# AN OPTIMIZATION MODEL FOR THE WORLD FOOD PROGRAMME'S "PROTRACTED RELIEF AND RECOVERY OPERATIONS" IN CHAD

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by

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

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Table of Contents

# List of Figures

# List of Tables

# Abstract

This thesis presents an optimization model for the World Food Programme's policy in Chad–Protracted Relief and Recovery Operations (PRRO). Chad is a landlocked country in Central Africa and around 87 percent of population lives below the poverty line. The World Food Programme(WFP) runs several operations in Chad to help refugees, displaced people, and other poor communities. The goal of PRRO policy is to build resilience, protect livelihoods and reduce malnutrition of refugee, returnees and other vulnerable people. The PRRO policy aims to enhance the capacity of the vulnerable population to respond to shocks more efficiently by supporting the development and integration of local markets – using a food voucher program. This thesis analyzes the WFP's PRRO policy and builds a mathematical model using mixed integer nonlinear programming (MINLP) techniques. It is a location-allocation (LA) problem. The model determines the optimal number of facilities to be placed such that the distance between beneficiaries and warehouses is minimized. Moreover, this model also determines what portion of the PRRO budget should be allocated for food supplies, food voucher, warehouse operational cost, and transportation cost, whilst minimizing the total cost.

# Chapter 1: Introduction

This chapter provides information concerning food insecurity around the world. Moreover, it describes the role of the World Food Programme in fighting food insecurity. Furthermore, this chapter provides background information of the Central African country Chad and reasons why Chad is facing severe food insecurity. Later on, this chapter introduces the Protracted Relief and Recovery Operations (PRRO) policy.

## Food Insecurity Around the World

The significant increase in global population, combined with the number of violent conflicts and global warming pose a serious threat to the state of food security around the globe. According to the World Food Programme, 1 out of every 9 people suffer from chronic hunger worldwide. Moreover, the Food and Agriculture Organization of the United Nations' (FAO) data confirms that the estimated number of undernourished people on the planet has increased from 777 million in 2015 to 815 million in 2016. The FAO states that currently, hunger affects approximately 11 percent of the global population. Specially, the food security situation visibly has been deteriorating in parts of sub-Saharan Africa, South Eastern and Western Asia due to slow economy, droughts, floods and other climate-related shocks (FAO, 2017). These parts of the world have urgent requirement for humanitarian assistance and with the limited budget available, humanitarian agencies are constantly looking for effective and efficient solutions. The World Food Programme (WFP) is one of the leading humanitarian organization committed to alleviating world hunger. The WFP works in 80 countries that are in need of humanitarian aid. According to the WFP, Chad is a sub-Saharan African country that has one of the highest levels of hunger in the world, consequently, the WFP runs several humanitarian operations in Chad.

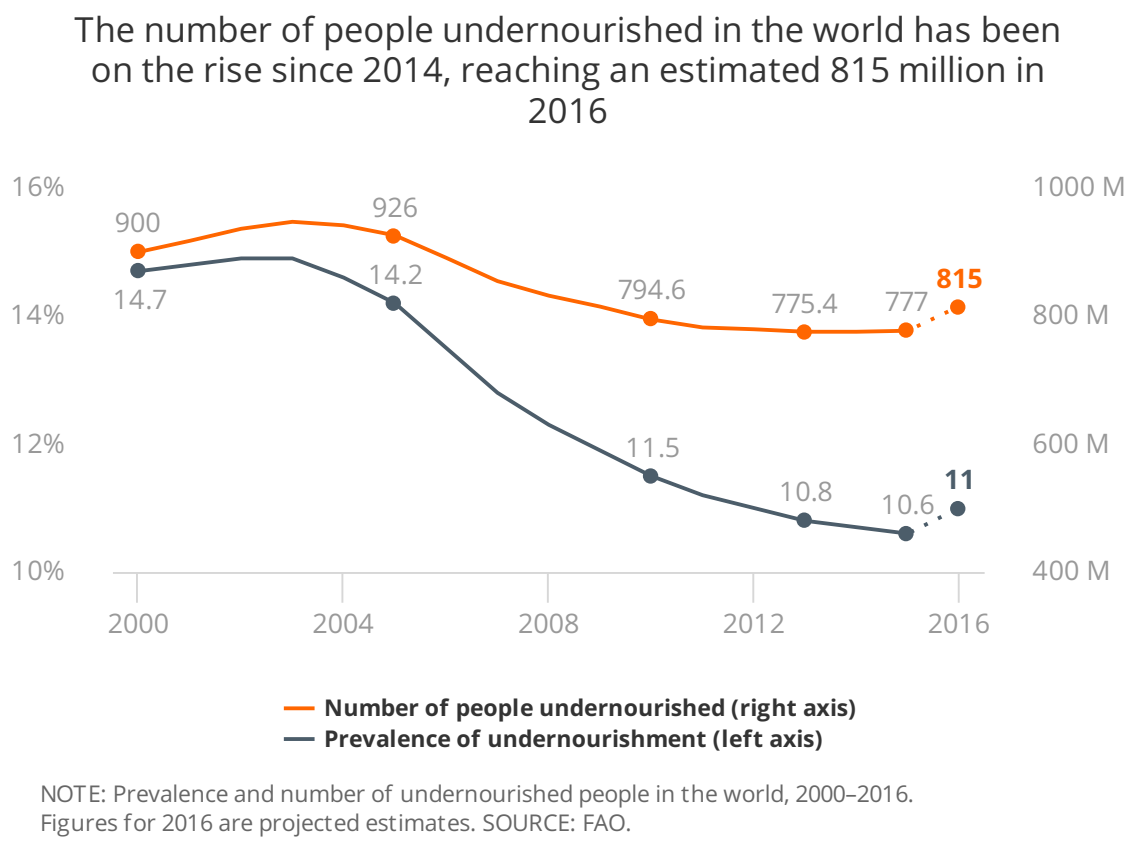



Figure 1. 1: World Hunger on Rise

Chad

Chad is a landlocked country in Central Africa with a population of 14 million. According to data provided by the WFP, 87 percent of the population live below the poverty line and it has been worsened by several conflicts and climate-related disaster over the past half century. According to 2015 Human Development Index list, Chad is ranked 185 out of 188 countries. Chad's GDP per capita is USD 1024 (World Bank, 2012). According to FAO, over 4 million Chadians suffer from food insecurity, the main factors that contribute to deteriorating food security in Chad are lean agricultural seasons, poor trade terms for pastoralists, conflicts and instability in neighboring countries, low economic development, and related population movements (FAO, 2017).

Furthermore, 80 percent of Chadians depend on farming and livestock for their livelihoods. An unpredictable rainy season or insufficient rain not only has a negative impact on agriculture but also on livestock. There is an increase in deteriorating body condition's of livestock and mortality rate owing to poor pasture and water. Herders are forced to travel long distances in search of food and water for their livestock, which in return depreciates the body conditions of livestock and their productivity level, thus decreasing their market price. These harsh conditions force Chadians to adopt adverse coping practices such as selling their lands or livestock, which usually do not compensate for the deficit in food consumption (WFP PRRO,4-5). Moreover, according to the WFP PRRO CHAD 200713 report, Chad hosts approximately 400,000 long-term refugees from its neighboring countries, which adds pressure to Chad's limited resources. The government has limited capacity to respond to food insecurity in Chad, hence organization like the United Nations High Commissioner for Refugees (UNHCR) and WFP play a crucial role in Chad to provide needed humanitarian aid.


Figure 1. 2: Map of Chad

Source: United Nations (2014)

World Food Programme

The World Food Programme is a branch of the United Nations that is committed to attain "Zero Hunger" around the world. The WFP works in 80 countries to provide assistance to around 80 million people every year (WFP, 2018). According to its own literature, "WFP focuses on emergency assistance, relief and rehabilitation, development aid and special operations" (WFP, 2018). The WFP provides immediate and long-term aid across the globe. Since world hunger is on the rise, in addition to providing immediate relief to beneficiaries, WFP is adopting several new strategies to seek long term solutions, such as shifting towards enhancing resilience so that the community can respond quickly to shocks. WFP has been in Chad since 1968 (WFP, "Chad Country Briefing 2017")

One of the WFP's operations– Protracted Relief and Recovery Operations (PRRO)- focuses on strengthening local communities and encouraging beneficiaries not to adopt negative coping strategies such as selling their livestock or land, in case of food deficit. The PRRO operation was designed by the WFP and consultation with the government, United Nations and NGO partners and other stakeholders (WFP, PRRO200713, 7). Unlike other WFP operations in Chad, the PRRO, favors shifting towards conditional asset-creation activities over free distributions, and market-based mechanism to enhance resilience (WFP, PRRO200713, 6). Furthermore, the PRRO policy does not differentiate between the beneficiaries based on their status, i.e. refugees or returnees; instead, humanitarian aid is provided based on the needs of beneficiaries.

Providing humanitarian aid in the right amount at the right time is a crucial aspect of WFP work, hence humanitarian logistics plays an important role for the WFP. This thesis analyzes WFP's PRRO policy and builds an optimization model whilst considering

three scenarios. Currently, the WFP does not use any mathematical model for the PRRO policy, instead they use historical data to perform the allocation process. However, the optimization model presented in the thesis investigates, how much money should be allocated for each activity of PRRO to maximize the number of beneficiaries who benefit from this operation policy. Moreover, harsh weather conditions make this situation even more challenging –since there are always high fluctuations in the number of beneficiaries, who require aid in Chad. Conflicts in neighboring countries and unpredictable rain patterns contribute to uncertainty in demand for the humanitarian aid. Three scenarios generated for this model are inspired by these situations.

# Chapter 2: Literature Review

This chapter reviews a theoretical framework related to the humanitarian logistics field. This chapter defines some basic terminology that are required to understand the work presented in the remainder of this thesis. This chapter discusses the definition of disaster, humanitarian logistics, three main stages of a humanitarian supply chain and existence of uncertainty in humanitarian logistics problems. Furthermore, this chapter sheds light on some studies that presented work on multiple-commodity network flow model, pre-positioning of aid and vehicle routing problem in case of emergency.

A disaster is a catastrophic event that can be natural or manmade and requires societal aid to alleviate suffering of the victims (Ince, 2014). Figure 2.1, below depicts different categories of disasters: Natural or Man-made, Sudden-onset or Slow-onset.

| | Natural | Man-made |
|---|---|---|
| Sudden-onset | Earthquake<br>Hurricane<br>Tornadoes | Terrorist attack<br>Coup d'Etat<br>Chemical leak |
| Slow-onset | Famine<br>Drought<br>Poverty | Political crisis<br>Refugee crisis |

**Source**: Van Wassenhove (2006), p.476

Figure 2. 1: Categories of disaster

This work focuses on slow-onset natural as well as man-made disaster scenarios. Chad is a landlocked central African country, where food insecurity is a serious issue. The WFP and other humanitarian organizations are actively working in Chad to provide assistance to the millions of Chadians who are victims of food insecurity and are in need of urgent care and attention. According to WFP, Food insecurity affects around 4 million Chadians. Food insecurity in Chad is both natural as well as man-made, as it is caused by adverse

weather conditions and by political crisis in its neighboring countries. This serious disaster in Chad requires the WFP to utilize all their resources effectively and hence, invites the attention of the humanitarian logistics field.

Humanitarian logistics

Thomas and Kopczak (2005) defines humanitarian logistics as:

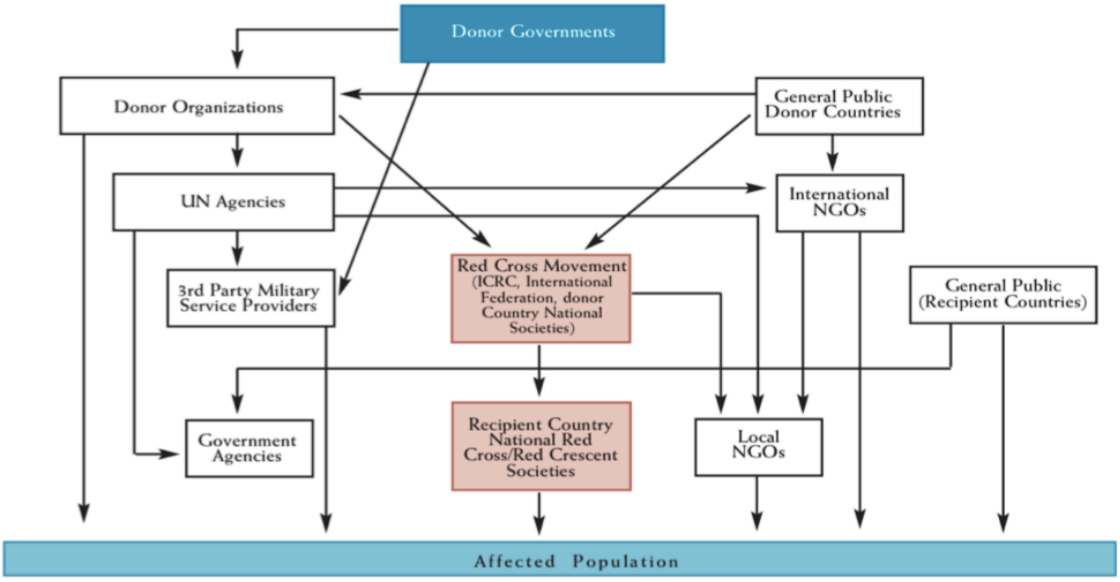
*'... the process of planning, implementing and controlling the efficient, cost- effective flow and storage of goods and materials, as well as related information, from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people. The function encompasses a range of activities, including preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance.'*

Humanitarian logistics is an important aspect of any humanitarian organization, since it focuses on providing efficient ways to manage the flow of information or goods to alleviate suffering among the targeted populations. Humanitarian logistics enables organizations to make the best use of available resources by providing the right amount of services, at the right time, to the vulnerable populations. (Van Wassenhove, 2006). Humanitarian logistics is a branch of logistics that "encompasses a range of activities, including preparedness, planning, procurement, transport, warehousing, tracking and tracing, and customs clearance, local transportation, warehousing and last mile delivery" (Thomas 2004). This thesis mainly focuses on the procurement, transportation, and warehousing stage of the PRRO policy. Later in this chapter, we will discuss each stage of a humanitarian supply chain network in detail. However, before that it is important to understand the complexity of a humanitarian supply chain and how it differs from a commercial supply chain.

Commercial & Humanitarian supply chains

Humanitarian logistics and commercial supply chain are very different on a strategic level. It is mainly because, for a commercial supply chain, the objective is to maximize profit or revenue. However, it is difficult to measure the performance of a humanitarian supply chain in terms of price, since disaster-related demand and supply are not regulated through price (Van Wassenhove, 2006). A humanitarian chain aims to provide as much of the needed services as possible to the beneficiaries. An organization in the humanitarian field focuses on "quick lifesaving" instead of maximizing their revenues (Berger & Garyfalakis, 2013). Not only it is difficult to measure the performance of a humanitarian supply chain, it is very difficult to manage one, due to intervention of several groups working together, to accomplish the same goal.

Figure 2.2 depicts several stages that information or services needs to flow through before reaching the targeted beneficiaries. Observe that a humanitarian supply chain is a series of complicated events. Many, but not all, of the coordinating organizations work under the United Nations (UN). The Protracted Relief and Recovery Operations (PRRO) is an operation run by the World Food Programme (WFP) in Chad, that aims to "build resilience, protect livelihood and reduce malnutrition of refugees, returnees and other vulnerable people" in Chad (WFP Chad). The PRRO is funded by the WFP and in case of emergency (fluctuation in demand), either the PRRO policy proposes a revised budget to the WFP and waits for the budget approval or it imports urgent humanitarian aid from foreign lands. Moreover, the PRRO receives donations from several organizations and countries. Hence, the funding of this operation is very crucial and impacts the flows through the various stages of this humanitarian supply chain.




**Source**: Thomas and Kopzack (2005), p.4

Figure 2. 2: Humanitarian Supply Chain

The supply chain in humanitarian logistics consists of three main steps: Procurement, pre-positioning and warehousing and transportation (Tomasini & Van Wassenhove, 2009). The following Figure 2.3, illustrates these three main steps. The figure has been adopted from Nikbaksh & Farahani, 2011.

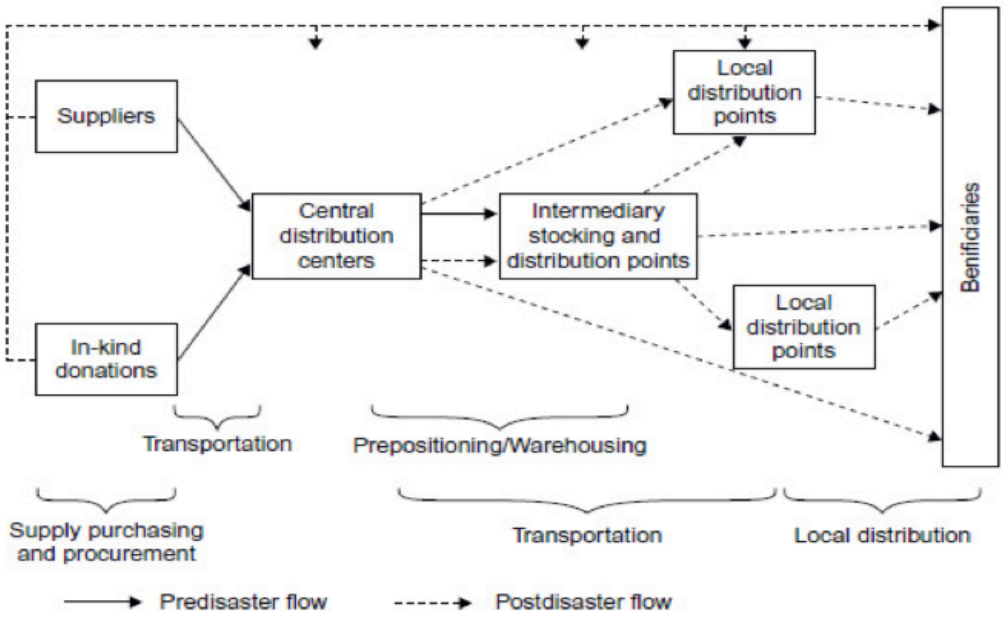



Figure 2. 3: Humanitarian Logistics Supply Chain Steps

Procurement:

The first stage in any humanitarian logistics supply chain is procurement. This step involves collection of humanitarian aid, which is usually generated from donations (Akhtar et al.,2012). The challenges at this stage, generally involve reducing the purchasing cost of supplies (Balcik et al., 2012). Generally, the procurement step attempts to provide "..ready-to-dispatch inventory with access to disaster prone regions" (Balcik & Beamon, 2008). Therefore, it is vital to assign the available budget for the operation with great care, in order to minimize suffering of the beneficiaries. Procurement is one of the most significant parts of humanitarian logistics since, it generally accounts for 65% of total expenditure (Falasca & Zobel, 2011). Figure 2.4, below is sourced from Falasca & Zobel, 2011.

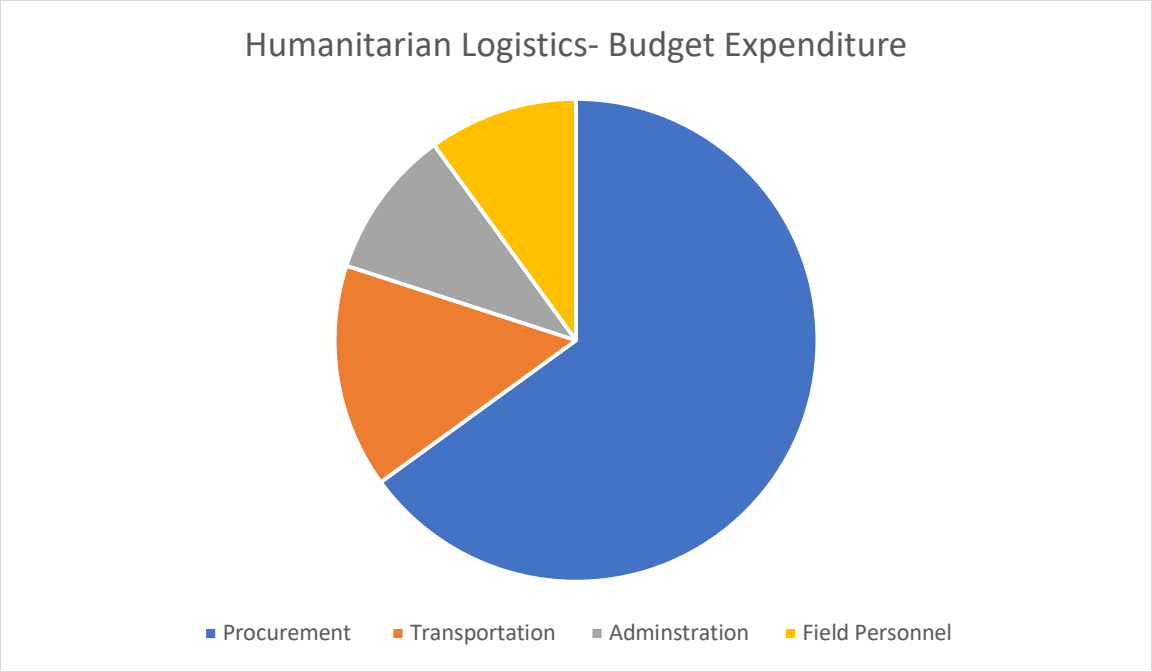



Figure 2. 4: Humanitarian Logistics- Budget Expenditure

Furthermore, humanitarian organizations such as WFP and others, function on donations received from countries or individuals, therefore, the process of operation has to be transparent and result-oriented (Van Wassenhove, 2006). Accordingly, these organizations have additional pressure to allocate their resources efficiently. Despite the significance of the procurement stage in humanitarian logistics, "existing literature about humanitarian relief logistics focuses mainly on problems related to facility location, inventory management or transportation" (Faslasca, 2011). This thesis focuses on the procurement stage. It builds a mathematical model that, using operations research techniques, aims to generate an efficient way of allocating the available budget for the PRRO policy.

Prepositioning/Warehousing

The second stage of a humanitarian supply chain is prepositioning/warehousing. There are several literatures available in this field. Akkihal (2006) investigates the impact of an optimally located facility on initial deployment in humanitarian operations. This author, provides a framework to readers to measure the stock level of inventory under uncertainty. A more recent work in this field is by Tofighi, Torabi & Mansouri (2016). These authors develop a two-echelon humanitarian logistics network. This study involves multiple central warehouse and local distribution centers and develops a two-stage model using stochastic programming. Uncertainty in this model is introduced through demand as well as the availability of transportation network. Beamon and Kotleba (2006) identify an optimal solution for a pre-positioned warehouse comparing a model with a heuristic and naïve inventory model. Bozorgi-Amiri et al. (2013) propose a multi-objective robust stochastic programming model to minimize total cost of preparation and reaction measures. This model also maximizes satisfaction by minimizing the sum of shortages in delivering of humanitarian aid in affected areas. This model provides an optimal number of order and re-order points for warehouse location in preparation of a humanitarian disaster. Several notable papers have been written on prepositioning of humanitarian aid to minimize the response time. However, sometimes these warehouses are affected by the disaster too. Lang and McGarvey (2016) propose a new optimization formulation for the prepositioning of humanitarian aid whilst considering reliability of network. This model ensures that demand can be satisfied even in the event of loss of access to a subset of storage sites.

Transportation

The next stage of a humanitarian logistics chain is transporting supplies from one point to another. Transportation is one of the most complex aspect of a humanitarian supply chain, since in case of an emergency, when infrastructure is deteriorated, sending aid to the affected beneficiaries becomes challenging. Uneddu & Goncalves (2014) provide a model to reduce the transportation cost of supplies. The mathematical model aims to optimize the distribution of mosquito nets in Ivory Coast, whilst considering the complex nature of transportation problems. In disaster scenarios, it is crucial to examine the conditions of roads beforehand. As noted in Long and Wood (1995), "Accurate assessment of the road infrastructure is critical...a road may be a five-foot wide strip of mud only inches above the water line that can accommodate only scooters and livestock, or it can be an eight-lane highway pocketed with bomb craters". Goncalves, Leiras & Chawaguta (2013) provide a two-stage stochastic optimization model for the World Food Programme in Ethiopia. This two-stage stochastic optimization model uses stochastic programming to minimize the transportation cost in case of uncertainty in demand and transportation infrastructure (unpredictable rain in Ethiopia often deteriorates the condition of poor infrastructure).

There are several notable works that have explored routing and scheduling of humanitarian aid. For example, Hamedi et al. (2012) address a mathematical model for routing and scheduling humanitarian supply transportation. The authors use a genetic algorithm-based heuristic to solve the proposed problem in reasonable time. The objective of the model is to minimize total cost, which is comprised of fixed cost to dispatch trucks, travel cost and reliability cost. Moreover, Barbarosoğlu et al. (2002) also propose a mathematical model that decides the routing and loading decision of humanitarian aid at

the base level. Zhang et al. (2011) present a path selection algorithm based on Q-learning for a disaster response management. Furthermore, Ferrer et al. (2018) develop a compromise programming model for a multi criteria optimization in last mile humanitarian aid distribution. The model provides a detailed schedule for each vehicle while taking convoys into consideration for security reasons. Also, Zabinsky and Mete (2010) propose a stochastic optimization method for the storage and distribution of humanitarian aid under possible disaster types and magnitudes. This model selects an optimal location for medical aid storage and inventory level whilst considering the uncertainties of disaster events.

Uncertainty

Uncertainty is one of the most challenging aspect of any humanitarian logistics problem. Uncertainty can arise from the inherent nature of the humanitarian organization or mission or from the nature of the demand (Van der Vorst and Beulens, 2002). Moreover, as a supply chain become larger and expands geographically, the nature of mission can easily disrupt the supply chain (Simchi-Levi et al., 2003). For example, as the number of beneficiaries increases, and the mission becomes geographically diverse, the nature of the problem becomes more challenging.

The United Nations Disaster Management Training Programme (DMTP) states that inadequate information about the potential uncertainty in supply chain often acts as a barrier to effective deliveries. DMTP stated that "consistently, many of the internationally supplied relief goods flown into countries...prove to be inappropriate and unnecessary...[and] may even be a barrier to more important deliveries" (DMTP, 1993). Therefore, a humanitarian organization needs to analyze the source of uncertainty meticulously, whilst considering potential solutions for the relief operations.

Demand for humanitarian aid in Chad is mercurial, due to challenging weather conditions, unpredictable rain and unforeseen conflicts. Several studies have addressed the resource allocation problem in the humanitarian logistics field. Moreover, budgeting is another popular research topic in the operations research field. This thesis is an attempt to combine knowledge across these two fields. This paper proposes an optimization model for the World Food Programme's- PRRO policy. The mathematical model uses MINLP techniques, in order to generate the most efficient way of allocating available budget for its activities, which are targeted to benefit the vulnerable populations of Chad.

# Chapter 3: Problem Overview & Methodology

This chapter provides detailed information about the PRRO operation. Later, we discuss the need of a mathematical model for the PRRO operation for its budget allocation process.

PRRO Policy

According to integrated context analyses (ICA) (conducted by the World Food Programme), food insecurity is on rise across the world. This study considered 17 countries with chronic food insecurity and derived the results, which are also consistent with the projected increase in the Prevalence of Undernourishment (PoU) described in FAO 2017 report (FAO 2017, 8). The following figure is sourced from the FAO "Food Security and Nutrition Around the World 2017" report and shows the current status of food insecurity across the world.


Figure 3. 1: Status of Food Insecurity around the world

According to data collected by the FAO in 2014-2016, one in every ten people suffer from severe food insecurity (FAO 2017,9-11). FAO provides the Food Insecurity Experience Scale (FIES), which is a metric to measure level of food insecurity. FIES

derived its results from direct yes/no responses to eight questions regarding food sufficiency (FAO 2017,10). According to FIES scale, there are three levels of food insecurity: mild, moderate and severe. Mild food insecurity is the state that applies when people have to worry about their ability to obtain food. Moderate food insecurity is applicable when people compromise with the variety and quality of food, also when they start to reduce quantities or skip their meals. Finally, severe food insecurity is the state where people are experiencing hunger (FAO, 2017,10). According to the "Food Security and Nutrition Around the World 2017" FAO report, African countries are four times more likely to experience severe food insecurity compared to other parts of the world. The FAO 2017 report states that 27.4 percent of the population in Africa suffers from severe food insecurity (FAO 2017, 11). Therefore, the WFP runs several operations in African countries to eradicate severe food insecurity and achieve its goal of "Zero-Hunger".

The World Food Programme is an active non-profit organization that is dedicated to alleviating food insecurity across the world. When an emergency strikes there are certain items such as food, shelter, water and medicines that are essential for survival. However, providing these humanitarian aid to the right place at the right time is not an easy task. There are several factors that might create complications such as uncertainty in demand, no access to the affected area or other unforeseen circumstances caused by disaster. Coordination is essential in such complex environment. Therefore, it is vital to create a platform where all the participants can come together to improve the logistics responses. Logistic Cluster provides this opportunity to all the participating groups. Logistic Cluster is group of organizations working together to improve the logistics response in case of emergencies (Logistic Cluster,2014). The WFP is the leading agency of the Logistic

Cluster due to its expertise in the humanitarian logistics field. Logistics is the backbone of any emergency response operation big or small. In case of an emergency, the Logistic Cluster maintains communication between all the humanitarian actors and helps them make informed decision. The Logistic Cluster ensures the humanitarian community has the ability to save lives (Logistic Cluster, 2014). The WFP operates 70 aircrafts, 40 shipments at sea, 5000 trucks and a network of 650+ warehouse every day to achieve the "zero hunger" goal (Logistic Cluster, 2017). Therefore, the WFP is the lead agency in the Logistic Cluster. The WFP is always one of the first humanitarian agency to respond in case of an emergency (WFP 2017).

Chad has a predominately rural population, and majority of households depends on farming or livestock to make their livings. Even though 46 percent of the gross domestic product comes from agriculture sector, Chad's brutal weather conditions have resulted in a significant cereal deficit in recent years (WFP, "PRRO 200713", 4). Moreover, Chad is vulnerable to crises in neighboring countries, as it hosts long-term refugees from Sudan, Central African Republic and Darfur (WFP, 2018). As mentioned before, the PRRO policy follows the need-based notion as opposed to status-based. In other words, the PRRO policy provides help to beneficiaries who are in needs despite of their status (refugee or returnee, etc). With PRRO policy, WFP is aiming to shift their operation from providing relief to strengthening the resilience of vulnerable populations (WFP, "PRRO200713", 3). According to WFP PRRO 200713, in a food insecure area with inadequate market integration, the targeted population receives humanitarian aid in the form of food supplies, however, in food insecure area with adequate market integration, WFP introduces food-vouchers, to strength the local economy. According to the WFP, there is evidence that

support the theory that introduction of food-vouchers in the local market makes the local economy stronger, and consequently, helps the vulnerable population to respond to a food deficit without adopting negative coping skills.

The WFP runs several operations across the world to achieve the goal of "Zero-Hunger". In this thesis, we focus on one of the WFP's policy in Chad – Protracted Relief and Recovery Operation (PRRO). According to PRRO 200713 literature, "The PRRO policy seeks to build resilience, protect the livelihood and reduce malnutrition of refugees, returnees and other vulnerable people". The main objectives of the PRRO policy are as follow:

1. Guarantee sufficient food consumption for targeted Sudanese and Central African refugees and returnees as well as other vulnerable population of Chad.
2. Provide assistance to the targeted food-insecure communities and household to maintain their livelihood.
3. Gradually introduce the WFP food voucher or cash system to the local community, allowing WFP to monitor the market's reaction and make sure that this new activity does not disrupt the already fragile economy.

PRRO policy builds resilience of the targeted vulnerable population by adopting a "mechanism that support the development and integration of local market: voucher-based transfer and local purchase of food" – (WFP, "PRRO 2001713", 3). According to the PRRO 200713 report, the PRRO policy contribute to Millennium Development Goals 1,4 and 5, where;

Millennium Development Goals 1 -Eradicate extreme poverty and hunger.

Millennium Development Goals 4- Reduce child mortality.

Millennium Development Goals 5- Improve maternal health.

The PRRO policy introduces food vouchers and cash to beneficiaries as an additional option to food supplies. PRRO policy encourages vulnerable populations to buy food from the local market, which in returns strengthens the economy. According to the WFP report PRRO 200713, local purchases of food, use of food vouchers and cash have been cost-efficient; also, increased efficiency of local market lessens production shortfall. However, it is important to realize that the local economy of Chad is very fragile and excessive inflow of cash could easily disrupt the economy. Therefore, budget allocation for food-vouchers should be performed with great care.

Budget Allocation:

Currently the WFP uses the PRRO budget for purchasing food supplies, food-vouchers, capacity development and augmentation and transportation cost. The Food supplies are purchased from both local and international markets and pre-positioned in the WFP warehouses. These cash or food vouchers are not available in every region in Chad, due to either the local economy of the region being too fragile or an insufficient food supply in the local market. Capacity development and augmentation accounts for 1 percent of the PRRO budget. Transportation is a significant factor since it involves both international and local travel as well as sea and land transportation. The following figures show the breakdown of the PRRO budget and current budget classification of the PRRO operation.

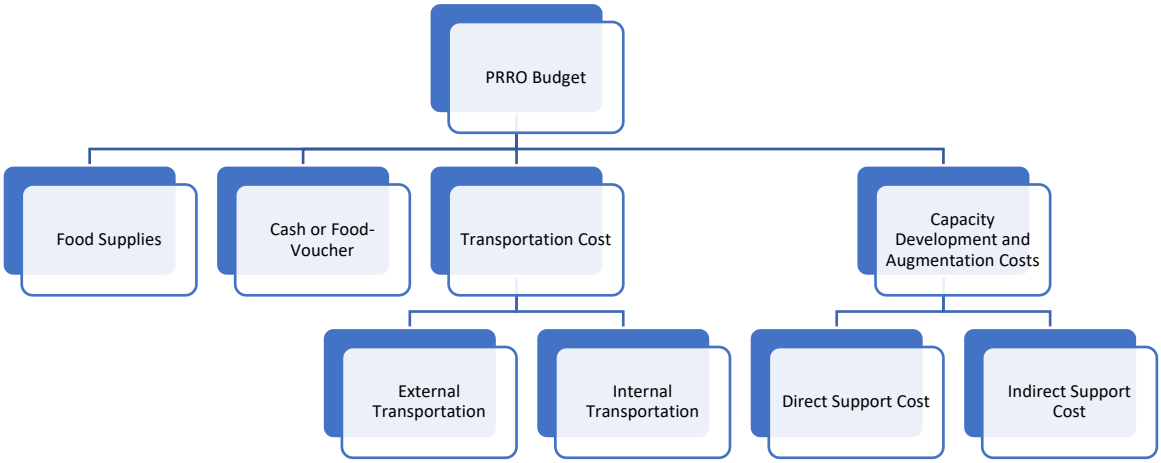



Figure 3. 2: Breakdown of PRRO Budget

Source: WFP, "PRRO 200713 Budget"

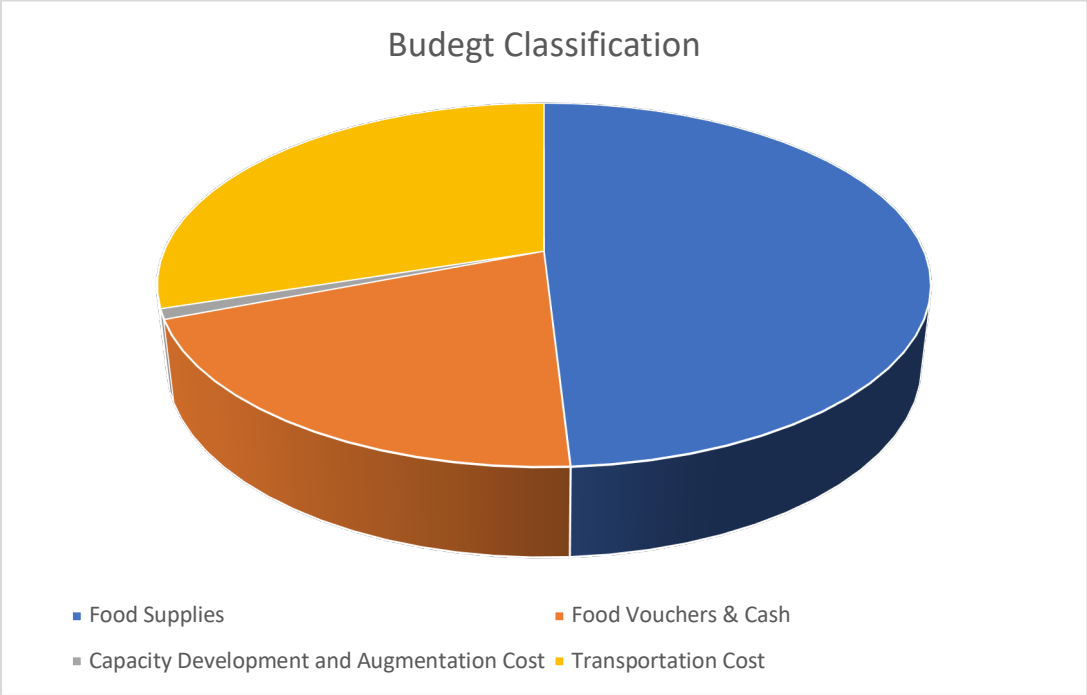



Figure 3. 3: Budget classification

Source: WFP, PRRO 200713 budget report, 2018

Food Supplies

The PRRO operation provides food supplies in the form of cereals, pulses, oil and fats and other mixed and blended food (WFP, "Chad PRRO"2018). Since chronic malnutrition is a serious problem in Chad and other African countries, the WFP provides special nutritious products to tackle this situation. One of these special products is Super Cereal. According to a WFP source "Super Cereal is a highly fortified blend of maize and soy flour and includes dairy protein". Refugees and returnees who receive full rations from the WFP also receive Super Cereals in order to prevent nutrition deficiency (WFP, "PRRO 200713",10).

According to its own literature, the PRRO operation spends approximately 50 percent of its total budget on food supplies. With the PRRO operation, the main objective of the WFP is to shift from providing relief to building resilience. Therefore, the WFP buys its food supplies from the local markets as much as possible to strengthen the Chadian economy. However, the WFP cannot entirely depend on the local market due to the unpredictable rainy season and brutal climate conditions. Therefore, WFP Chad purchases much of their food supplies from international markets. In addition to encouraging local purchase, the WFP also adopts the community-based approach in Chad, that is encouraging the local population to become a facilitator of the PRRO operation activities (WFP, "Chad country briefing", 2017). Caregivers and volunteer of the PRRO policy also receive food rations in the form of cereals, pulses, vegetable oil and salt. The following table shows the amount of food supplies distributed among beneficiaries, caregivers and volunteers.

Table 3. 1: Food Ration by Beneficiaries (g/person/day)

| | Refugees & Returnees | Vulnerable Chadian population | Volunteer & Caregivers |
|---|---|---|---|
| Super Cereal | 50 | - | - |
| Cereals | 425 | 225 | 450 |
| Pulses | 50 | 50 | 100 |
| Vegetable Oil | 25 | 15 | 25 |
| Sugar | 15 | - | - |
| Salt | 5 | 5 | 5 |
| Total | 570 | 295 | 580 |

Source: WFP, PRRO 200713 B-4 budget report

Food-Voucher

The PRRO operation provides humanitarian aid in two forms –food supplies and food-voucher. A food-voucher for general distribution has a transfer value of USD 11.25 per person per month (USD 0.375/person/day), which is equivalent to the cost of a typical food basket (WFP, "PRRO 200713", 10). However, the introduction of food vouchers in all the regions is not feasible due to inadequate food availability in some of the local markets. According to a WFP source "Running on Empty: Survival Food in Chad", due to the hostile nature of the land and unpredictable rainy season, it is almost impossible to grow any food in some regions such as Eastern Chad. Therefore, the WFP carries out intensive performance monitoring in order to assess the capabilities of the local market. These performance monitoring techniques are aligned with the Country Office Monitoring and Evaluation tools, these performance monitoring tools are also applicable to food supplies activities as well (WFP, "PRRO 200713", 14). WFP Chad is utilizing market mechanisms

–food vouchers—to enhances its assistance capacities. WFP supports local farmers and advancing local market through food-vouchers and it is also building capacity of the Chadian government institutions.

Currently, the food vouchers are on paper, but the WFP is hoping to replace the paper voucher with electronic transfers which would be more cost-effective (WFP, "PRRO 200713", 13). According to its own literature, the PRRO operation's food vouchers are distributed through WFP's corporate partners, WFP give contracts to banks or other microfinance institutions to pay to traders. These financial practices follow WFP financial guidelines to pay traders. This in returns benefit both WFP, Chad and the local economy.

The process of budget allocation for cash/food-vouchers is very important. WFP Chad conducts intensive research before introducing food-vouchers in a local economy. WFP Chad involves the Chadian government in every step of this activity to ensure that WFP does not disrupt the local economy. Moreover, the budget for food vouchers accounts for 21 percent of the total PRRO budget. Furthermore, value of a food voucher varies depending on the targeted population, in some cases, food voucher value can go up to USD 2 per day (WFP, "PRRP 200713", 10). The following table shows the value of a food voucher for different beneficiaries.

Table 3. 2: Food Voucher by beneficiaries (USD/person/day)

| | Refugees and Returnees | Vulnerable Chadian Population | Volunteer and Caregivers |
|---|---|---|---|
| Food Voucher | 0.375 | 0.19 | 2.00 |

Source: WFP, PRRO 200713 B-4 budget report

Transportation Cost

In most of Africa, transportation price is a major obstacle to economic growth (Raballand and Macchi, 2009). A number of studies have shown that higher transportation cost in African countries is caused by several factors. Some of these factors include –lack of competition between commercial truck industries (Rizet and Hine, 1993 and Pedersen, 2001) and poor infrastructure (Limao and Venables, 2001). Figure 3.4 and figure 3.5 depict that transportation is expensive and poorly managed in Central African countries.

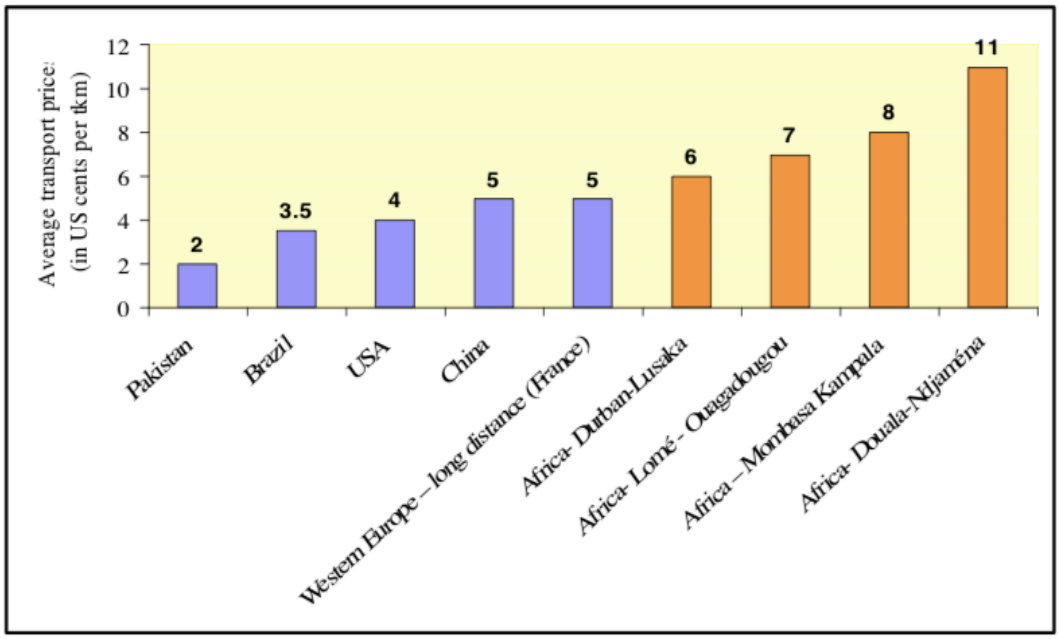



Figure 3. 4: Transport Price comparison

**Source:** Macchi, "Transport Prices and Costs: The Need to Revisit Donors' Policies in Transport in Africa"

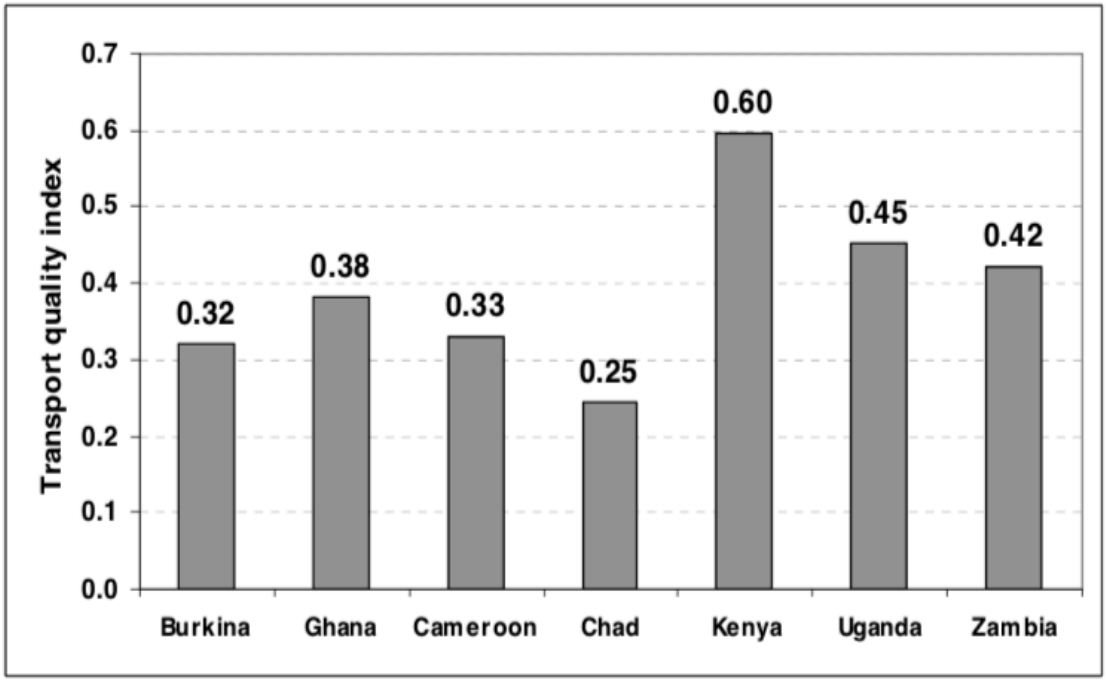



Figure 3. 5:Transport Quality

**Source:** Macchi, "Transport Prices and Costs: The Need to Revisit Donors' Policies in Transport in Africa"

Moreover, According to Roballand and Macchi, transportation cost in African landlocked countries is generally 3 to 4 times higher than in most developed countries and it also accounts for 15 to 20 percent of import cost (MacKellar et al., 2002). Therefore, transportation in Chad is challenging. Chad is a landlocked country with poor infrastructure. The nearest port is Douala, Cameroon, 1800 km (1118 miles) from the capital city N'Djamena (Logistic Cluster, 2015). Main roads in Chad are paved; other roads are mainly dirt and sand (US Embassies abroad- Chad, 2018). According to a WFP source "WFP in Chad", it is challenging to drive on other roads in Chad due to poor road side emergency services or deteriorated road conditions. Moreover, drivers are subjected to attack by armed bandits (US Embassies abroad- Chad, 2018). The network of main roads in Chad is not well maintained and driving on sand can create life threating conditions, such as vehicle malfunction, which can lead to being stuck in desert without any help for

days (WFP in Chad, 2015). Figure 3.6 presents a map of the Chadian road network, despite all these challenges, WFP is committed to provide humanitarian assistance in one of the most isolated and dangerous parts of Chad.

Food aid is transported through the nearest port, Douala. Port Sudan is another port is this region, however Port Sudan is not a reliable source because of conflicts in the region (WFP, "PRRO 200713, 13). Therefore, WFP transports food through Douala. Moreover, WFP is a registered non-profit organization, therefore is exempt from paying any custom tax at the Cameroon-Chad boarder whilst transporting humanitarian aid from Douala to Chad boarder (Logistic Cluster, "Customs Procedures for Chad/Cameroon"). Transporting food in eastern and southern Chad is a time sensitive task, since these regions become inaccessible from July- September due to rainy seasons (WFP, "PRRO 200713", 13). Therefore, pre-stocking humanitarian aid in eastern and southern Chad is very crucial.


Figure 3. 6: Road Map of Chad

Source: Maps of World

Land transportation is the main way of transporting food aid in Chad. WFP also operates several aircrafts in the African continent, however, air service is reserved for emergency cases due to its expensive nature. Figure 3.7 is sourced from the Logistic Cluster and it provides comparison matrix for different modes of transportation.

| MODE / CRITERIA | ROAD | RAIL | SEA | AIR |
|---|---|---|---|---|
| Relative speed | Moderate | Moderate | Slow | Very high |
| Reliability | Good | Good | Limited | Very good |
| Cost per tonne/km | Medium | Low/medium | Low/very low | High |
| Flexibility | High | Low | Low | Medium |
| Other considerations | Extensive network | Limited and fixed infrastructure | Restricted network | Limited network |
| | Short and medium distances e.g. Europe/Middle East. From a neighbouring country to operation site Internal transport; Short/medium distance | Large consignments. From port of discharge to inland operation site (warehouse). Ecological. | Large quantities; Less urgent; Pre positioning phase; Second phase; Long distance with no time constraint. | Emergency phase; Expensive goods; Fragile or perishable goods; Cold chain; No alternative option; Small shipments; e.g. diplomatic pouch; Long distance with time constraint. |
| Advantages | Relatively fast; No transhipment; Direct delivery; Flexible; Cost. | Economical; Large loading capacity; Range and speed (in most countries). | Economical; Large loading capacity; No restriction on loading capacity; Cheap. | Fast; Reliable; Limited losses; Direct; Easy tracking and trac-ing. |
| Disadvantages | Roads may be dangerous (land mines) or blocked (rainy season); Sometimes, driver's nationality or vehicle regis-tration not acceptable | Difficulty finding freight cars; Delays; Transhipment; Inflexible; Tracking. | Slow; Transhipments at ports; Use as a second means of transport for large volumes; Higher theft risk in the port; Not flexible. | Expensive; Restricted to journeys between airports; Restricted loading capacity (dangerous goods, size of shipment, weight, fuel, size of packages, etc.). |

Figure 3. 7: Comparison Matrix for different modes of transportation

**Source:** Logistic Cluster

Moreover, WFP uses service from commercial providers for land transportation, whenever there is need. Tariffs are calculated based on the bulk transportation request. There is no standard price calculator, it depends on the service provider, distance to be covered, type of land and corresponding season (Logistic Cluster, "Fuel-meeting notes"). For effective routing and scheduling of vehicles the Logistic Cluster considers the following objectives:

- Minimizing distance (eliminating overlapping deliveries)
- Maximizing vehicle payload and vehicle utilization
- Maximizing customer satisfaction (meeting beneficiaries'' requirement in terms of humanitarian need)

Capacity Development and Augmentation Cost

Capacity development and augmentation uses only 1 percent of the total budget (WFP, "PRRO budget report"). According to its own literature, PRRO allocates budget for WFP staff-related cost and implementation inputs. WFP staff-related cost includes payments for international professionals, consultants and local staff. Implementation cost includes payments for travel purposes, vehicle leasing and communication and IT services, etc.

Problem Overview

Currently, WFP Chad performs budget allocation for the PRRO operation based on historical data. WFP Chad carefully examines weather reports and events in neighboring countries to predict trends in fluctuation in demands to determine the most accurate budget allocation method for the PRRO operations. However, very often PRRO Chad operations needs budget revision in the midst of the operation time period due to fluctuations in

demand. Budget revision is a long process that can take up to one to three months for approval (Karl Sevesson, personal communication). According to Mr. Sevesson, a WFP Chad employee, in case of budget shortage, WFP submits a revised budget proposal to the United Nations and waits for it to get approved. Meanwhile, WFP Chad is left with very little resources to alleviate suffering of the vulnerable population. Therefore, this thesis works to develop a mathematical model for the PRRO operation, that performs the budget allocation process for three different demand scenarios.

Thesis Objective:

Develop a mathematical model using Mixed Integer Non-Linear Programming techniques to perform budget allocation for the WFP's PRRO operations. The model formulation, with full definition of its notation, is as follows:

**Sets**

$I$: Set of warehouses
$J$: Set of demand points
$K$: Set of beneficiaries
$\Xi$: Set of scenarios

**Parameters**

$H$: Total budget available for food supplies
$A$: Total budget available for food-voucher
$O_i$: Storage capacity of warehouse $i$
$X_i$: Operational cost of warehouse $i$
$Ext(\xi)$: External food supply upper bound in scenario $\xi$
$E(\xi)$: External food transportation unit cost in scenario $\xi$
$D_{jk}(\xi)$: Demand in region $j$ for beneficiaries $k$ in scenario $\xi$
$T$: Cost to transport one-dollar worth of food for one kilometer
$Dis_{ji}$: Distance between warehouse $i$ and demand point $j$
$P(\xi)$: Minimum required percentage of fulfilled demand scenario $\xi$
$M(\xi)$: Non-negative penalty factor for unsatisfied demand in scenario $\xi$

**Binary Variables**
$Y_i$: 1 if warehouse is located in $i$, otherwise 0
$B_{ij}$: 1 if food is sent from warehouse $i$ to demand point $j$
$Q_i(\xi)$: 1 if warehouse $i$ receives external food supply in scenario $\xi$

**Decision Variables**
$r_i$: Inventory level for warehouse $i$
$G_{ij}(\xi)$: Food aid sent from warehouse $i$ to demand point $j$ in scenario $\xi$
$L_{jk}(\xi)$: Food aid supply region $j$ for beneficiaries $k$ in scenario $\xi$
$C_{jk}(\xi)$: Food-voucher supply region $j$ for beneficiaries $k$ in scenario $\xi$
$Z_{jk}(\xi)$: Amount of unsatisfied demand in region $j$ for beneficiaries $k$ in scenario $\xi$
$S_i(\xi)$: Amount of external food supply in scenario $\xi$

$TC_{ij}(\xi)$:Transportation cost to move one-dollar worth of food from warehouse $i$ to demand point $j$ in scenario $\xi$

$$TC_{ij}(\xi) = Dis_{ij}(\xi) * T$$

**Model**

$$\boldsymbol{Min\ z} \tag{3.1}$$

Where,

$$z = \sum_{i} X_i Y_i + \sum_{i\epsilon I}\sum_{j\epsilon J} TC_{ij}(\xi) G_{ij}(\xi) * B_{ij} + \sum_{i\in I} S_i(\xi) E(\xi) * Q_i(\xi) + \sum_{j\epsilon J}\sum_{k\epsilon K} C_{jk}(\xi) + \sum_{j\epsilon J}\sum_{k\epsilon K} L_{jk}(\xi) + \sum_{j\epsilon J}\sum_{k\epsilon K} M(\xi) * Z_{jk}(\xi)$$

such that,

$$r_i + S_i(\xi) * Q_i(\xi) \leq O_i Y_i \qquad \forall\, i \in I \tag{3.2}$$

$$L_{jk}(\xi) = \sum_{i\epsilon I} G_{ij}(\xi) * B_{ij} \qquad \forall\, j \in J, \forall\, i \in I \,\&\, \forall\, k \in K \tag{3.3}$$

$$\sum_i S_i(\xi) \leq Ext(\xi) \qquad \forall\, i \in I \tag{3.4}$$

$$\sum_{j\epsilon J} G_{ij}(\xi) \leq r_i + S_i(\xi) * Q_i(\xi) \qquad \forall\, j \in J, \forall\, i \in I \tag{3.5}$$

$$C_{jchildren} = 0 \qquad \forall\, j \in J \,\&\, Children\ \epsilon\ K \tag{3.6}$$

$$D_{jk}(\xi) * P_{jk}(\xi) \geq L_{jk}(\xi) + C_{jk}(\xi) \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.7}$$

$$Z_{jk}(\xi) = D_{jk}(\xi) - (L_{jk}(\xi) + C_{jk}(\xi)) \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.8}$$

$$C_{jk}(\xi) \leq 0.21 * (L_{jk}(\xi) + C_{jk}(\xi)) \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.9}$$

$$\sum_j \sum_k C_{jk} \leq A \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.10}$$

$$\sum_j \sum_k L_{jk} \leq H \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.11}$$

$$M(\xi) \geq 0 \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.12}$$

$$S_i(\xi) \geq 0 \qquad \forall\, j \in J \,\&\, \forall\, k \in K \tag{3.13}$$

$$Z_{jk}(\xi) \geq 0 \qquad \forall j \in J \ \& \forall k \in K \tag{3.14}$$

$$C_{jk}(\xi) \geq 0 \qquad \forall j \in J \ \& \forall k \in K \tag{3.15}$$

$$L_{jk}(\xi) \geq 0 \qquad \forall j \in J \ \& \forall k \in K \tag{3.16}$$

$$G_{ij}(\xi) \geq 0 \qquad \forall j \in J \ \& \forall k \in K \tag{3.17}$$

$$r_i \geq 0 \qquad \forall i \in I \tag{3.18}$$

$$Y_i \in (0,1) \qquad \forall i \in I \tag{3.19}$$

$$Q_i(\xi) \in (0,1) \qquad \forall i \in I \tag{3.20}$$

$$B_{ij} \in (0,1) \qquad \forall i \in I \tag{3.21}$$

Objective function (3.1) attempts to minimize z, in this equation, [1]the first term presents the cost of maintaining a warehouse at location i. Furthermore, the second term in the objective function represents the transportation cost between warehouse and demand points in scenario ξ. The third and fourth terms represent money spent on food-supplies and food-vouchers respectively. The fifth term ensures that there is a penalty for every unsatisfied demand in any region j for beneficiaries k. Lastly, the sixth term shows the transportation cost for the external food supplies.

Constraint (3.2) is a warehouse capacity constraint. It ensures that inventory level $(r_i)$ in warehouse i does not exceed its storage capacity $O_i$, if this warehouse is utilized.

[1] WFP Chad already has a set of warehouses across Chad that can be used for any operation run by WFP Chad. Moreover, WFP Chad also has access to warehouses operated by other non-profit organization such as Logistic Cluster, Red Cross and UNHCR (Logistic Cluster, 2017). According to Logistic Cluster, if a location *i* is selected for a warehouse location, then the PRRO operation pays for its maintenance cost and pre-stocks humanitarian aid in selected warehouse.

Constraint (3.3) ensures that all the food aid supplied to a region is distributed among beneficiaries. $G_{ij}(\xi)$ represents the amount of food aid sent from warehouse i to demand point j. And summation of $L_{jk}(\xi)$ over k is the total food aid supplied in region j across all its beneficiaries. This constraint ensures that all the aid sent in a region is distributed to beneficiaries. In case of an emergency, there can be instances when WFP might be required to bring food aid from other countries. However, constraint 3.4 imposes there is an upper bound ($Ext(\xi)$) on how much, WFP PRRO operation is allowed to spend on the external food supply. Constraint (3.5) makes sure that total amount of food aid sent to region $j$ from warehouse $i$, does not exceed the amount of inventory level available in warehouse $i$. Constraint (3.6) makes sure that children beneficiaries do not receive and food-vouchers. According to the PRRO operation children receive humanitarian aid in the form of food aid only.

Furthermore, constraint (3.7) imposes a minimum service level on demand satisfaction for every scenario. $P_{jk}(\xi)$ represents the minimum required service satisfactory level in scenario $\xi$, in the event that a shortfall cannot be avoided. This ensures that shortfalls are not concentrated in one region of for one beneficiary type. Constraint (3.8) calculates the unsatisfied demand in region $j$ for beneficiaries $k$. As mentioned before, there is penalty for every unsatisfied demand. Here, $D_{jk}(\xi)$ represents the demand in region $j$ for beneficiaries $k$ and ($L_{jk}(\xi) + C_{jk}(\xi)$) represent humanitarian aid provided by the PRRO operation in region $j$ for beneficiaries $k$ either in the form of food-vouchers or food.

As mentioned before, Chad's economy is very fragile and an excessive inflow of cash in local market can easily disrupt the economy. The purpose of food-voucher is to strengthen the economy, not to damage it. Therefore, the flow of food-vouchers in the local

markets are closely monitored. Constraint (3.9) forces food-voucher activity not to be more than 21 percent of total humanitarian aid supply in the region. Constraint (3.10) and (3.11) imposes an upper limit of money allocated for food items and food-vouchers. The remaining constraint (3.12)-(3.18) ensures the non-negativity of the penalty factor, external supply, unsatisfied demand, food-voucher and food aid supply, amount of food supply sent from a warehouse to demand point and inventory level respectively. Moreover, constraint (3.19) enforces the binary nature of $Y_i$, it can only take the value of 0 or 1. If warehouse at location $i$ is selected to store humanitarian aid then $Y_i$ becomes 1 or otherwise it takes the value of 0. Similarly, constraint (3.20) and (3.21) shows the binary nature of $Q_i$ and $B_{ij}$.

# Chapter 4: Results and Conclusion

This chapter compares results obtained from the mathematical model for three different scenarios. This chapter also highlights the significance of this model and discusses the potential use of this model by the WFP Chad.

Case Study: World Food Programme Chad, PRRO 200713

The WFP Chad allocates the available budget into four categories: Food related costs, Food-voucher related cost, capacity development and augmentation cost and direct and indirect support cost. However, this model only considers cost for the food supplies, food-voucher, transportation, and warehouse operations. Figure 4.1 shows the current budget allocation according to the World Food Programme for the PRRO 200713 report 2015. Note that the food cost in the figure below includes transportation cost.

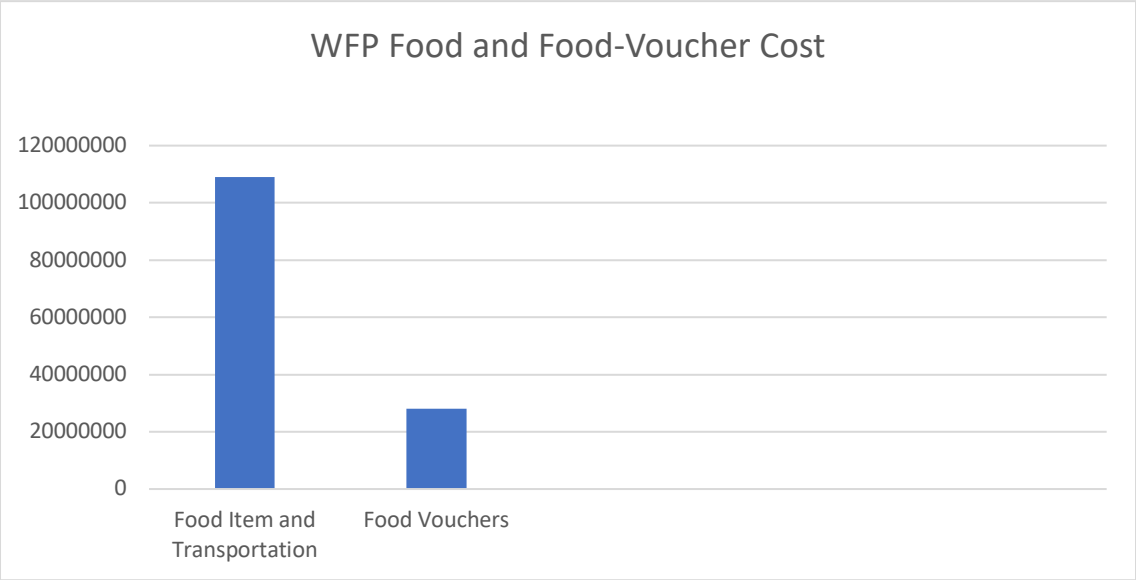



Figure 4. 1: WFP Budget Allocation

**Source**: World Food Programme PRRO 200713

The mathematical model proposed in this thesis minimizes transportation cost, warehouse operational cost, penalty cost for unsatisfied demand, food supplies, and food-voucher cost. Moreover, the time frame for this model is one year. To illustrate the working of the model, we implement the WFP PRRO 200713 data.

Since direct and indirect support cost are constant, we only consider minimizing the summation of food-voucher, food supplies and transportation cost.

The model determines the followings:

- If warehouse $i$ is selected for operation
- The inventory level of warehouse $i$
- Amount of food aid sent from warehouse $i$ to demand point j
- Amount of external food supply
- Amount of food-voucher distributed in region j for beneficiary k
- Amount of food aid distributed in region j for beneficiary k
- Unsatisfied demand in region j for beneficiary k

As was mentioned earlier, the WFP Chad offers humanitarian aid in two forms: food items and food-vouchers. In order to maintain consistency in the model, all variables and parameters were converted into USD.

This model assumes that children only receive humanitarian aid in form of food items and do not receive any food-vouchers. Furthermore, as a result of harsh climate conditions, agriculture is impossible in some parts of Chad. Therefore, cash distribution is restricted in these regions. Furthermore, this model considers [2]20 potential warehouses

[2] 20 warehouse locations considered in this thesis are currently used by the WFP. This information was sourced from the Logistic Cluster literature.

locations, 22 demand points and 3 beneficiaries. Figure 4.2 shows the location of these 20 warehouses. According to the World Food Programme and the University of Greenwich literature "Food Storage Manual", a typical WFP warehouse contains 85 percent of cereal, with the remaining 15 percent is composed of the pulse, oil and fat, mixed blended food and other miscellaneous products.

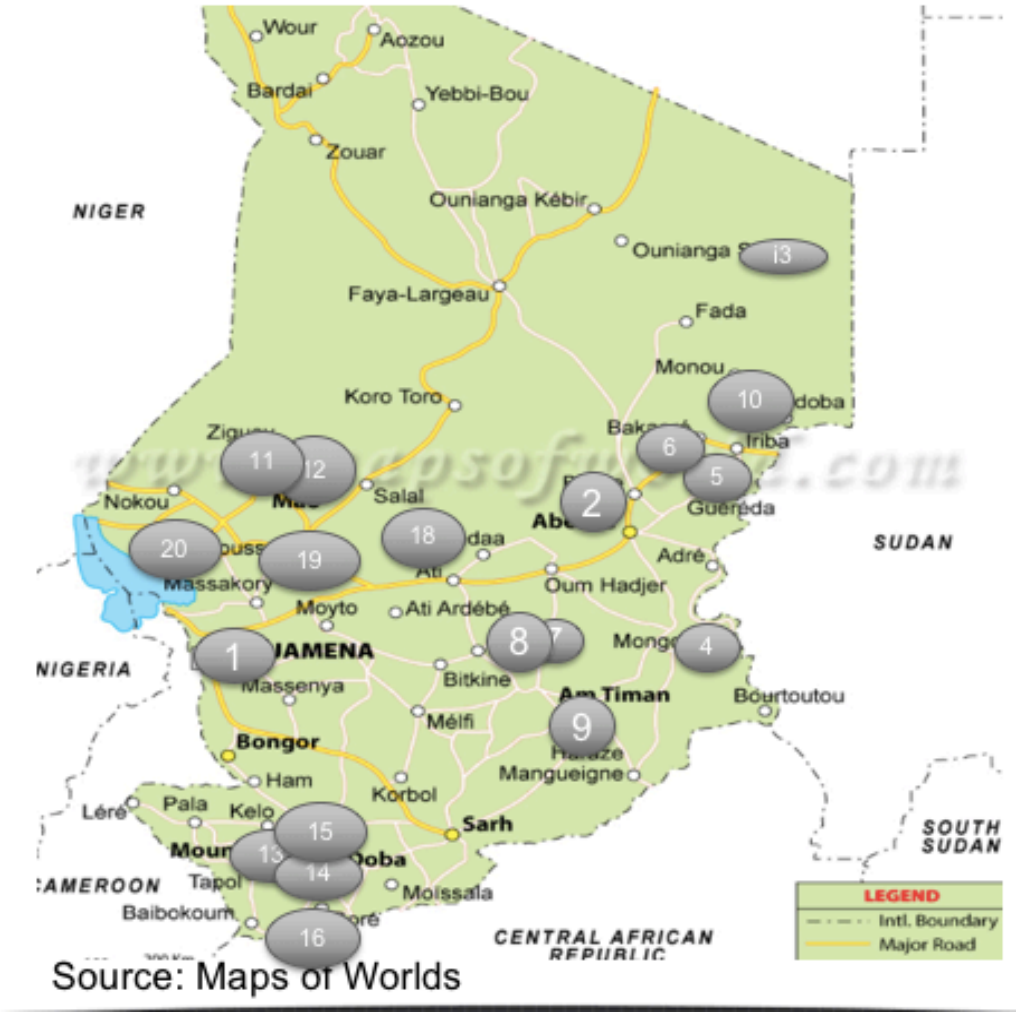



Figure 4. 2 Potential Warehouse Locations

Source: Logistic Cluster and Maps of Worlds

Therefore, we assume that the 85 percent of any WFP warehouse is comprised of cereals and the rest 15 percent is constituted of the pulse, oil and fat, mixed blended food and other miscellaneous products. Table 4.1 shows the price these food items.

Data Sets and Methodology

Table 4. 1: Price of commodity per metric tons

| Commodity | USD/MT |
|---|---|
| Cereals | 328 |
| Pulses | 561 |
| Oil and Fats | 1170 |
| Mixed and Blended Food | 715 |
| Others | 507 |

Source: World Food Programme PRRO 200713 literature

According to the WFP CHAD PRRO200713 budget report, a total of USD 67,532,100 is available to place food in these warehouses. Furthermore, according to Mr. Sevesson, a WFP Chad employee, a typical WFP warehouse is replenished four to six times a year under ideal circumstances. Therefore, this model assumes that every selected warehouse is replenished four times a year. Given a warehouse capacity ($WC_{tons}$), stated in metric tons (Mt) for each warehouse, we can compute a warehouse capacity stated in terms of value in USD ($WC_{USD}$), as follows,

[3] $$WC_{USD} = 4 * \{(WC_{tons} * 0.85 * 328) + (WC_{tons} * 0.15 * 738)\} = 1558 * WC_{tons}$$

[3] Cereal's price per metric tons is $328 and average price of pulses, oils and fats, mixed blended food and other miscellaneous food items is $738.

Table 4.2 shows the capacity of WFP warehouses, the $WC_{tons}$ data given in this table is sourced from the Logistic Cluster.

Table 4. 2: Warehouse capacity

| Warehouse (i) | $WC_{tons}$ (Mt) | $WC_{USD}$ (USD) |
|---|---|---|
| Ndjamena | 1000 | 1,558,000 |
| Abeche Biltine | 6500 | 10,127,000 |
| Amdjaras | 2500 | 3,895,000 |
| Koukou | 4050 | 6,309,900 |
| Guereda | 4400 | 6,855,200 |
| Farchana | 7600 | 11,840,800 |
| Mongo | 2900 | 4,518,200 |
| Mongo | 2850 | 4,440,300 |
| Haraze | 1500 | 2,337,000 |
| Iriba | 5950 | 9,270,100 |
| Mao | 2200 | 3,427,600 |
| Mao | 1050 | 1,635,900 |
| Moundou | 800 | 1,246,400 |
| Moundou | 1700 | 2,648,600 |
| Moundou | 1000 | 1,558,000 |
| Gore | 4800 | 7,478,400 |
| Maro | 2000 | 3,116,000 |
| Ati | 2500 | 3,895,000 |
| Moussoro | 2000 | 3,116,000 |
| Bol | 3600 | 5,608,800 |

**Source:** Logistic Cluster

Similarly, the demand of each beneficiary in region j is converted into USD. According to the WFP Chad literature, depending on their status every beneficiary receives a different amount of humanitarian aid by the WFP. Table 4.3 shows the amount of humanitarian aid in USD given to beneficiaries.

Table 4. 3: Humanitarian aid per beneficiary (USD)

| Beneficiary | USD/beneficiary/day | USD/beneficiary/month |
|---|---|---|
| Children ($k_1$) | 0.21 | 6.3 |
| Refugee ($k_2$) | 0.27 | 8.1 |
| Chadian ($k_3$) | 0.64 | 19.2 |

**Source:** World Food Programme PRRO 200713 literature

Table 4.4 depicts the demand by beneficiary k in region j in scenario I (the same logic is used to compute demand in scenario II and III). Number of beneficiary served in a month by the WFP Chad is sourced from "Plan 2018" (a document provided by the WFP). Therefore, demand for beneficiary k is calculated by:

Demand in region j for beneficiary ($k_1$) = 12*(Number of beneficiary ($k_1$) in region j *6.3)

Demand in region j for beneficiary ($k_2$) = 12*(Number of beneficiary ($k_2$) in region j *8.1)

Demand in region j for beneficiary ($k_3$) =12*(Number of beneficiary ($k_3$) in region j *19.2)

Table 4. 4**:** Demand of humanitarian aid by beneficiaries for scenario I(USD)

| Demand point ( j) | $k_1$ | $k_2$ | $k_3$ |
|---|---|---|---|
| Abeche | 129,780 | 0 | 105,864 |
| Am Nabak | 31,122 | 1,278,863 | 93,503 |
| Amboko | 83,790 | 2,640,503 | 4,127,689 |
| Ati | 84,000 | 0 | 1,671,436 |
| Bagasola | 0 | 0 | 584,094 |
| Bol | 201,600 | 194,400 | 4,556,738 |
| Breidjing | 12,600 | 2,800,875 | 189,561 |
| Djabal | 50,400 | 1,346,979 | 772,180 |
| Farchana | 9,450 | 1,742,891 | 277,768 |
| Gaga | 70,182 | 1,622,892 | 282,781 |
| Goz-Amir | 27,418 | 1,959,636 | 338,150 |

| | | | |
|---|---|---|---|
| Haraze Mag. WH | 5,670 | 366,930 | 563,283 |
| Iridimi | 0 | 1,597,414 | 312,575 |
| Kounoungou WH | 53,449 | 1,186,674 | 151,386 |
| Mao Magasin 1 | 428,400 | 0 | 1,460,192 |
| Maro | 34,314 | 2,175,663 | 1,123,318 |
| Mille | 19,320 | 1,146,042 | 253,459 |
| Mongo Mag. | 147,000 | 0 | 1,314,694 |
| Moussoro | 138,600 | 0 | 1,196,947 |
| Oure Cassoni | 11,865 | 1,909,209 | 39,168 |
| Touloum | 0 | 1,317,298 | 87,231 |
| Treguine | 58,968 | 1,580,599 | 264,697 |

**Source:** World Food Programme PRRO 200713 literature

As mentioned earlier, transportation is challenging in Chad due to poor infrastructure, long distances and insecurity (WFP Chad "Country Briefing, January 2017"). Since in this model, both warehouse capacity and demand are in USD, we define total transportation cost (TC) as follow:

$$\mathrm{TC}(i,j) = \mathrm{T}(i,j) * \mathrm{G}(i,j)$$

Where,

$\mathrm{T}(i,j)$: Cost to send one dollar's worth of food from warehouse $i$ to demand point $j$

$\mathrm{G}(i,j)$: Food aid sent (in USD) sent from warehouse $i$ to demand point $j$

Also,

$$\mathrm{T}(i,j) = \mathrm{Dis}(i,j) * \mathrm{Foodaid} * \mathrm{cost}$$

Where,

$\mathrm{Dis}(i,j)$: Distance between warehouse $i$ and demand point $j$

$\mathrm{Foodaid}$: Kilograms of food associated with one dollar's worth of food aid

$\mathrm{cost}$: Cost to transport one kilogram of food for one kilometer

The same logic is used to calculate the transportation cost for the external food supply in scenario III.

Results:
This thesis constructs three demand scenarios for this mathematical model and compares the results obtained from these models. All three scenarios are inspired by the real situations and carefully implemented in the model. Three scenarios are as follow:

**Scenario I**: Original Demand
Scenario I examine the model with no instabilities in demand. This model was solved using General Algebraic Modeling System (GAMS 24.8.5). The solution time is 0.063 seconds. Table 4.5 shows that the optimal value for this scenario is 84,905,451 USD. However, for the same number of beneficiaries WFP currently spends 137,141,050 USD.

**Scenario II:** Drought Scenario
In Scenario II, the model observes an increase in demand due to severe drought in the Lac region. The Lac region is one of the most vulnerable regions in Chad as it experiences severe drought every other year (PRRO 200713, WFP Chad). For this scenario, we assume that 20,000 Chadians are affected by this drought and require immediate humanitarian aid. Since drought limits the availability of food in the local market, food-vouchers cannot be used in this region. Therefore, the WFP provides aid in form of food items to these beneficiaries in the affected region. This model was also solved using GAMS 24.8.5. The solution time is 0.047 seconds. Table 4.5 shows the optimal cost values for this scenario.

**Scenario III:** External Supply
As was mentioned earlier, Chad receives thousands of refugees from its neighboring countries. According to the UNHCR, in the 2017 clash between Mouvement National Pour de le Centrafrique (MNLC) and Revolution et Justicec (RJ), 75000 refugees were forced to leave Central African Republic (CAR). Similarly, thousands of refugees came to Chad

fleeing conflict in South Sudan. Therefore, for this scenario, we assume that total of 200,000 refugees seek shelter in Chad. To satisfy this huge increase in demand, the model uses external food supply. This model was also solved using GAMS 24.8.5. The solution time is 0.063 seconds. Table 4.5 shows the optimal cost values for this scenario and figure 4.2- figure 4.6 graphical representation of these results.

Table 4. 5: Results from scenario I, II &III

| | Scenario I | Scenario II | Scenario III | WFP Budget Allocation |
|---|---|---|---|---|
| Optimal Value | 84,905,451 | 95,833,873 | 119,752,896 | 137,141,050 |
| Food Cost | 38,067,193 | 40,664,358 | 48,241,249 | 67,532,100 |
| Food-Voucher Cost | 7,144,322 | 6,518,157 | 7,216,764 | 28,031,362 |
| Operational Cost | 91,884 | 98,952 | 98,952 | [4]141,360 |
| Transportation Cost | 39,602,052 | 48,552,406 | 64,195,931 | 41,436,228 |
| External Supply | 0 | 0 | 2,000,000 | 0 |
| Unsatisfied Demand | 0 | 0 | 0 | 0 |

[4] WFP currently uses all 20 warehouses.

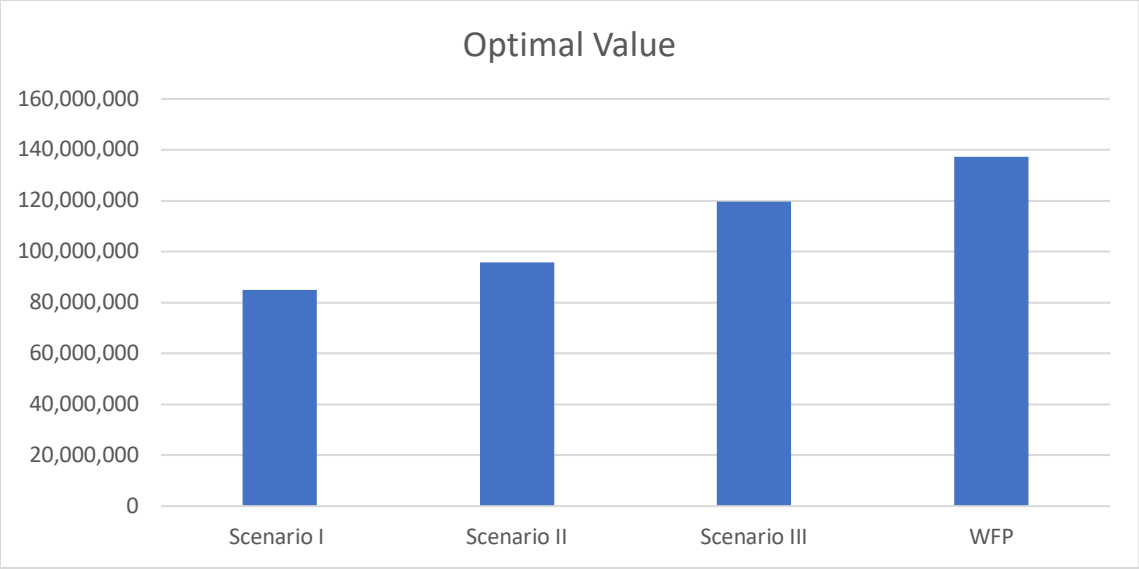


Figure 4. 3 Optimal Value for Scenario I, II & III and current WFP budget

Figure 4. 4: Food Aid Cost in Scenario I, II &III and current WFP Budget

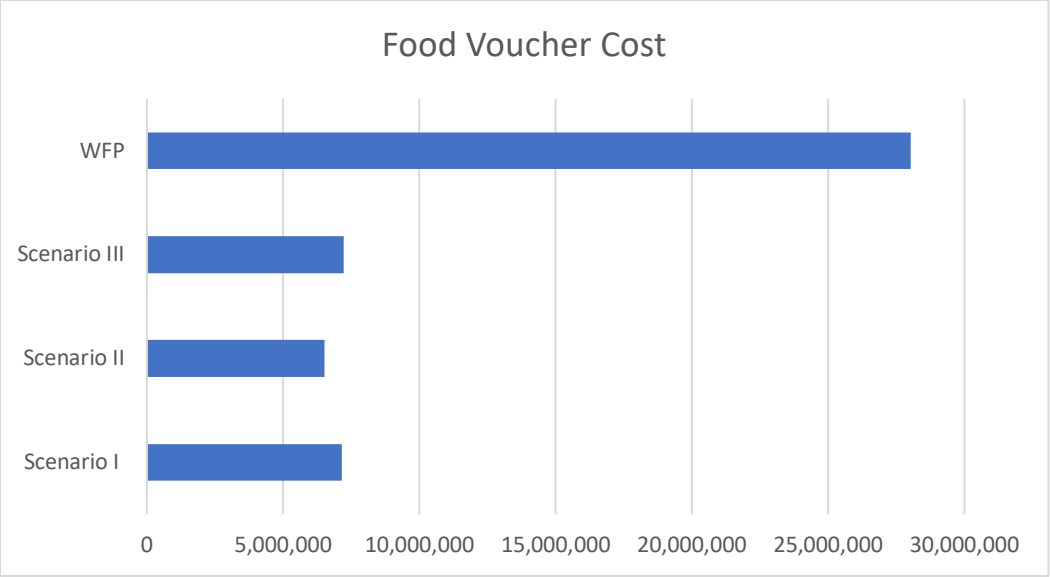


Figure 4. 5: Food Voucher Cost in Scenario I, II &III and current WFP Budget

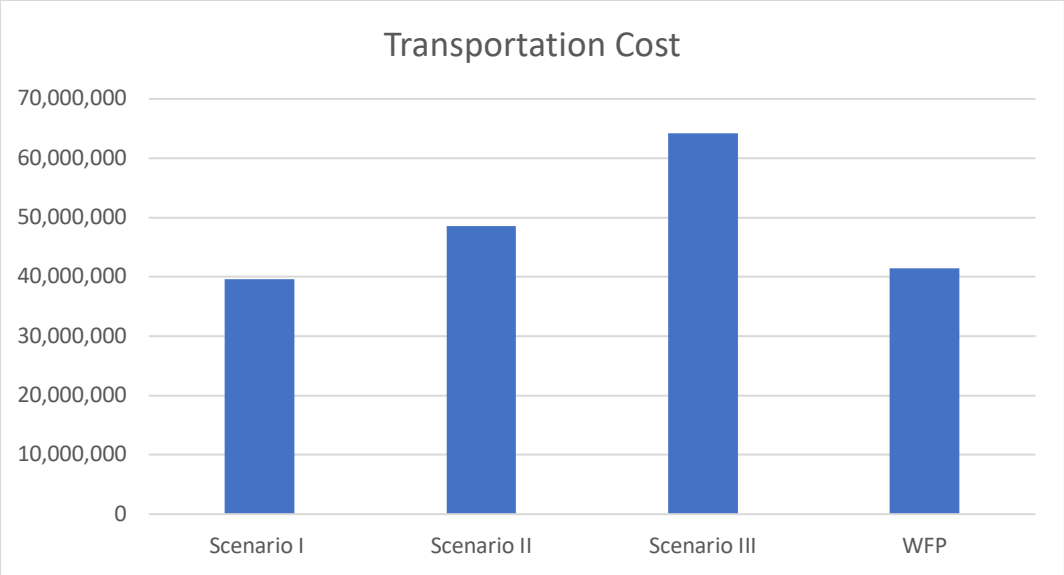


Figure 4. 6: Transportation Cost in Scenario I, II &III and current WFP Budget

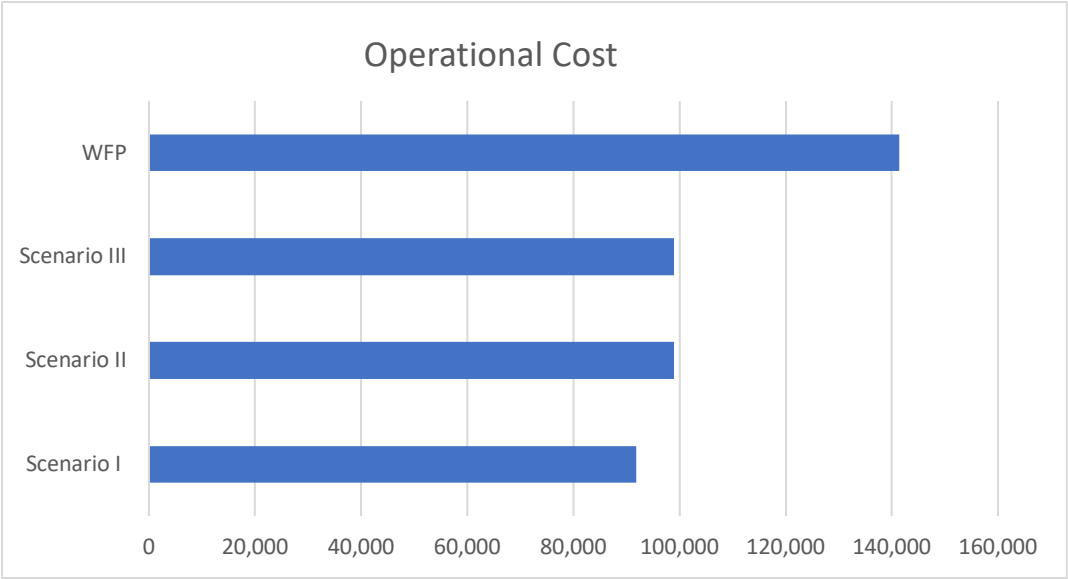



Figure 4. 7: Operational Cost in Scenario I, II &III and current WFP Budget

To satisfy the demand of Scenario I, 13 warehouses are utilized. Moreover, transportation cost is minimized by assigning warehouses to the closest demand points. Table 4.6 depicts the assignment of warehouses to demand points. Since warehouse Abeche Biltine ($i_2$) and Farchana ($i_6$) are the warehouses with the largest capacity, they are assigned to provide humanitarian aid to multiple demand points.

Furthermore, note that the cost of the WFP solution in figures 4.3 through 4.7 are generally much larger than those for Scenario I (WFP and scenario I serve the same demand), the potential reasons for this are losses due to security (bandits), or perhaps food waste, or other categories that we don't understand.

Table 4. 6 Warehouse-Demand point assignment for Scenario I

| Warehouses | Demand Points |
|---|---|
| i2 | j10,j15,j17,j20 |
| i3 | j3 |
| i4 | j16 |
| i5 | j18,j21 |
| i6 | j11,j12,j13,j14 |
| i7 | j4,j9 |
| i9 | j16 |

| | |
|---|---|
| i10 | j3 |
| i11 | j5 |
| i15 | j8 |
| i18 | j2 |
| i19 | j1,j19,j21 |
| i20 | j6,j7 |

Table 4. 7 Inventory Level of warehouse (i) in Scenario I

| Warehouse | Capacity of Warehouse (i) | Inventory Level | Utilization (%) |
|---|---|---|---|
| i2 | 10,127,000 | 6,533,907 | 64.5 |
| i3 | 3,895,000 | 3,895,000 | 100.0 |
| i4 | 6,309,900 | 296,303.6 | 4.7 |
| i5 | 6,855,200 | 2,559,268 | 37.3 |
| i6 | 11,840,800 | 5,184,442 | 43.8 |
| i7 | 4,518,200 | 3,416,904 | 75.6 |
| i9 | 2,337,000 | 2,337,000 | 100.0 |
| i10 | 9,270,100 | 1,518,066 | 16.4 |
| i11 | 3,427,600 | 1,364,890 | 39.8 |
| i16 | 7,478,400 | 1,713,952 | 22.9 |
| i18 | 3,895,000 | 1,403,488 | 36.0 |
| i19 | 3,116,000 | 3,116,000 | 100.0 |
| i20 | 5,608,800 | 4,727,972 | 84.3 |

For Scenario II, to satisfy the increase in demand, the model allocates more money for food supplies, which also increases the transportation cost. To satisfy demand in this scenario 14 warehouses are utilized. Since the distribution of food-vouchers is restricted in the drought affected regions, we notice a decrease in total amount of money allocated for the food vouchers. Since more money is allocated for food supplies transportation cost increases too. Table 4.8 shows the assignment between warehouse and demand point for scenario II.

Table 4. 8: Warehouse-Demand point assignment for Scenario II

| Warehouse | Demand Point |
|---|---|
| i1 | j7 |
| i2 | j10,j15,j17,j20 |
| i3 | j3 |

| | |
|---|---|
| i4 | j16 |
| i5 | j18,j21 |
| i6 | j11,j12,j13,j14 |
| i7 | j4,j9 |
| i9 | j16 |
| i10 | j3 |
| i11 | j5,j7,j19 |
| i16 | j8 |
| i18 | j2 |
| i19 | j1,j19,j22 |
| i20 | j6,j7 |

Table 4. 9: Inventory Level of warehouse (i) in Scenario II

| Warehouse | Capacity of Warehouse (i) | Inventory Level | Utilization (%) |
|---|---|---|---|
| i1 | 1,588,000 | 1,588,000 | 100 |
| i2 | 10,127,000 | 6,533,907 | 64.5 |
| i3 | 3,895,000 | 3,895,000 | 100.0 |
| i4 | 6,309,900 | 296,303.6 | 4.7 |
| i5 | 6,855,200 | 2,559,268 | 37.3 |
| i6 | 11,840,800 | 5,184,442 | 43.8 |
| i7 | 4,518,200 | 3,416,904 | 75.6 |
| i9 | 2,337,000 | 2,337,000 | 100.0 |
| i10 | 9,270,100 | 1,518,066 | 16.4 |
| i11 | 3,427,600 | 1,364,890 | 39.8 |
| i16 | 7,478,400 | 1,713,952 | 22.9 |
| i18 | 3,895,000 | 1,403,488 | 36.0 |
| i19 | 3,116,000 | 3,116,000 | 100.0 |
| i20 | 5,608,800 | 4,727,972 | 84.3 |

For Scenario III, there is a huge increase in demand, which exceeds the total amount budget available for the PRRO policy. Since the purchase of food from the local market cannot satisfy this massive increase in demand, WFP is left with only one option: importing food from overseas. In this scenario, we assume that the WFP imports food from the closet [5]logistic hub in Spain (the external transportation cost is calculated assuming that the food

[5] Logistic hub is a WFP logistic base that supports assistance operations across the Horn of Africa. The logistic hubs are stocked with humanitarian aids in advance to reduce the response time during emergency.

supplies are imported from Spain). Moreover, to satisfy demand in this scenario 14 warehouses are utilized. As Table 4.5 and Figure 4.5 show, the transportation cost in scenario III is very high, since it includes both internal and external transportation. Internal transportation include distance travelled between warehouses and demand points. External transportation includes cost of importing food from overseas. Similar to Scenario II, there are restrictions on using food-vouchers in the affected regions (where refugees are seeking shelters). Therefore, there is an increase in the total cost. Table 4.10 shows the assignment of warehouse and demand point for Scenario III.

Table 4. 10: Warehouse-Demand point assignment for Scenario III

| Warehouse | Demand Point |
|---|---|
| i1 | j7 |
| i2 | j10,j15,j17,j20 |
| i3 | j3 |
| i5 | j18,j21 |
| i6 | j11,j12,j13,j14 |
| i7 | j4,j9 |
| i9 | j16 |
| i10 | j3 |
| i11 | j7,j19 |
| i12 | j5,j7 |
| i16 | j8 |
| i18 | j2 |
| i19 | j1,j19,j22 |
| i20 | j6,j7 |

Table 4. 11 Inventory level of warehouse (i) in Scenario III

| Warehouse | Warehouse Capacity | Inventory Level | Utilization (%) |
|---|---|---|---|
| i1 | 1,558,000 | 1,558,000 | 100.0 |
| i2 | 10,127,000 | 6,533,907 | 64.5 |
| i3 | 3,895,000 | 3,895,000 | 100.0 |
| i5 | 6,855,200 | 2,559,268 | 37.3 |
| i6 | 11,840,800 | 5,184,442 | 43.8 |

| | | | |
|---|---|---|---|
| i7 | 4,518,200 | 3,416,904 | 75.6 |
| i9 | 2,337,000 | 2,337,000 | 100.0 |
| i10 | 9,270,100 | 4,162,984 | 44.9 |
| i11 | 3,427,600 | 3,115,604 | 90.9 |
| i12 | 1,635,900 | 1,635,900 | 100.0 |
| i16 | 7,478,400 | 1,713,952 | 22.9 |
| i18 | 3,895,000 | 1,403,488 | 36.0 |
| i19 | 3,116,000 | 3,116,000 | 100.0 |
| i20 | 5,608,800 | 5,608,800 | 100.0 |

Observe that 13 warehouses are utilized to satisfy the demand in scenario I solution. These same 13 warehouses are also utilized across three scenarios. The optimal solution for scenario II and III utilizes these 13 warehouses (same as scenario I) with an addition of warehouse $i_{1.}$ for both scenarios II and III. These 13 warehouses are close to demand points and have large storing capacities, consequently selection of these warehouses decreases transportation cost.

Conclusion:

This model is a useful tool to generate results for several demand scenarios. One can also modify constraints based on the scenario and obtain valid results. We can advance this model by using the stochastic optimization techniques, which will enable this model to generate results whilst considering uncertainty in demand.

This model determines the optimal number of facilities to be placed such that the distance between beneficiaries and warehouses is minimized. Moreover, this model also determines what portion of the PRRO budget should be allocated for food supplies, food voucher, warehouse operational cost, and transportation cost, whilst minimizing the total cost. The model is solved using mixed integer non-linear programming (MINLP). This thesis generates three scenarios considering real-life situations. Then model minimizes cost for transportation, food supply, food-voucher, unsatisfied demand and warehouse operations. In addition to minimizing cost, this model can also be used to identify important warehouse locations. For this case study, Abeche Biltine($i_2$), Farchana($i_6$) and Moussoro($i_{19}$) are identified as one of the most important warehouse locations. Warehouse in Abeche Biltine ($i_2$) and Farchana ($i_6$) have one of the largest storing capacity. Additionally, these warehouses are closer to several demand points, which reduces transportation cost. Therefore, storing humanitarian aid in these two warehouses can minimize the total cost. While warehouse Moussoro ($i_{19}$) does not have large storing capacity, its location makes it an important warehouse location. As it is mentioned earlier, transportation in Chad is expensive, therefore identifying important warehouses can potentially save millions of dollars.

Furthermore, the model proposed in thesis imposes a fixed cost for every warehouse that is selected for operation. However, when this fixed cost is eliminated, the optimal solution for each scenario decreases. For example, in scenario I, 19 warehouses are utilized, for scenario II, 17 warehouses are utilized and for scenario III, 16 warehouses are chosen for operation. Since the total number of utilized warehouses increases in each scenario, we observe a decline in total transportation cost. For scenario I the optimal cost is reduced to 84,813,567 and for scenario II updated optimal cost is 95,734,921and finally for scenario III the optimal cost is reduced to 119,653,944.

Furthermore, this model also minimizes unsatisfied demand by imposing the penalty factor for every unsatisfied demand. This model forced the unsatisfied demand to be zero for the three scenarios, by assigning a large value (500,000) to the penalty factor. Therefore, using this model, WFP can save millions of dollars, which in return will enable WFP to save more lives.

The World Food Programme is committed to providing humanitarian aid in Chad, aiming to eradicate hunger and minimize the suffering of beneficiaries. However, providing humanitarian aid in Chad is extremely difficult due to its poor infrastructure, geographical location, political conflicts, a fragile economy and harsh climate. Therefore, this model has many limitations. This model assumes that every WFP warehouse is replenished four times a year, however, the WFP often runs low on budget and many WFP warehouses are empty. Moreover, this model does not consider the complexity of transportation in Chad. Transportation in Chad is not only expensive but also a risky task. WFP warehouses and trucks carrying food aid are very often vandalized and looted, which, makes WFP's job more challenging. The WFP constantly works with minimal resources.

Moreover, fluctuation in demand due to the political crisis in neighboring countries and climate related disasters, makes WFP's job more difficult. The mathematical model proposed in this thesis does not account for fluctuations in demand. We constructed three demand scenarios considering increase in demand due to political crisis and natural disaster separately. However, the model assumes that there is no variation in demand during policy operational time period. To account for uncertainty in demand during the PRRO policy operation period we can use stochastic optimization technique.

Despite all these challenges WFP supports millions of vulnerable people in Chad. WFP runs several operations in Chad to alleviate the suffering of the vulnerable populations. The PRRO policy aims to build resilience among the beneficiaries. Even though this model does not capture all these uncertainties and complexities that WFP faces, it can still be used to minimize cost on fundamental levels. Moreover, this model identifies important warehouse locations whilst considering distance from the demand points and warehouse capacity.

# Stake Holders

- World Food Programme (WFP)
- Office of the United Nations High Commissioner for Refugees (UNHCR)
- United Nations(UN)
- Logistic Cluster
- Food and Agriculture Organization of the United Nation (FAO)
- United Nations Children's Fund (UNICEF)
- Government of Chad

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