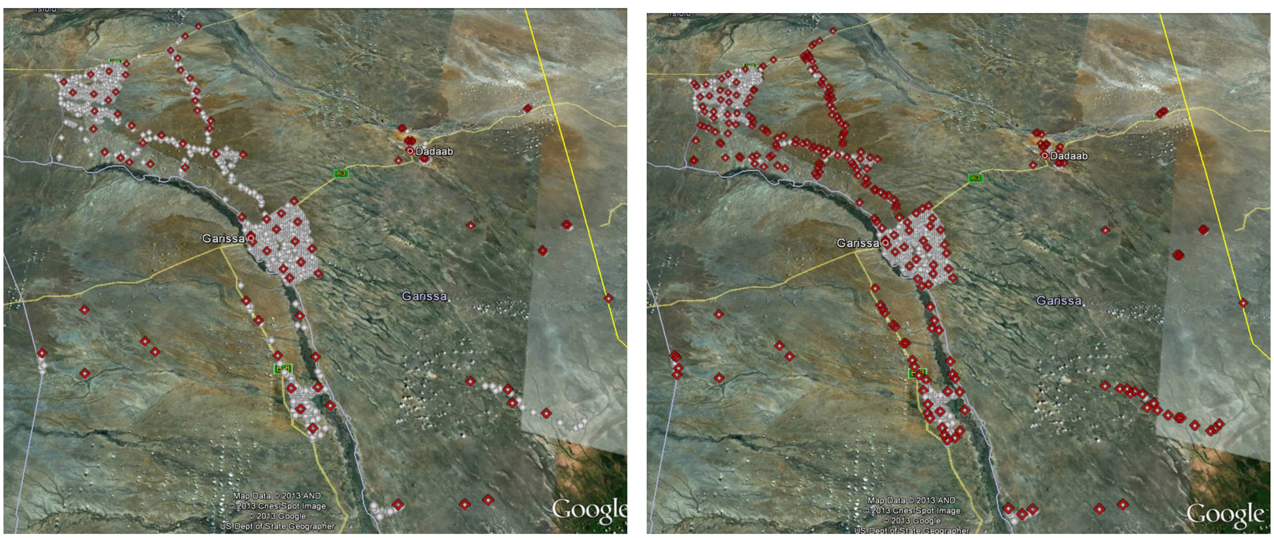
4.2 Solution illustrations

We now present some optimal solutions obtained by solving Model 1 with CPLEX, using a 0.1% gap. Table 3 provides the values of the attributes of three different solutions obtained with $\bar{r} = 5, 10$

and 55 km, and Figure 14 illustrates the two extreme case solutions on a map. We do not claim that these solutions are those that should be implemented since it is up to the decision maker to assess the impact of various parameters on the design of the food distribution network while taking into account the interest of the various stakeholders. We believe, however, that a multicriteria optimization tool such as the one we have described helps generate good quality solutions from which the decision maker can choose. This represents an improvement over the current practice where most decisions are made without a strong analytical support.

Table 3: Characteristics of three representative optimal solutions

Solution	Costs				DCs	Beneficiary statistics		CPLEX
$\bar{r}$	Total	Beneficiary	Supply	Hand-out	#	Not covered (%)	Average walk time (hr)	CPU time (sec)
55	46,078,345.46	15,457,251.17	28,688,800.29	1,932,294	91	0	3.99	2,0345.71
25	43,438,031.79	11,029,998.54	30,135,995.25	2,272,038	107	3.62	2.84	2,297.95
5	40,671,491.26	3,688,771.978	31,376,943.28	5,605,776	264	19.94	0.89	10,331.91



(a) Solution with $\bar{r} = 55$ km.

(b) Solution with $\bar{r} = 5$ km.

Figure 14: Optimal solutions with $\bar{r} = 55$ km and $\bar{r} = 5$ km.

5 Conclusions

We have considered a tactical location problem arising in food aid distribution in Kenya. The problem was modeled and solved by means of a mathematical programming methodology. Several sensitivity analyses were conducted to validate the results provided by the model and to study the effects of various parameters on the solutions. We have shown how mathematical programming can be used to design last-mile food aid distribution network using real data for the case of Garissa District in Kenya. Our results show that the most important part of the total cost is related to transporting the food from the district warehouse to the distribution centers. We have also shown the importance of valuing the beneficiary time, which is by itself a new contribution.

This paper bridges part of the gap between theory and practice in the development of humanitarian logistics support decision tools. Solving this problem contributes to the long-term food security of the country. A decision tool such as the one we have developed can help decision makers handle simultaneously the objective of several decision makers and select a suitable solution from those that are generated. This tool should be welcome in the context of food aid distribution in developing countries such as Kenya.

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