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**Abstract.** Aid agencies implement food aid programs to alleviate the chronic hunger faced by millions of people. These agencies can choose to distribute food commodities directly in-kind, or they can provide cash or vouchers to the beneficiaries. Empirical evidence from the literature shows that cash and voucher programs can decrease the logistics costs, improve the nutritional outcomes, and contribute to the local economy. After carefully reviewing the modality selection practices of humanitarian agencies, we develop a new model for determining the modality and the quantity of aid to allocate for a selected group of beneficiaries. The proposed model has three objectives to assess potential solutions: the program costs, the beneficiaries' nutrition levels, and the economic contributions to the local economy. The beneficiaries' consumption behavior is incorporated into the model through a bilevel optimization structure to capture and prevent inefficient cash use by beneficiaries. We validate the model using data from the World Food Programme's operation from their operations in the Garissa county of Kenya. We analyze the robustness of our solutions to possible variations in different cost components, including the food commodity prices and operational costs, to measure the robustness to these parameters. Finally, we demonstrate how the model can be used to evaluate common policies intended to improve the program outcomes, such as educating beneficiaries about nutrition or fortifying grains available in local markets.

**Keywords**. Humanitarian logistics, food aid, cash and vouchers, bilevel optimization

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# 1. Introduction

Each year, aid agencies deliver millions of tons of food commodities to developing countries to alleviate hunger. However, in 2018, 815 million people faced hunger on a daily basis, and even more (one third of the world's population) suffered from malnutrition (WFP, 2018c). It is expensive to deliver food aid to the most remote and underserved regions of developing countries. Each year, 40% to 70% of the food-aid budget is spent on logistics (WFP, 2015), significantly draining the limited resources of the aid agencies. Additionally, the agencies are criticized for creating a dependency on aid programs by de-incentivizing local production and further impoverishing local producers (Moyo, 2009). Cash and voucher programs overcome this drawback since the aid is spent on commodities harvested and distributed locally (Taylor *et al.*, 2016). Such programs help the recipient country, not only by reducing hunger but also by empowering the local producers. In the last decade, the idea of distributing aid in the form of cash and vouchers has gained much attention in the humanitarian community.

Vouchers can be redeemed for food items at selected retailers. They are distributed in regions where food is available in the local markets, but the targeted households do not have the resources to buy it. The agencies sign contracts with local retailers, then the beneficiaries purchase items in exchange for their vouchers. Similarly, food availability in local markets is a prerequisite for cash distribution to be feasible. Cash programs do not require retailer selection: the money can be spent anywhere.

Each organization has its own guidelines for modality selection. Pilot studies provide valuable empirical results and credible evidence for the consequences of each option, but they do not indicate how to design aid programs in different contexts with different parameters (Gentilini, 2016). A mathematical model could assist decision-makers with the modality selection. It is important, however that the modeling framework considers the program objectives, the economics of food consumption, the characteristics of the local markets, and the beneficiary preferences. We define a new Food Aid Modality Selection (FAIMS[1]) model, that incorporates these factors. The model determines whether or not it is worthwhile to invest in cash or voucher distribution infrastructure and to

[1]The name FAIMS is a reference to the French word "faim", which means hunger.

abolish the current in-kind distribution. We assess not only the program costs but also the nutritional improvements of the beneficiaries and the economic contribution to the local economy. We combine these three objectives to measure the total welfare resulting from the proposed aid program. In addition, we incorporate a lower-level model to capture the beneficiaries' undesirable use of cash on non-nutritious items. The resulting framework is a bilevel optimization model, where in the upper level the agency decides the amount and type of aid, and in the lower level the beneficiaries decide how to use this aid.

Cash and vouchers can be distributed for different purposes (nutrition, health, etc.) and in different contexts (disaster response, refugee settlements, etc.), and each of these settings requires further consideration. This paper aims to study the complex mechanisms associated with cash and voucher distribution, and it focuses on the implications in a chronic hunger response context. To demonstrate the potential use of this model for program design and policy evaluation, we performed numerical analyses using data gathered from the World Food Programme (WFP)'s aid operations in the Garissa county of Kenya.

Our analyses reveal that in-kind aid is the cheapest option for this region, since the food commodities available in the local markets are expensive. Indeed, the program can achieve substantial improvements in terms of nutrition and economic contributions if WFP increases its budget by 20%; the improvements quickly diminish for increases beyond this level. We have evaluated two alternative aid improvement policies. The first is educating beneficiaries to encourage them to make more responsible dietary choices. Our results indicate that this is worthwhile if the cost is less than \$2 million, otherwise the costs outweigh the benefits. The second is the mass fortification with micronutrients of the grains available locally. This policy contributes to the community from both nutrition and economic perspectives. Therefore, we suggest a collaboration between WFP and the Kenyan government to accelerate the ongoing efforts on mass fortification since it would decrease Kenya's dependence on international food aid.

Although this study is inspired by the existing food aid practices of WFP, it can be adapted to other aid programs since the cost and benefit structures are defined in a generalizable fashion in the mathematical model. Aid modality is currently addressed through decision-trees and guidelines by practitioners. These approaches fall short in assessing the long-term effects of the chosen modality. We contribute to the literature by providing an analytical approach that enables *ex-ante* analysis of program costs, nutritional and economic contributions of the food aid program. One of the unique aspects of our paper is that the effects of the aid program on each stakeholder's welfare is modeled realistically and tested using real-data.

The rest of this paper is organized as follows. In Section 2, we discuss the related literature. In Section 3, we give a formal problem definition and the mathematical formulation. In Section 4, we briefly describe the data used for the numerical analysis and give the sensitivity analysis results. In Section 5, we demonstrate how our model can be used for policy evaluation. Section 6 concludes the paper with a discussion of the implications of the model and future research directions.

## 2. Related Literature

The literature on aid modality selection can be classified into two categories: discussions of current practices of humanitarian agencies, and field studies on the effectiveness of different options. To date, there has been no study of the application of operations management to the modality selection problem. We also briefly refer to bilevel optimization problems in resource allocation settings since this research stream is relevant to our methodology.

### 2.1. Guidelines developed by aid agencies

Initially developed for emergency responses, almost all modality selection guidelines are based on decision trees. By answering yes/no questions, given the collected data, the agency selects the modality of the aid. The interested reader can view the following representative examples: European Commission (2013), OXFAM (Cretì and Jaspers, 2006), and Market Information and Food Insecurity Response Analysis (Barrett *et al.*, 2009). WFP distinguishes the emergency (Ockwell, 2009) and developmental (WFP, 2014) contexts and has two separate guidelines. Based on its experience, WFP concluded that cash and vouchers would be more efficient in developmental contexts (WFP, 2008). Here, we summarize the shared characteristics of the guidelines from different organizations. First, the decision trees are designed to ease administration and to promote effective communication between the stakeholders. Answering yes/no questions ensures a swift disaster response. Secondly, a decision tree tends to yield a single option. If the market conditions are suitable, then cash distribution is selected. This approach relies on prior pilot studies, which reveal that cash interventions are more cost-effective than vouchers and in-kind. Operational efficiency is critical for aid agencies operating in developmental contexts with tightly constrained budgets (Aflaki and Pedraza-Martinez, 2016). However, this myopic approach may compromise food security because of misuse of cash by the beneficiaries.

Emergency response efforts are usually short-term, so multiple modalities may not be feasible due to the required infrastructure investment (e.g., cash distribution systems). On the other hand, food aid efforts have been ongoing in certain regions of the world. Better solutions can be achieved by combining several options instead of selecting the single option suggested by a decision tree. Another downside of trees is that they cannot be used for *ex-ante* comparison of the options. In the event of changes in the environment (price changes, market failures, etc.), the expected financial and nutritional outcomes cannot be assessed by trees. However, mathematical models can be used for such scenario analyses and provide more robust solutions.

## 2.2. Field Studies on Effectiveness of Cash and Vouchers

The prioritization of cash in decision trees is in line with field studies that examine the effects of different options. Save the Children (2005) compares four case studies conducted in Ethiopia, Lesotho, Mozambique, and Zambia. The analysis reveals that cash distribution enables families to purchase more nutritious but more expensive food. Das (2005) compares different cash transfer programs incentivizing outcomes such as increasing school attendance and decreasing child labor.

Some field studies explore the modality selection problem via randomized controlled trials. The treatment groups receive one type of aid and the control groups receive another, so that the outcomes can be compared. Studies in Malawi (Harnett, 2008) and in Congo (Aker, 2014) favor cash distribution because of the low distribution costs in these areas. According to Hidrobo *et al.* (2014), vouchers are the most cost-effective option in terms of costs and nutritional outcomes, but beneficiaries find them restrictive. Skoufias *et al.* (2011) find that cash-only policies are insufficient for nutritional purposes, especially in terms of micronutrients. Basu (1999) states that people are unwilling to make sacrifices for outcomes in the distant future: they prefer to spend on non-urgent items instead of saving money. The author indicates that people lack self-control and tend to misuse assets. The advantages and disadvantages of the three modalities derived from the literature are summarized in Table 1, which gives the basis for the main assumptions underlying our model.

Table 1 Advantages and disadvantages of aid modalities

| | In-kind | Vouchers | Cash |
|---|---|---|---|
| **Advantages** | • Applicable even if food is not available in local markets or the markets are not functioning well (e.g., delays and disruptions in the value chain, inflated market prices due to lack of competitors).<br>• The only option for drought- or famine-related emergency interventions.<br>• Significantly more nutritious than other options because distributed grains are fortified with nutrients. | • Enable the purchase of fresh food.<br>• Wealth is transferred to local retailers and producers, so other low-income groups (farmers, retailers) are supported alongside the beneficiaries.<br>• No logistics cost since no commodity distribution. | • Enables the purchase of fresh food.<br>• Wealth is transferred to local retailers and producers, so other low-income groups (farmers, retailers) are supported alongside the beneficiaries.<br>• No logistics cost since no commodity distribution.<br>• No need for contracts with local retailers. |
| **Disadvantages** | • Requires effective management of complex supply chains: high overhead costs.<br>• May hamper local food production.<br>• Food is fortified but cannot satisfy all nutritional needs; other products needed for support. | • Requires a well-functioning market and adequate food supply near beneficiaries.<br>• Valid for specified commodities, so the availability of those commodities may decrease, or their prices may increase with excessive voucher distribution.<br>• Significant vendor management incurring high operational costs. | • Requires a well-functioning market and adequate food supply near beneficiaries.<br>• May compromise food security and nutrition if spent on non-food or non-nutritious items.<br>• High fixed costs and initial operational burden; requires financial infrastructure, especially in rural areas. |

### 2.3. Literature on Modeling

Cash gives beneficiaries freedom of choice. The agency has little or no control over how the beneficiaries spend. Therefore, it is essential to incorporate beneficiary consumption behavior into the model. In a bilevel optimization approach, the agency decides the amount and type of aid, and then the beneficiary decides how to use it. Both the agency and the beneficiaries optimize their objectives. In an approach similar to ours, Wang and Lootsma (1994) build a resource allocation model for multiple departments, where each department maximizes the gains claimed, and the decision-maker maximizes the total profits. Wu *et al.* (2016) use the same approach to evaluate potential gains from mergers.

Although bilevel optimization problems have many applications, including energy production and hazmat transportation, they have not often been applied to humanitarian logistics. One of the few examples is the work of Camacho-Vallejo *et al.* (2015), who consider the international aid planning problem in a post-disaster setting, where the international community minimizes the response time and the local government minimizes the cost of delivering the aid. We believe that bilevel models are appropriate for humanitarian logistics since aid efforts almost always have a hierarchical structure: the agency is the leader and the beneficiaries are the followers.

In bilevel problems the goals of the two parties conflict. In our context, the beneficiaries' spending choices are determined by the utility of the consumption of certain items. Moreover, the goal of the agency is not straightforward. Cost minimization is a concern, but Holguín-Veras *et al.* (2013) argue that it is unproductive to address complex humanitarian problems without comprehensive objective functions. Recent studies on humanitarian logistics consider cost minimization in addition to minimizing response time (Vanajakumari *et al.*, 2016), stock-outs (Jahre *et al.*, 2012), or casualties (Salmerón and Apte, 2010). The efficient allocation of limited resources in the presence of conflicting goals for different stakeholders can be achieved by the adoption of social welfare cost functions. The dynamic aid allocation model with multiple receiving countries (Carter *et al.*, 2015) provides a good example of a social welfare function. We also consider the welfare of all the stakeholders: the agency, beneficiaries, and non-beneficiaries.

## 3. Food Aid Modality Selection (FAIMS)

The FAIMS problem involves the strategic decision of an aid agency concerning the quantity and type of aid to be provided to different beneficiary groups in a jurisdiction. The beneficiaries decide how to spend cash aid; the agency does not control that. Thus, the agency must consider the beneficiaries' expenditure patterns beforehand. We formulate this via a bilevel optimization model: an upper-level (leader) model for the agency and a lower-level (follower) model for the beneficiaries. In this section, we first describe the agency's problem, then we summarize the beneficiaries' expenditure behavior underpinning their decisions. Finally, we formulate the FAIMS problem by combining these two components.

## 3.1. Upper-Level Model: Agency's Perspective

### 3.1.1. Social Welfare Objective Function

Humanitarian logistics problems provide more inclusive solutions if they have a social welfare objective rather than merely focusing on costs (Holguín-Veras *et al.*, 2013). This holistic approach is one of the main factors that distinguish humanitarian agents from the private sector. Donation-based agencies aim to minimize their costs, but they also need to incorporate the benefits to the other stakeholders: the beneficiaries and non-beneficiaries in the local economy. We reflect these three perspectives through three objectives: minimizing the program costs, maximizing the nutritional state of the beneficiaries, and maximizing the contribution of the program to the economy.

***The program costs*** include the fixed costs to build or maintain the distribution infrastructure and the variable costs (operational and procurement costs). ***Improved nutrition*** is the contribution of the program from the beneficiary well-being perspective. Micronutrient deficiencies cause serious illnesses that impose additional malnutrition treatment costs on local governments and humanitarian agencies. A well-designed food aid program provides these micronutrients before malnutrition-related illnesses emerge. ***Contribution to the local economy*** captures the economic effect of the program on the local food producers and retailers.

### 3.1.2. Agency Constraints

The agency's main goal is to provide to each household sufficient food for a healthy lifestyle. Regardless of the modality, the first need is to satisfy calorie intake requirements. Another issue concerns voucher distribution in relatively isolated markets. Vouchers are valid only for selected items in selected stores. Thus, there can be disruptions to the value chain of voucher-admissible commodities (Michelson *et al.*, 2012). Prices may spike due to limited supply and harm non-beneficiaries or supplies may run out, harming both groups. Vouchers should therefore be limited so that market prices and availabilities are not adversely affected (Gentilini, 2007).

## 3.2. Lower-Level Model: Beneficiary's Perspective

An important concern within the humanitarian community is the possibility of misuse of cash by beneficiaries (Heaslip *et al.*, 2016). They may spend on non-nutritious commodities (e.g., soft beverages, alcohol, tobacco). Therefore, aid agencies should be aware of the risk of misuse when opting for a cash program.

### 3.2.1. Beneficiary Constraints

The beneficiary's problem follows the agency's decision. The agency must take into account the beneficiary's perspective when choosing the modality. This is why the beneficiary model is the lower-level problem. If the beneficiaries receive in-kind or voucher aid, we assume that they fully consume it. On the other hand, they allocate cash aid so as to maximize their utility while respecting the calorie-consumption constraint. Jensen and Miller (2010) observe that beneficiaries seek satiation: extremely poor households consume sufficient calories to achieve a certain subsistence level, if they have sufficient funds. They maximize their utility subject to the subsistence constraint, and we incorporate this into our beneficiary model. Although expecting beneficiaries to know how many calories they need to satisfy the subsistence constraint may seem unrealistic, when people feel hungry they know they have not consumed enough food (Douglas and Peggy, 2006).

### 3.2.2. Beneficiary Objective

Defining the exact expenditure pattern of beneficiaries *a priori* is challenging, but consumer theory models provide insights. Neoclassical consumer theory assumes that a household's objective is to maximize utility. This is achieved by the consumption of the purchased items and services subject to the budget available. The main underlying assumption is that individuals are rational and capable of understanding and maximizing their utility (Felder, 1988). The available commodities can be grouped into three categories based on observed commonalities in beneficiary diets: ***basic***, ***tasty***, and ***temptation*** foods. Extremely poor households rely on diets that consist of ***basic foods*** such as bread, potato, maize, and rice (Loftas, 1995). Basic foods are usually rich in carbohydrates and cheaper than other sources of nutrition such as meat and dairy products. Basic food lacks many micronutrients and should be supported by other food groups such as vegetables and meat. These more nutritious foods are also tastier. When poor households receive extra income, they favor better-tasting but more expensive options, keeping their overall calorie intake constant (Subramanian and Deaton, 1996). This indicates that a higher utility is associated with ***tasty food***. A third group, ***temptation food***, represents beneficiary expenditure on non-nutritious items such as coffee, tea, soda, and alcohol. We must include such expenditure to adequately capture spending patterns.

### 3.3. Parameters and Decision Variables

In this section, we explain the parameters and variables needed to formulate the problem.

***Beneficiary Parameters***

We model the households by distinguishing them based on their preferences (or utility functions). Let $h \in \{1, \ldots, |H|\}$ be different household types with different preferences for food items $I = \{1{:}\, basic\ food,\ 2{:}\, tasty\ food,\ 3{:}\, temptation\ food\}$. These preferences may be affected by spatial factors or the gender of the head of household (Gentilini, 2007). Moreover, each beneficiary region $r \in \{1, \ldots, |R|\}$ may differ in terms of the cost of delivering the aid, the availability of food, the market prices, etc. In region $r$, we assume that all beneficiaries residing in household type $h$, with total population $\pi_{hr}$, receive the same type of aid.

***Cost Parameters***

Let $G$ be the set of aid modalities, $g \in G = \{1{:}\ in\text{-}kind,\ 2{:}\ voucher,\ 3{:}\ cash\}$. There are two costs associated with each modality $g$: fixed costs ($c_{0g}$) and variable costs ($c_{rg}$). The fixed costs represent the initial investment to implement the program in a region. Thus, they are paid if at least one household is served by the program with the corresponding modality. For in-kind ($c_{01}$), the fixed costs include warehouse rents and staff costs. For vouchers ($c_{02}$), they include the staff costs incurred to determine reliable retailers. For cash ($c_{03}$), these costs are incurred by the cash provider (mobile money operators, banks, government safety net programs, etc.). The variable costs are required for each unit of aid to be distributed and may depend on the region. The in-kind variable costs ($c_{r1}$) are the procurement, storage, handling, and transportation costs. The voucher variable costs ($c_{r2}$) include printing and distribution costs. The main component is the payments made to retailers in exchange for redeemed vouchers. The cash variable costs ($c_{r3}$) are the commissions paid to the cash provider for the transactions.

***Market Parameters***

In rural areas, markets are located near major roads or population centers, and there may not be a market in every region. However, for cash and vouchers, there should be a market $m \in \{1, \ldots, |M|\}$ sufficiently close to the beneficiaries. Cash and voucher distribution costs may differ, especially if commodity prices fluctuate across markets. Our model therefore tracks commodity costs by market ($p_{mi}$). Let $\beta_{rm}$ be a binary parameter that indicates whether or not market $m$ is the closest to the beneficiaries in region $r$. Using a data preprocessing procedure, we can define the commodity prices in a region as $p_{ri} = \beta_{rm}\, p_{mi}$. As explained previously, one of the drawbacks of voucher distribution is the resulting pressure on supply chains. Since the agencies contract with a limited number of retailers for a limited number of items in each region, the demand for these commodities spikes and causes food shortages threatening the overall population ($\kappa_m$) in that region. To avoid this, we introduce a cap on the proportion of beneficiaries receiving service from a single market ($\Pi$). The final parameter associated with the markets is the economic contribution generated as a spill-over effect ($\Lambda$) of the cash and vouchers spent. When this effect is present, one dollar spent in the local economy improves the livelihoods of local farmers and retailers by a factor of $1+\Lambda$ (FAO, 2016).

### *Nutrition Parameters*

Nutrition parameters are included in our model to measure the nutritional benefits of the program. The beneficiary model takes into account the calorie-intake requirement of the beneficiaries. However, the consumption of certain vitamins and minerals on a regular basis is also essential. Their absence has serious effects, including the retardation of physical and mental development, chronic illnesses, reduced productivity, and eventually death (Caulfield *et al.*, 2006; Ezzati *et al.*, 2006). If malnutrition is not prevented, the burden on the health system increases considerably. By keeping track of the nutrient deficiency alleviated by an aid program, one can estimate the future savings from the costs of malnutrition treatment via supplements and medicines, the costs of hospitalization, and eventually the loss of human capital by death (Shaw, 2011). Let $k \in \{1, \dots, |K|\}$ be the set of micronutrients. If a person ingests sufficient quantity of a micronutrient ($\Theta_k$) by consuming food (i.e., $\sum_{i \in I} \theta_{ik}$), malnutrition related to that nutrient is prevented, yielding future savings ($\tau_k$).

### *Decision Variables*

In-kind aid is confined to basic food because it is high in calories, durable, and inexpensive. In the FAIMS model, there is a decision variable for each modality, representing the amount distributed to all households of type $h$ in region $r$: $x_{hr}$ for in-kind aid, $y_{hri}$ for voucher aid of food type $i$; and $z_{hr}$ for cash aid. Given an aid bundle ($x_{hr}$, $y_{hri}$, $z_{hr}$), the households $h$ in region $r$ choose their level of consumption of each food type $i$, $q_{hri}$. They directly consume the in-kind and voucher aid and purchase items of price $p_{ri}$ with the cash aid. They derive a utility $\phi_{hri}$ for each unit of consumption of item *i*. In addition, we define a binary variable, $s_{hrk}$, indicating whether or not nutrient *k* is adequately consumed by each household in each region. Finally, binary variables, $w_g$, are defined to account for the fixed cost components of each modality in the objective function.

### 3.4. FAIMS Model

In this section, we present the bilevel mixed integer formulation of the FAIMS problem.

## Sets

| | |
|---|---|
| $H$ | Set of household types, $H$={1, …, \|$H$\|} |
| $I$ | Set of food types, $I$={1: basic, 2: tasty, 3: temptation} |
| $R$ | Set of regions, $R$={1, …, \|$R$\|} |
| $M$ | Set of markets, $M$={1, …, \|$M$\|} |
| $K$ | Set of micronutrients, $K$={1: calories, …, \|$K$\|} |
| $G$ | Set of modalities, $G$={1: in-kind, 2: voucher, 3: cash} |

## Parameters

| | |
|---|---|
| | *Cost Parameters* |
| $c_{0g}$ | Annual fixed costs to distribute modality $g \in G$ |
| $c_{rg}$ | Variable costs of distributing modality $g \in G$ in region $r \in R$ |
| | *Market Parameters* |
| $p_{mi}$ | Price of item $i \in I$ in market $m \in M$ |
| $\beta_{rm}$ | Set to 1 if market $m \in M$ is the closest to region $r \in R$, and 0 otherwise. |
| $p_{ri}$ | Price of item $i \in I$ in region $r \in R$ |
| $\kappa_m$ | Population served by market $m \in M$ |
| $\Pi$ | Percentage of beneficiaries that can receive service from a single market |
| $\Lambda$ | Spill-over effect coefficient |
| | *Nutrition Parameters* |
| $\theta_{ik}$ | Amount of nutrient $k$ in one unit of item $i \in I$ |
| $\Theta_k$ | Required daily intake of nutrient $k \in K$ |
| $\tau_k$ | Deficiency-related cost savings per person for nutrient $k \in K$ |
| | *Other Parameters* |
| $T$ | Planning horizon |
| $L$ | Sufficiently large number |
| $\alpha,\beta,\gamma$ | Weights of objective function components, $\alpha+\beta+\gamma = 1$ |
| | *Beneficiary Parameters* |
| $\phi_{hri}$ | Taste acquired by unit consumption of item $i \in I$ by household $h \in H$ in region $r \in R$ |
| $\pi_{hr}$ | Population of household $h \in H$ in region $r \in R$ |

## Decision Variables

| | |
|---|---|
| $x_{hr}$ | In-kind aid distributed to all households of type $h \in H$ in region $r \in R$ |
| $y_{hri}$ | Voucher amount for item $i \in I$ distributed to all households of type $h \in H$ in region $r \in R$ |
| $z_{hr}$ | Cash aid distributed to all households of type $h \in H$ in region $r \in R$ |
| $q_{hri}$ | Total consumption of item $i \in I$ by all households of type $h \in H$ in region $r \in R$ |
| $s_{hrk}$ | Set to 1 if households of type $h \in H$ in region $r \in R$ satisfy nutrient requirement $k \in K$; and 0 otherwise. |
| $v_{hr}$ | Set to 1 if vouchers are distributed to household type $h \in H$ in region $r \in R$; and 0 otherwise. |
| $w_g$ | Set to 1 if modality $g \in G$ is distributed; and 0 otherwise. |

## Mathematical Formulation

*Upper Level:*

$$\max \left(\sum_{h\in H}\sum_{r\in R}\sum_{k\in K}\pi_{hr}\tau_k s_{hrk}\right)$$
$$\max \left((1+\Lambda)\left(\sum_{h\in H}\sum_{r\in R}\sum_{i\in I} y_{hri}p_{ri} + \sum_{h\in H}\sum_{r\in R} z_{hr}\right)\right) \quad (1)$$
$$\min \left(\sum_{g\in G} c_{0g}w_g + \left(\sum_{r\in R}\sum_{h\in H} c_{r1}x_{hr} + C_{r2}\left(\sum_{i\epsilon I} y_{hri}\right) + c_{r3}z_{hr}\right)\right)$$

*s.t.*

$$\theta_{11}\left(x_{hr} + \frac{z_{hr}}{p_{r1}}\right) + \sum_{i\in I}\theta_{i1}y_{hr1} \ge T\,\Theta_1\pi_{hr} \qquad \forall h \in H, \forall r \in R \quad (2)$$
$$\sum_{i\in I}\theta_{ik}q_{hri} - T\,\Theta_\mathrm{k}\,\pi_{hr} \le L\,s_{hrk} \qquad \forall h \in H, \forall r \in R, \forall k \in K \quad (3)$$
$$T\,\Theta_\mathrm{k}\,\pi_{hr} - \sum_{i\in I}\theta_{ik}q_{hri} \le L(1 - s_{hrk}) \qquad \forall h \in H, \forall r \in R, \forall k \in K \quad (4)$$
$$x_{hr} \le L\,w_1 \qquad \forall h \in H, \forall r \in R \quad (5)$$
$$y_{hri} \le L\,w_2 \qquad \forall i \in I, \forall h \in H, \forall r \in R \quad (6)$$
$$z_{hr} \le L\,w_3 \qquad \forall h \in H, \forall r \in R \quad (7)$$
$$\sum_{i\in I} y_{hri} \le L\,v_{hr} \qquad \forall h \in H, \forall r \in R \quad (8)$$
$$\sum_{h\in H}\sum_{r\in R}\beta_{rm}\pi_{hr}v_{hr} \le \Pi\kappa_m \qquad \forall m \in M \quad (9)$$
$$x_{hr}, y_{hri}, z_{hr} \ge 0 \qquad \forall i \in I, \forall h \in H, \forall r \in R \quad (10)$$
$$s_{hrk}, w_g, v_{hr} \in \{0,1\} \qquad \forall h \in H, \forall r \in R, \forall g \in G, \forall k \in K \quad (11)$$

*Lower Level:*

$$max\, f(q_{hri}) = \sum_{i\in I}\sum_{h\in H}\sum_{r\in R} \phi_{hri} q_{hri} \tag{12}$$

*s.t.*

$$\sum_{i\in I} \theta_{i1} q_{hri} \geq \Theta\pi_{hr} \qquad \forall h \in H, \forall r \in R \tag{13}$$

$$q_{hr1} \geq y_{hr1} + x_{hr} \qquad \forall h \in H, \forall r \in R \tag{14}$$

$$q_{hr2} \geq y_{hr2} \qquad \forall h \in H, \forall r \in R \tag{15}$$

$$q_{hr3} \geq y_{hr3} \qquad \forall h \in H, \forall r \in R \tag{16}$$

$$p_{r1}(q_{hr1} - y_{hr1} - x_{hr}) + p_{r2}(q_{hr2} - y_{hr2}) + p_{r3}(q_{hr3} - y_{hr3}) \leq z_{hr} \qquad \forall h \in H, \forall r \in R \tag{17}$$

$$q_{hri} \geq 0 \qquad \forall i \in I, \forall h \in H, \forall r \in R \tag{18}$$

The first component of the objective (objective 1) measures the improvements in the nutrition of the population in terms of the averted health care costs. If household type *h* in region *r* consumes a sufficient quantity of nutrient *k* ($s_{irk}=1$), then future malnutrition treatment costs are averted for that household. The second component (objective 2) measures the total contribution of the aid program to the local economy. Finally, the third component (objective 3) measures the total fixed and variable costs of the program. The three components of the objective function can be weighted (by $\alpha$, $\beta$, $\gamma$, respectively) and combined to reflect the decision-maker's overall preferences since they are all measured in monetary terms.

In the upper-level problem, constraints (2) ensure that each household receives sufficient aid to satisfy their calorie-consumption constraints (13) in the lower-level model. In other words, this constraint reinforces the mandate of the agency and also prevents the lower-level model from being infeasible. Constraints (3) and (4) determine whether or not the households are consuming sufficient micronutrients. Constraints (5), (6), and (7) measure the fixed costs associated with in-kind, voucher, and cash distribution, respectively. Constraints (8) and (9) limit the number of people redeeming vouchers in a single market. Constraints (10) and (11) define the domains of the variables.

The optimal solution of the lower-level problem represents the consumption bundles of food commodities that maximize the total utility derived by each household type in every region. The first priority of the beneficiaries is to achieve sufficient calorie intake to maintain daily activities. This level is denoted by $\Theta$ and is defined per person.

Constraints (13) ensure that the total calories of the consumed foods are sufficient for the household. Constraints (14)–(16) ensure that the voucher and in-kind aid is consumed by the household. Constraints (17) ensure that the consumption of the beneficiaries does not exceed the amount of aid provided. Constraints (18) are non-negativity constraints.

Bilevel problems often require sophisticated algorithms (Bard, 1998). However, we exploit the fact that our lower-level problem is a linear program. By constructing the Karush–Kuhn–Tucker optimality conditions of this lower-level problem, we obtain a single-level problem that is equivalent to the original one and can be solved by an efficient commercial solver. The details are provided in Appendix A.

# 4. Case Study: WFP Kenya

In this section, we illustrate how the FAIMS model can be used to design aid programs through the lens of the world's largest humanitarian organization, United Nation's WFP. We provide a numerical analysis based on its operations in Kenya. Each year WFP reaches 80 million people in 80 countries with food assistance and distributes more than 2 million metric tons of in-kind aid (WFP, 2018b). Since 2008, the relative share of cash and vouchers has increased considerably. In 2017, WFP provided US $1.3 billion in cash transfers worldwide (WFP, 2018a). WFP would like to further increase cash- and voucher-based assistance and eventually graduate all the beneficiaries from in-kind aid programs.

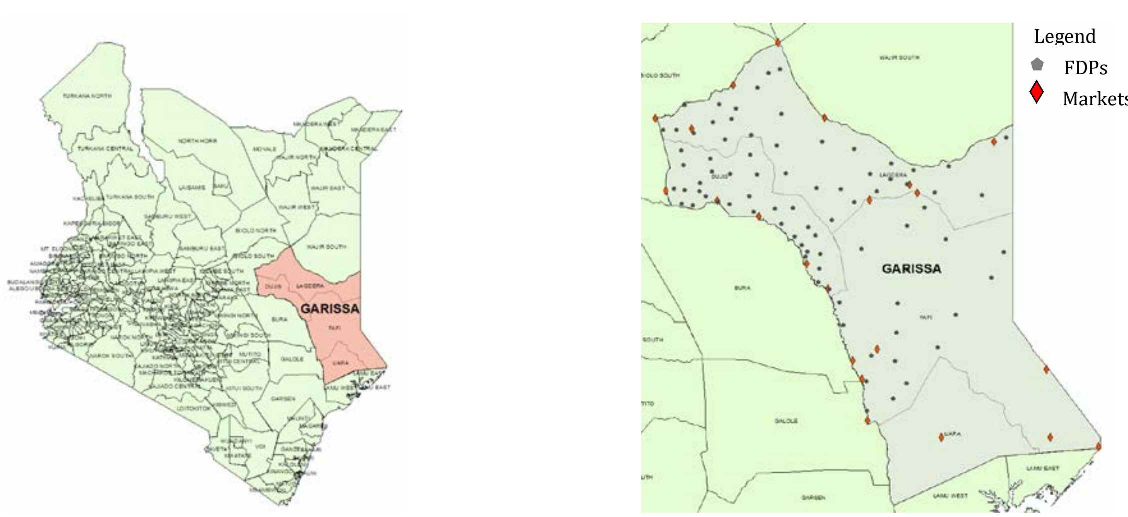
## 4.1. WFP Kenya's In-kind Aid Distribution Network

We selected the Garissa county in Kenya for our analyses for three reasons. First, WFP already has a cash program in Dadaab refugee camp, located in Garissa. This allows us to estimate cash distribution costs more realistically. Second, Garissa is considered an undesirable destination because of security and road-quality concerns, so reducing in-kind operations is an attractive option. Finally, there are numerous markets within an acceptable distance of the beneficiary settlements, therefore Garissa is a good candidate for cash and voucher distribution.

It is vital to develop a proper understanding of the humanitarian context to achieve applicable and impactful methodological developments (Van Wassenhove, 2006; Pedraza Martinez *et al.*, 2011). We went on a field-trip to develop a solid understanding of food aid distribution from an operational perspective before the modeling phase.

We gathered data from the WFP Kenya logistics office. In addition, we used reports that are available online in the WFP's database. Parameter estimation for a realistic program design requires a tremendous effort, which we explain in detail in the *online companion*. Here, we briefly give the overall data structure for each parameter group described in Section 3.3.

WFP provides in-kind aid to vulnerable households through final delivery points (FDPs), which are temporary structures close to the settlements. The beneficiaries walk to the FDPs and collect their monthly rations, approximately 50 kg of food. Since the FDPs are located close to the beneficiaries (Rancourt *et al.*, 2015), we clustered the beneficiaries around them, and we divided the county into regions ($r \in R$) accordingly. We described each region using two parameters provided by WFP: the coordinates and the number of beneficiaries receiving service at each FDP. In Figure 1, the locations of the 68 FDPs serving 112,402 beneficiaries, and the 22 markets are depicted. For each market $m \in M$, the commodity price for item $i \in I$, is defined as $p_{mi}$.




(a) Garissa county on Kenya map

(b) FDP and market locations in Garissa

Figure 1 GIS maps depicting Garissa data

The beneficiaries are also grouped by their household types, $h \in H$. This allows us to model spending behavior more realistically. In a feasibility analysis of cash- and voucher-based interventions, WFP determined the types and prevalence of the households in the arid parts of Kenya (WFP, 2013). Table 2 shows the types of households in the Garissa county, their prevalence, and the average number of people in each household type, $h \in H$ = {1:

male-headed polygamous, 2: male-headed monogamous, 3: female-headed}. Using historical aid distribution data from WFP and the household prevalence statistics, we can allocate the beneficiaries to household types and estimate how many beneficiaries are living in household type *h* in region *r* ($\pi_{hr}$). The utility functions for each household type ($\phi_{ihr}$) are determined based on the expenditure survey conducted by WFP Kenya (WFP, 2013).

Table 2 Household statistics for Garissa county

| Household Type | Percentage | Average Population per Household |
|---|---|---|
| Male-headed polygamous | 40 | 15 |
| Male-headed monogamous | 35 | 8 |
| Female-headed | 24 | 7 |

To estimate the parameters associated with the nutrition outcomes we focus on the most common micronutrient deficiencies in Sub-Saharan Africa (SSA), namely vitamin A, iron, iodine, and zinc deficiencies ($\theta_{ik,}\,\Theta_k$) (Caulfield *et al.*, 2006; Ezzati *et al.*, 2006). The prevalence and the associated treatment costs ($\tau_k$) are estimated using information from the Global Burden of Disease Database (Institute for Health Metrics and Evaluation, 2017). Finally, the costs associated with in-kind ($c_{01,}\,c_{r1}$) and cash ($c_{03,}\,c_{r3}$) distribution are directly collected from WFP reports (WFP, 2016), and the voucher costs ($c_{02,}\,c_{r2}$) are estimated based on a voucher program operated by Action Against Hunger in the Garissa county (Dunn, 2009).

### 4.2. Minimizing program costs

In this section, we solve the FAIMS model with the cost objective using Garissa data ($\alpha=0, \beta=0, \gamma=1$) as the base case. The solution enables us to evaluate the current WFP program from the cost perspective. Then, we perform sensitivity analyses on selected cost parameters—local market prices, voucher fixed costs, and in-kind distribution costs—to evaluate the robustness of the results found in the base case.

Currently, WFP solely distributes in-kind aid under the general distribution program in Garissa. First, we investigated whether or not in-kind aid is the cheapest option. We found that the in-kind program is indeed optimal from the cost perspective (see the first bars in Figures 3a and 3b). This is expected, since WFP's unit in-kind costs including procurement, storage and transportation expenses (maximum $0.79/kg for maize) are cheaper than the local market prices (minimum $0.84/kg for maize).

Figure 2 shows the price index of maize in different markets in Garissa. It shows that maize prices are prone to significant variations over time, and these do not follow a clear seasonal pattern. For example, a 120% change in six months is observed in the main markets between January and July 2009 (yellow line in the color print). To understand the robustness of the optimal FAIMS solutions to such price fluctuations, we changed the local prices in 10% decrements and found the minimum-cost program design at each price level. A 90% decrease may seem unlikely, but it is within the observed fluctuation range.

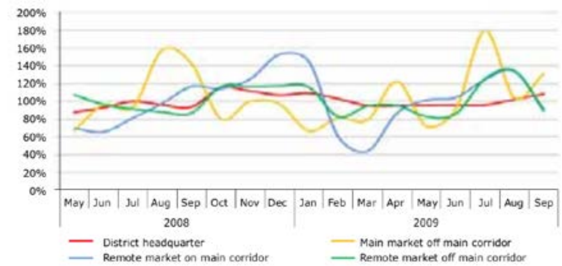
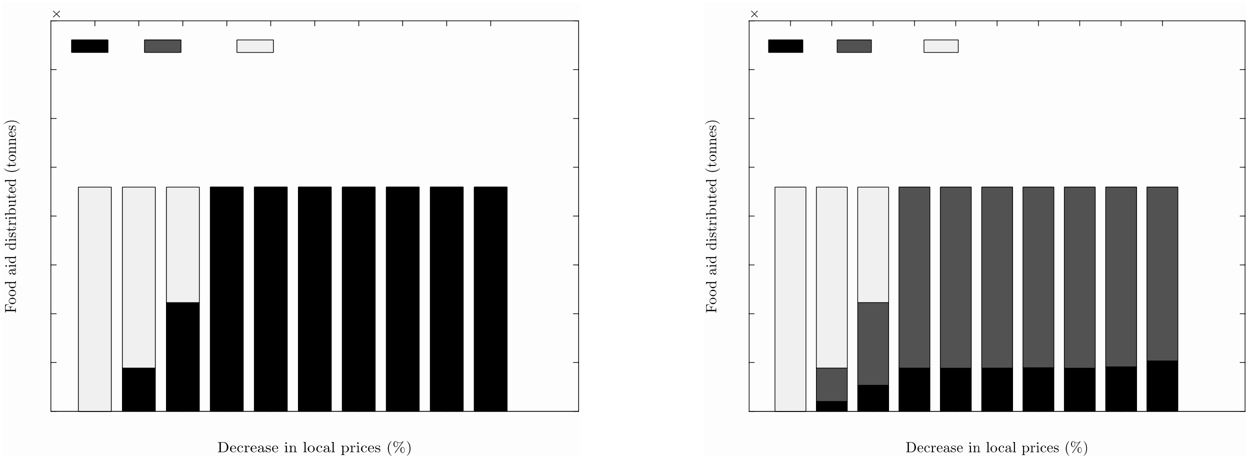



Figure 2 Seasonal index: maize retail prices in northeastern corridor
Source: WFP (2013).

Figure 3a shows the results of this sensitivity analysis. Each bar represents the total tonnage and type of the aid distributed as the retail price decreases in the local markets. For a direct comparison between tonnage-based aid (in-kind and voucher) and cash distribution, we report the tonnage of consumed food provided by the lower-level model. The first column indicates that with the effective commodity prices, all aid is distributed in-kind. Note that, even a 10% decrease in these local market prices introduces some cash distribution and at 30% decrease, all the beneficiaries receive cash.




(a) As local commodity prices decrease

(b) No fixed costs associated with vouchers

Figure 3 Sensitivity of the optimal quantity and type of aid distributed.

As the local prices decrease, FAIMS proposes a transformation from in-kind to cash, and vouchers are not distributed at all. The main reason for this may be the high fixed costs associated with vouchers in the Kenyan context. To test this hypothesis, we set these costs to zero and gradually decrease the local commodity prices. As shown in Figure 3b, vouchers are now provided, but they do not completely replace cash. This is because of the market-capacity constraint on vouchers, i.e., constraints (8) and (9); we observed a complete switch from in-kind to vouchers when that constraint was relaxed. While eliminating the fixed costs makes the vouchers more favorable, the total program cost decreases by only 1%, and the malnutrition treatment and economic contributions are unchanged.

Many studies claim that cash and vouchers are cost-effective, which contradicts our results. It must be notes that, WFP receives most commodities as donations its supply chain is one of the most efficient among all the humanitarian agencies. It has operated in Kenya for decades and developed long-term relationships with suppliers within the country. In 2014 its operational costs were $794/tonne. For comparison, USAID’s 2018 fact sheet reports a $64.3M budget for Kenyan operations, 70% of which is spent on 51,150 tonnes of in-kind distribution (USAID, 2018). Adjusting these numbers to 2014 dollars gives an estimate of $868/tonne. Note that USAID partners with WFP and benefits from WFP’s infrastructure; the costs would likely be higher for a non-partner agency. Thus, for other agencies in the same region, cash and vouchers may indeed be cost-effective.

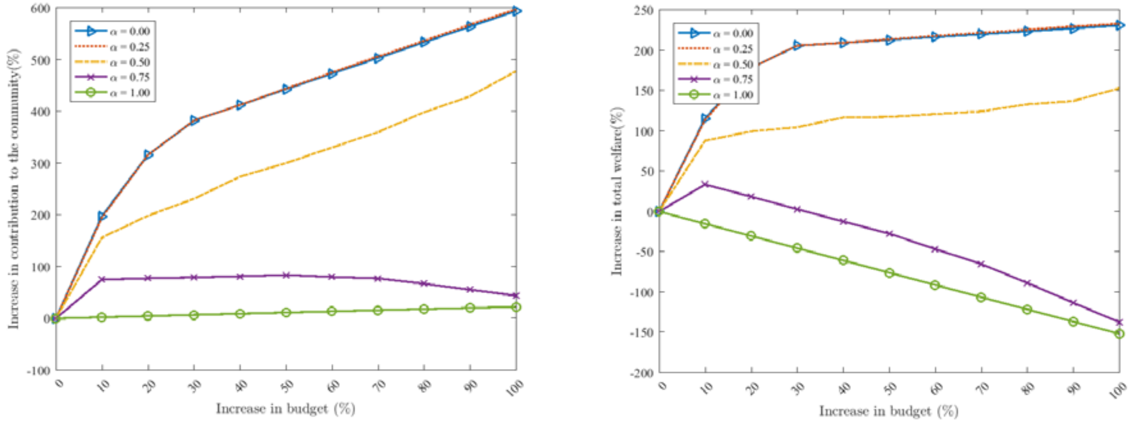
# 5. Policy Evaluation

In-kind aid is the cheapest for the Garissa county, but its contribution to the local economy is negligible and the micronutrient deficiencies are not completely avoided. In this section, we examine three approaches for improving the well-being of the beneficiaries and the non-beneficiaries: increases to the program budget, education about nutrition, and centralized fortification of the basic food.

## 5.1. Increases to Program Budget

Our previous results show that the minimum annual budget for distributing sufficient aid to all the beneficiaries in Garissa is about $18.2 million. To measure the potential improvements in terms of nutrition and economic contribution, we solve FAIMS with a weighted combination of these two objectives, while increasing the budget by up to 100% in 10% increments. We use a multi-criteria approach to combine them, adapting the reference point method (Clímaco *et al.*, 2006) for generic multi-criteria problems. Using absolute minimum and maximum bounds on each criterion, we normalize the multi-criteria objective function, and we generate alternative optimal solutions by altering the weight of these two objectives. For these experiments, we define the weights of the nutrition objective to be $\alpha = \{0, 0.25, 0.5, 0.75, 1\}$ and the weights of the economic contribution to be $\beta = 1-\alpha$.

Our analyses reveal that the optimal solutions are sensitive to the weights. For $\alpha = (0.75, 1)$, i.e., a stronger emphasis on nutrition, the corresponding objective increases with the budget due to higher levels of in-kind aid distribution, which is fortified with micronutrients and therefore provides more nutritional benefits per dollar spent. However, contribution to the economy remains rather limited. For $\alpha = (0, 0.25)$, the economic contribution increases rapidly with the budget because more households receive cash. At a 30% budget increase, for these $\alpha$, the optimal program is a cash-only program. Consequently, the economic contribution continues to grow linearly in parallel with further budget increase, even if the amount distributed exceeds the demand for aid. The online companion gives the detailed aid distribution levels for all $\alpha$ values; here we discuss the policy implications of our analyses.




(a) Contribution of aid program to community

(b) Total welfare

Figure 4 Contribution to the community and total welfare changes as budget increases for different α values.

We compare the contribution of the program to the community and the total welfare generated by the program to fully comprehend the impact of budget increases under different α values. Figure 4a shows how the contribution of the program to the community, that is the combination of the nutrition and economic objectives change as the budget increases, under different weights. The contribution to the community grows with increasing budget, especially for $\alpha \geq 0.5$.

On the other hand, WFP pays to achieve these contributions to the community. If we take the program costs into account, we obtain the change in the total welfare generated by the program by combining the three objectives to reflect the perspectives of all three stakeholders. Figure 4b shows the change in the total welfare for all α values. Clearly, setting $\alpha \geq 0.75$ does not contribute to total welfare much since the nutrition objective, which yields limited monetary return in comparison to the economic contribution objective, is overemphasized. On the other hand, for $\alpha \leq 0.75$, a 10% budget increase significantly improves the total welfare. Furthermore, a 20% increase can be considered if WFP sets $\alpha \leq 0.5$. Ee provided detailed numerical results for $\alpha = 0.5$ in Appendix B. However, an increase beyond 30% is not worthwhile, regardless of the α value. To summarize, a budget increase can give significant improvements (up to 200%) in the total welfare, as long as WFP assigns a nonzero weight to the economic contribution. However, the total welfare function flattens or decreases beyond an increase of 30%.

### 5.2. Nutrition Education

In this section, we investigate the policy of educating households about dietary choices and nutrition, and we measure the effects on the total welfare. A market analysis conducted by WFP Kenya (WFP, 2013), revealed that female-headed households spend cash aid on nutritious food (prudent behavior), while male-headed households place alcohol in second place after food in their spending priorities (hedonistic behavior). We assume that an education program can convert households from hedonistic to prudent, valuing tasty food above temptation food.

Similar programs have been executed in Kenyan refugee camps (WFP, 2016), and beneficiaries change their food expenditure and improve their nutritional well-being after receiving the training. To study the impact in Garissa, we assume that the taste functions of male-headed households converge to those of female-headed households after the training, so males no longer purchase temptation items. We then re-solve the instances and compare the results with those from Section 5.1.

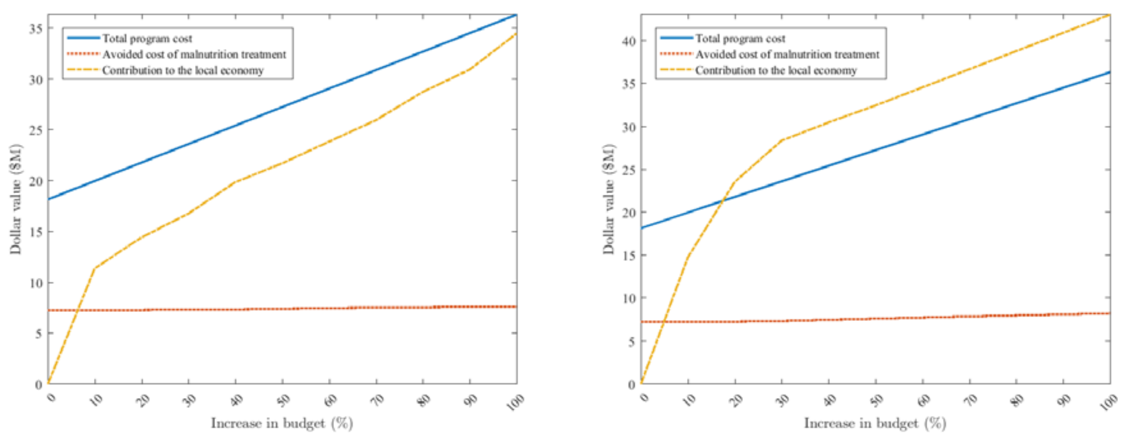
For $\alpha > 0.5$, we do not observe a deviation from the base case, since WFP mostly provides in-kind in these scenarios, and if cash is provided, it is only sufficient to cover the calorie constraint. Household type matters only when WFP provides more cash than calorie requirements, as is the case for instances with $\alpha \leq 0.5$. We provided detailed numerical results for $\alpha = 0.5$ in Appendix B. In these instances, the beneficiaries' taste functions determine how to spend the extra cash. Given a successful education program, the results show that WFP should distribute more cash, knowing that it will not be misused. In light of the expected economic contribution, an educational program targeting male-headed households should be considered if it costs less than $2 million.

### 5.3. Centralized Fortification of Staple Food

The food distributed by WFP is fortified with micronutrients. If WFP wants to phase out its in-kind aid operations, an important step would be lobbying the government for mass fortification of the local basic food. In this section, we investigate the effects of such a policy on the total welfare.

Food fortification occurs during the processing (milling, packaging, etc.) of grains: vitamins and minerals are added. The World Health Organization (WHO) lists fortification as one of four strategies to reduce nutrient deficiencies at the global level (WHO and FAO, 2006). In 2011, the Kenyan Government mandated the fortification of packaged maize flour with vitamin A, iron, and zinc. However, this did not occur immediately. Fiedler *et al.* (2014) estimated a fortification level of 28% after three years of the legislation, and a more recent report from the Kenyan Ministry of Health indicates that 40% of maize flour is fortified (Atinda, 2016). To study the impact of 100% fortification, we increased the local maize nutrition values to the fortified level and compared the outcomes with the unfortified case. In this analysis, we assume that the fortification costs are subsidized by the government.

With fortification, in-kind distribution decreases significantly. Figure 5 compares the objectives under the two policies (for numerical results see Appendix B). Under this policy, the program's contribution to the community surpasses the cost and leads to a positive total welfare. As discussed previously, the nutrition objective favors the cheaper and more nutritious in-kind modality, whereas the economic objective is maximized by a cash or voucher program. With fortification, the cash and voucher options contribute to both objectives simultaneously. Given the significant increase in the local economy and the improved nutrition in Garissa, the Kenyan Government should not hesitate to undertake mass fortification provided it costs less than $10 million.




(a) No fortification (b) Mass fortification

Figure 5 Nutrition and economic contribution changes with and without fortification.

## 6. Conclusions

In this study, we developed a model that enables decision-makers to choose aid modalities for different households. The model takes into account the welfare of all the stakeholders involved and accommodates them in the objective function. We built a bilevel optimization model to represent the hierarchical dynamics of the distribution activities between the beneficiaries and the agency. We then demonstrated how this model can be used to design an aid program and to evaluate different hunger response policies.

Our experiments for Garissa in Kenya showed that in-kind aid is the best option under the current cost structure and market prices. On the other hand, even a 10% decrease in local prices makes cash distribution a more cost-effective option for households near the main markets. We also established that for other aid agencies, which have higher in-kind distribution costs, cash is more cost-effective. We then evaluated three policies commonly adopted to improve nutrition.

One major contribution of our model is that it enables a program design where multiple aid types can be administered simultaneously. As explained by Gentilini (2007), a single-mode program is not necessarily optimal. A combination may provide superior outcomes, as shown by the scenarios in this paper. Another contribution of our model is that we incorporate the beneficiaries' consumption behavior by modeling them as economic agents maximizing their utility. In the literature, it is widely stated that cash transfers give the beneficiaries more choice. Numerous aid programs prefer to avoid the risk of cash misuse because donors are reluctant to support programs where the outcomes are uncertain (Devalkar *et al*., 2017). The FAIMS model can evaluate the outcomes of a cash distribution program while taking into account the potential for misuse. Overall, our model incorporates the objective function of every stakeholders and provide solutions that maximizes the total welfare. Such approaches are especially critical for studies conducted in developmental contexts because the aid programs tend to have much longer time-spans in contrast to disaster response programs. As a result, their effects on the community lasts longer.

This is a complex problem with many inter-connected factors and ever-changing dynamics, and any decision-making tool is prone to shortcomings. The literature states that the success of cash and voucher programs is closely tied to continuous monitoring of prices. Our experiments also show the importance of price monitoring by indicating the sensitivity of the results to the prices. We have access to point estimates of the local prices, and our analyses are only as robust as these estimates. Since we have designed our model for a strategic decision, we have not considered food price fluctuations throughout the year. However, an operational-level model would require such information. Furthermore, we assume in our model that beneficiaries consume all the aid that they receive. In reality, they can sell on in-kind aid or vouchers. Our assumption is reasonable since we mostly focus on relatively isolated communities. However, a future study for refugee settlements should definitely take selling behavior into account since it is commonly observed in such settings (WFP and UNHCR, 2012).

FAIMS is inspired by a food distribution setting, but with simple modifications it can be used for other aid programs. Similar problems arise in all areas of humanitarian efforts, including HIV protection, clothing and footwear distribution, malaria prevention, and clean-water solutions. Therefore, the model and outcomes discussed in this paper may find many applications. One example is insecticide-treated bed net distribution programs for malaria. By changing the malnutrition treatment costs to malaria treatment costs, we can easily adapt FAIMS to such programs.

Finally, a robust optimization approach can be used to model food supply shocks such as famines, which drastically increase the number of people in need of aid. These scenarios can be constructed based on rainfall and crop vegetation indexes. In addition, more diverse household types could be represented in the model within a robust optimization structure. Instead of assuming that all households of a specific type behave in a certain way, we could model different preferences in more detail. For example, a male-headed household may value nutrition more if there are toddlers or pregnant women present.

In conclusion, this study is a first step toward data-driven aid modality selection approaches based on analytical frameworks rather than guidelines and expert opinions. Cash and voucher programs seem to be promising tools for rapid and effective aid distribution, especially in development contexts. In our study, we provided an extensive summary of the literature, mainly composed of randomized trials and pilot studies on the effectiveness of these modalities. We present the existing operational challenges associated with each modality to the operations management community. We believe that these analyses inspire many researchers to work on aid modalities, a topic that receives increasing attention from humanitarian community, especially after the Syrian refuge crisis and conflicts in Sub-Saharan Africa.

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# Appendix A

The lower-level beneficiary model forms part of the upper-level constraints; however, it is a standalone optimization model with an objective function. Therefore, every feasible upper-level solution is required to be an optimal solution for the lower-level model. Bilevel problems are often difficult and require special algorithms such as double penalty function methods, rectangular partitioning, and sub-gradient descent methods (Bard, 1998). However, in many cases, exploiting the special features of the problem allows a simpler strategy. In our case, the lower-level beneficiary problem is a linear program. Thus, we can construct Karush–Kuhn–Tucker (KKT) optimality conditions for this problem and add these new conditions to the upper-level problem. This transformation yields a new single-level problem that is equivalent to the original one.

We can replace the lower-level model by the KKT optimality conditions, namely primal feasibility, dual feasibility, and complementary slackness. L*et* $\lambda$, $\mu$ *be* the dual variable vectors for constraints (13) and (17), and let $\gamma_i$ ($i \in \{1,2,3\}$) be the dual vector of consumption constraints (14), (15), and (16). The complementary slackness conditions of these constraints are:

$$\lambda_{hr}\left(\Theta\pi_{hr} - \sum_{i\in I}\theta_i q_{hri}\right) = 0 \qquad \forall h \in H, \forall r \in R \qquad (1)$$

$$\gamma_{hr1}(y_{hr1} + x_{hr} - q_{hr1}) = 0 \qquad \forall h \in H, \forall r \in R \qquad (2)$$

$$\gamma_{hr2}(y_{hr2} - q_{hr2}) = 0 \qquad \forall h \in H, \forall r \in R \qquad (3)$$

$$\gamma_{hr3}(y_{hr3} - q_{hr3}) = 0 \qquad \forall h \in H, \forall r \in R \qquad (4)$$

$$\mu_{hr}\left(z_{hr} - \left(p_{r1}(q_{hr1} - y_{hr1} - x_{hr}) + p_{r2}(q_{hr2} - y_{hr2}) + p_{r3}(q_{hr3} - y_{hr3})\right)\right) = 0 \qquad \forall h \in H, \forall r \in R \qquad (5)$$

The dual feasibility condition is:

$$\lambda_{hr}\theta_{i1} - \mu_{hr}p_{ri} + \gamma_{hri} + \phi_{hri} = 0 \qquad \forall h \in H, \forall r \in R, \forall i \in I \qquad (6)$$

Note that the complementary slackness conditions (1)–(5) are nonlinear. However, a constraint in the form $ab = 0$ can be linearized by replacing it with the two expressions $a \le Lu, b \le L(1-u)$, where $L$ is a sufficiently large number and $w$ is a binary variable (Fortuny-Amat and McCarl, 1981). Let us define such binary variable vectors $u_{hr}^1, u_{hr}^2, u_{hr}^3, u_{hr}^4, u_{hr}^5$ for the complementary slackness conditions. The linearization procedure generates two linear inequalities for each nonlinear constraint. As an example, the linear inequalities for constraint (1) are:

$$\lambda_{hr} \leq L\, u_{hr}^1 \qquad \forall h \in H, \forall r \in R \qquad (1')$$

$$\Theta\pi_{hr} - \sum_{i \in I} \theta_i q_{hri} \leq L(1 - u_{hr}^1) \qquad \forall h \in H, \forall r \in R \qquad (1'')$$

Since $u_{hr}^1$ is a vector of binary variables, the left-hand side of at least one of the inequalities above must be equal to zero, as intended by the nonlinear equation (1). If we apply this procedure to the remaining complementary slackness equations, we again obtain two linear inequalities for each nonlinear equation. We can express the bilevel FAIMS model as a single-level mixed integer problem by adding these constraints to the upper-level problem.

# Appendix B

Table 3 Objective function values and distributed aid modalities under different scenarios

| | Budget Increase ( in 1000$) | Program cost (in 1000$) | Economic contribution (in 1000$) | Avoided malnutrition (in 1000$) | Cash (in 1000$) | Voucher (tonne) | | In-kind (tonne) |
|---|---|---|---|---|---|---|---|---|
| | | | | | | basic | tasty | |
| Increasing program budget | 0 | 18,177 | - | 7,289 | - | - | - | 22,960 |
| | 10 | 19,995 | 11,396 | 7,289 | 9,265 | - | - | 13,330 |
| | 20 | 21,813 | 14,451 | 7,314 | 10,036 | 1,868 | 29 | 12,300 |
| | 30 | 23,630 | 16,787 | 7,364 | 10,080 | 4,136 | 11 | 12,199 |
| | 40 | 25,448 | 19,887 | 7,371 | 10,514 | 6,101 | 107 | 11,302 |
| | 50 | 27,266 | 21,735 | 7,438 | 9,810 | 9,168 | 13 | 11,564 |
| | 60 | 29,084 | 23,872 | 7,498 | 9,639 | 11,285 | 38 | 11,666 |
| | 70 | 30,901 | 25,987 | 7,550 | 9,200 | 13,967 | 9 | 11,645 |
| | 80 | 32,719 | 28,759 | 7,576 | 9,250 | 15,898 | 139 | 11,099 |
| | 90 | 34,537 | 30,956 | 7,628 | 8,998 | 18,378 | 80 | 11,128 |
| | 100 | 36,354 | 34,508 | 7,607 | 9,397 | 19,831 | 351 | 9,764 |
| Nutrition education | 0 | 18,177 | - | 7,289 | - | - | - | 22,960 |
| | 10 | 19,995 | 11,396 | 7,289 | 9,265 | - | - | 13,330 |
| | 20 | 21,813 | 15,235 | 7,289 | 12,311 | - | 19 | 11,604 |
| | 30 | 23,630 | 18,608 | 7,284 | 15,129 | - | 0 | 10,358 |
| | 40 | 25,448 | 20,498 | 7,351 | 13,590 | 3,533 | 16 | 10,596 |
| | 50 | 27,266 | 22,965 | 7,393 | 13,944 | 5,539 | 3 | 10,348 |
| | 60 | 29,084 | 25,025 | 7,447 | 12,864 | 8,694 | 19 | 10,401 |
| | 70 | 30,901 | 27,341 | 7,498 | 12,822 | 11,049 | - | 10,320 |
| | 80 | 32,719 | 30,044 | 7,523 | 12,993 | 12,815 | 80 | 9,828 |
| | 90 | 34,537 | 33,145 | 7,520 | 13,018 | 15,201 | 231 | 8,805 |
| | 100 | 36,354 | 34,423 | 7,628 | 12,267 | 18,094 | 32 | 9,780 |
| Centralized fortification | 0 | 18,177 | - | 7,289 | - | - | - | 22,960 |
| | 10 | 19,995 | 14,769 | 7,289 | 12,008 | - | - | 9,817 |
| | 20 | 21,813 | 23,584 | 7,289 | 19,174 | - | - | 2,896 |
| | 30 | 23,630 | 28,391 | 7,366 | 21,110 | 2,316 | - | 1 |
| | 40 | 25,448 | 30,505 | 7,507 | 19,760 | 5,825 | - | - |
| | 50 | 27,266 | 32,478 | 7,643 | 17,889 | 9,927 | - | - |
| | 60 | 29,084 | 34,589 | 7,778 | 16,704 | 13,052 | - | - |
| | 70 | 30,901 | 36,695 | 7,907 | 15,615 | 16,007 | - | 2 |
| | 80 | 32,719 | 38,816 | 8,026 | 14,026 | 19,201 | - | - |
| | 90 | 34,537 | 40,935 | 8,146 | 12,491 | 22,351 | - | - |
| | 100 | 36,354 | 43,054 | 8,265 | 10,876 | 25,576 | - | 2 |

# Online companion for the manuscript:
# *"Food Aid Modality Selection Problem"*

This online companion consists of two parts. In the first part, we explain the details of the parameter estimation for our numerical analyses. In the second part, we discuss in detail our sensitivity analysis of the food aid program budget. FAIMS incorporates numerous factors concerning the beneficiaries, the local economy, and the aid distribution channels, and we believe that explaining the parameter estimation for a realistic case study could enable the academic community to grasp the dynamics involved and to further develop the methodology.

## 1. Parameter Estimation

Our mathematical model has four main parameter sets: beneficiary, market, nutrition, and cost parameters. We now discuss how we estimated each of these for the aid program in Garissa, Kenya.

### 1.1. Beneficiary Parameters

The WFP has large-scale operations in Garissa, Kenya. This county not only hosts the world's second-largest refugee camp (Dadaab Camp, population: 245,000) but is the home of 623,000 people, 47.2% of whom live below the poverty line (Commission on Revenue Allocation, 2011). The WFP provides food aid to these poor households through various programs.

WFP delivers food via final delivery points (FDPs) that are temporary structures close to the beneficiaries' villages. These structures are active only on the day of the distribution. On that day the beneficiaries arrive on foot and collect their rations. Since the locations were chosen for proximity to the beneficiaries (Rancourt *et al.*, 2015), we clustered the beneficiaries around them and divided the county into regions accordingly ($r \in R$). For this we used data provided by WFP: the coordinates and the number of beneficiaries receiving service at each FDP. We also group the beneficiaries by household type, $h \in H$. Introducing these types allows us to differentiate the taste functions of the households so that spending behavior can be modeled realistically. In a feasibility study for cash- and voucher-based interventions, WFP determined the types and prevalence of households in arid parts of Kenya (WFP, 2013). Table 1 shows the household types in Garissa, their composition, and the average number of people in each type of household: $H$ = {1: male-headed polygamous, 2: male-headed monogamous, 3: female-headed}.

WFP's data indicates how many beneficiaries are living in a region. With these values, we can allocate the beneficiaries to household types and estimate how many beneficiaries are living in household type $h$ in region $r$ ($\pi_{hr}$).

Table 1 Household statistics for Garissa county

| Household Type | Percentage | Average Number per Household |
|---|---|---|
| Male-headed polygamous | 40 | 15 |
| Male-headed monogamous | 35 | 8 |
| Female/orphan-headed | 24 | 7 |

Once the household types and regions are established, we can define utility functions for each group. In the lower-level model, the beneficiaries need to choose from $i \in$ {1: basic food, 2: tasty food, 3: temptation food} based on the utility ($\phi_{ihr}$) that they derive from those items. It has been established in the literature that tasty food has higher utility than basic food, so $\phi_{1hr} < \phi_{2hr}$ for all $h$ and $r$ . On the other hand, temptation goods can vary from household to household so estimating the preference for temptation items over tasty food is challenging.

WFP (2013) has investigated the expenditure preferences of different household types. Figure 3 shows how female and males would spend hypothetical cash assistance. This study includes both beneficiaries and non-beneficiaries, and there are non-food items in the list. We ignore these to derive conclusions about the taste vectors of the beneficiaries. First, the preferences depend on the gender of the household leader. A general rule confirmed by many focus groups is that men can purchase goods without consulting their partner(s), while women must consult their husbands, even if the cash assistance is provided to the female in a male-headed household. We therefore assume that the decision-makers are men in male-headed households and women in female-headed households.

For both men and women, food is the highest priority, but it is much more important for women than men. Almost all female-headed households below the poverty line reported that food is their priority. It is noteworthy that men have a number of unproductive spending priorities. Alcohol or miraa (a type of plant-based drug) is the second-highest priority for men in this region.

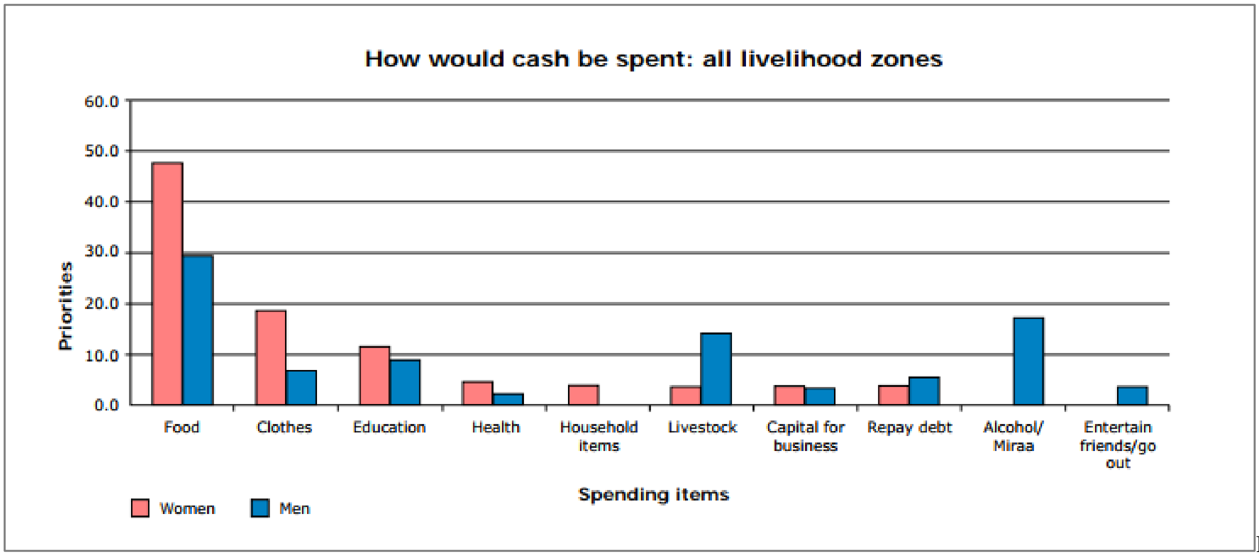



Figure 1 Spending priorities of female- and male-headed households given hypothetical cash assistance.

This expenditure preference is quite similar to that suggested by Jensen and Miller (2010), whose work forms the basis for our model. Extremely poor households spend their money on cheap food commodities until they reach a subsistence level. Therefore, the prioritization of basic food items by both male- and female-headed households is reflected in the calorie requirement constraint. If we increase the cash aid beyond the subsistence level, as Subramanian and Deaton (1996) established, beneficiaries consume tastier but more expensive calorie resources (i.e., tasty food), while their calorie consumption remains the same. Male-headed households may spend the cash on alcohol or miraa, since these items are their second priority and are available at food retailers. We do not claim that all male households would spend additional money unproductively. However, from a modeling perspective we believe it is important to take into account the risk of unproductive spending. It is of concern to donors and agencies, and there is evidence for such behavior. Note that, because of desirability bias, the survey responders may not have stated their true spending intentions: the actual tendency to misspend may be even higher. We therefore model the preference relationship between items for male-headed households (h= 1 or 2) as $\phi_{3hr} > \phi_{2hr} > \phi_{1hr}$ and for female-headed households (h=3) as $\phi_{2hr} > \phi_{3hr} > \phi_{1hr}$.

We have thus established the ordinal utility of each item using spending priorities. This is insufficient since we need the cardinal values of $\phi_{ihr}$ to solve the lower-level model. In our case the lower-level model has a linear knapsack problem structure: the beneficiary wants to maximize profit subject to a budget. It is well established that the optimal solution of such problems is to purchase the item with the highest taste to unit price ratio ($\phi_{ihr}/p_{ir}$).

If we choose taste values that yield ratios reflecting the household's preference rankings, the actual values need not be precisely determined. However, we must choose $\phi_{ihr}$ values that match the taste-to-price ratios with the ordinal values of the taste vectors. We first need to estimate the $p_{ir}$ parameters, which are discussed in the next subsection.

### 1.2. Market Parameters

Not all beneficiary regions have a market. Markets are usually located along transportation corridors, but there are a few in remote regions. Figure 2 shows the location of 22 markets on the Garissa map; their coordinates were provided by WFP. WFP (2013) has established that the maximum distance between beneficiaries and markets is 30 km. Beneficiaries living outside this range should not receive cash or vouchers. We therefore excluded regions that are not within 30 km of a market. This yielded a set of 68 regions where beneficiaries are eligible for cash and vouchers. We assigned each region *r* to its closest market *m* using geographical information system (GIS) data. We set $\beta_{rm}$ to 1 if region *r* is assigned to market *m*. Table 2 gives the summary statistics for the Garissa instance.

Table 2 Summary statistics for Garissa instance

| | | |
|---|---|---|
| Total # beneficiaries | | 112,402 |
| # beneficiaries per region | Min | 100 |
| | Avg | 1,653 |
| | Max | 5,629 |
| Total # eligible regions | | 68 |
| Total # markets | | 22 |
| Distance to market (km) | Min | 0.73 |
| | Avg | 14.67 |
| | Max | 28.96 |

The market prices of the commodities ($p_{rm}$) depend on their connectedness to the transportation network. WFP divides the markets into five categories depending on their distance from the transportation corridors (on corridor, off corridor) and from the center of the county (main, remote), which also hosts WFP's headquarters. Table 3 shows how our 22 markets fit into these categories.

Table 3 Categories for Garissa markets

| Category | Number |
|---|---|
| District Headquarter (HQ) | 1 |
| Main market on transportation corridor (TC) | 3 |
| Main market off transportation corridor | 1 |
| Remote market on transportation corridor | 3 |
| Remote market off transportation corridor | 14 |
| TOTAL | 22 |
| Total population served | 623,600 |

Figure 4 shows two examples of markets.

Figure 2 Two markets: Remote market off TC (left); Main market on TC (right).

WFP (2013) lists the prices of various commodities in different market types. These commodities include: maize flour, beans, rice, potatoes, tomatoes, goat meat, and sugary products. From these we chose representative items for each commodity type in our model. We chose maize flour as the basic food ($i$=1) since it is also distributed by WFP in their in-kind donations. We chose goat meat for the tasty food ($i$=2) since it is the main source of animal protein in this region. Alcohol prices are not listed in the analysis, so we chose sugary products as the temptation food ($i$=3) since they do not contribute to the nutrition of the household. Table 4 gives the prices of these commodities.

Table 4 Prices (USD) of representative foods in different markets

| Market Type | Maize | Meat | Sugar |
|---|---|---|---|
| District HQ | 0.88 | 4.82 | 1.41 |
| Main Market on TC | 0.85 | 4.29 | 1.47 |
| Main Market off TC | 0.90 | 3.85 | 1.50 |
| Remote Market on TC | 0.95 | 4.33 | 1.54 |
| Remote Market off TC | 1.04 | 3.90 | 1.70 |

We can estimate the $p_{ir}$ values as the product of $p_{im}$ and $\beta_{rm}$, and we can also estimate the taste vectors $\phi_{ihr}$ of the beneficiaries. Any taste vector satisfying $\frac{\phi_{3hr}}{p_{3r}} > \frac{\phi_{2hr}}{p_{2r}} > \frac{\phi_{1hr}}{p_{1r}}$ for male-headed households ($h$=1 or 2) and $\frac{\phi_{2hr}}{p_{2r}} > \frac{\phi_{3hr}}{p_{3r}} > \frac{\phi_{1hr}}{p_{1r}}$ for female-headed households ($h$=3) would yield the same results, so we arbitrarily choose the weights shown in Table 5.

Another market-related parameter is the proportion ($\Pi$) of the population that can be served with vouchers at each market ($\kappa_m$). For this, we gathered the subcounty populations from the GIS online database; Figure 2 shows the subcounty borders. Assuming that the population is evenly distributed around the markets, we divided the population of the subcounty by the number of markets there to roughly estimate the population receiving service from each market ($\kappa_m$). The proportion of the population that can be served via vouchers may change depending on how strongly the markets are conntected to the food supply chain. As a rule of thumb, in a cash and voucher guideline developed collaboratively by a number of assistance organizations including USAID, CARE, Mercy Corps, and World Vision, the maximum number of beneficiaries receiving voucher support should not exceed 20% of the total population in the market service zone (Barrett *et al.*, 2009). In our analyses, we used this benchmark as the $\Pi$ value.

Table 5 Utility of each representative commodity for different household types

| Household type | Basic ($i$=1) | Tasty ($i$=2) | Temptation ($i$=3) |
|---|---|---|---|
| Male-headed ($h$=1,2) | 1 | 10 | 20 |
| Female-headed ($h$=3) | 1 | 10 | 5 |

Finally, we need to estimate the contribution of the cash and vouchers to the local economy ($\Lambda$). They have a spill-over effect on non-beneficiaries, especially food producers and retailers. In other words, the aid program indirectly contributes to non-beneficiaries who also have low or middle incomes. These spill-overs emanate from the generalequilibrium effects of such aid programs on geographically isolated rural economies. Because of this isolation, we can calculate how much contribution is generated for each dollar spent in the local market via cash or vouchers. In a study by FAO (2016) on the impact of cash transfer on the local economy, data from previous cash aid programs was collected for seven African countries and the spill-over effect was estimated. Figure 5 shows the results of this study: each dollar spent created an additional \$0.23 ($\Lambda$) of impact in the local economy in Garissa.

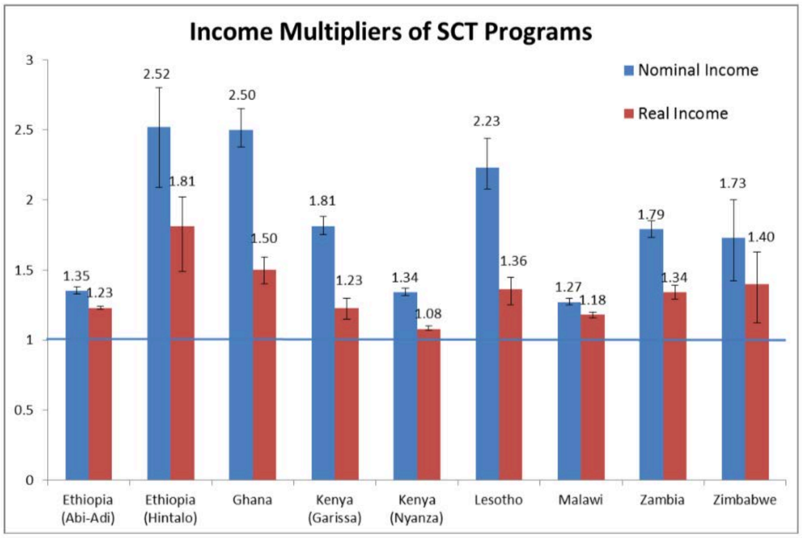



Figure 3 Economic impact of cash transfers for each dollar transferred.

### 1.3. Nutrition Parameters

In this section, we explain how we estimate the nutrition-related parameters $\theta_{ik}$, $\Theta_k$, and $\tau_k$. These parameters measure the nutritional outcome of the aid program. By consuming different foods, beneficiaries ingest different nutrients $k \in K$. When the nutrient intake reaches the level ($\Theta_k$) suggested by health guidelines, the beneficiaries achieve well-being, and the effects of malnutrition (healthcare expenditure and human capital loss) are reduced.

WFP aims to prevent malnutrition via fortification. The commodities distributed are treated to provide higher levels of vitamins and minerals. If beneficiaries become malnourished due to inadequate food intake, then they can be supported via nutrient supplements. However, these supplements are less cost-effective than fortified food. If disabilities cannot be avoided, the country must pay treatment costs ($\tau_k$) as well as indirect costs associated with productivity losses due to nutrient deficiencies (Horton, 2006).

There are two main types of malnutrition: macronutrient (protein-calorie) deficiencies and micronutrient deficiencies. The most common micronutrient deficiencies in Sub-Saharan Africa (SSA) are vitamin A, iron, iodine, and zinc deficiencies. Micronutrient deficiencies constitute a disproportionate burden on the health care systems of low-income countries. SSA has 11% of the world's population and more than half of deaths due to deficiencies of vitamin A, iron, zinc, and iodine (Caulfield *et al.*, 2006; Ezzati *et al.*, 2006).

Health risk statistics for each condition and each country are available via the Global Burden of Disease (GBD) Database[1]. In Kenya, child wasting, a development problem caused by malnutrition, is the second-highest health risk: see Figure 6. Iron and vitamin A deficiency are also among the 20 highest risk factors. A closer look at nutritional risks reveals that the main challenge is the simplest form of malnutrition: insufficient calorie intake causing child wasting, stunting, or low weight. Iron deficiency ranks second, with a steep increase in the last two decades. Vitamin A and zinc deficiencies are also a concern. We exclude the remaining two factors: non-exclusive breastfeeding of infants and discontinued breastfeeding. Although malnutrition may indirectly affect this behavior, the link is unclear.

[1]GBD data is available to researchers and can be downloaded from the Institute of Health Metrics and Evaluation`s Global Health Data Exchange Platform (GHDx). This platform not only provides the disability adjusted life years (DALYs) but also mortality, life expectancy rates, and risk factor estimates at the global, regional, and country level (Institute for Health Metrics and Evaluation (IHME) and University of Washington, 2016).

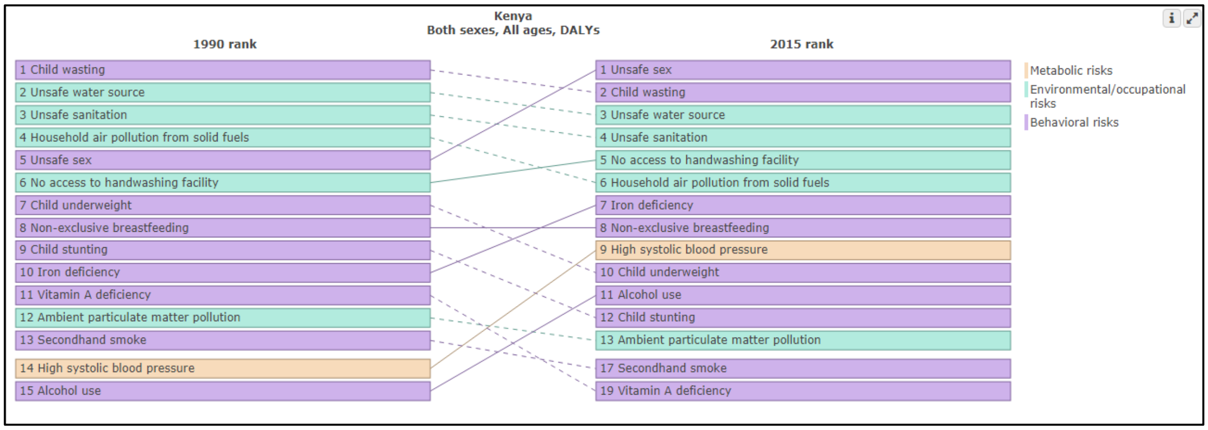



Figure 4 Major health risk factors in Kenya ranked by total DALYs.

A minimum calorie intake requirement covers wasting, low weight, and stunting, but iron, vitamin A, and zinc deficiencies must be modeled separately. In FAIMS these nutrients are represented as $K$= {1: calories, 2: vitamin A, 3: iron, 4: zinc}, and the daily nutrient requirements are modeled as $\Theta_k$. In addition, the level of nutrient $k$ in food $i$ is represented as $\theta_{ik}$. These two parameters are estimated using a food-aid nutrition calculator developed for WFP by the University of London Institute for Child Health. The NutVal tool (NutVal 4.1 Ration Calculator, 2014) is used to calculate and compare the nutritional values of different rations for different household compositions. Table 6 lists the nutritional values ($\theta_{ik}$) for the foods used in our model and the daily requirements. We have listed both WFP's fortified maize flour and the most common form of maize available in local markets, since the beneficiaries receive the latter if they purchase basic food via cash or voucher.

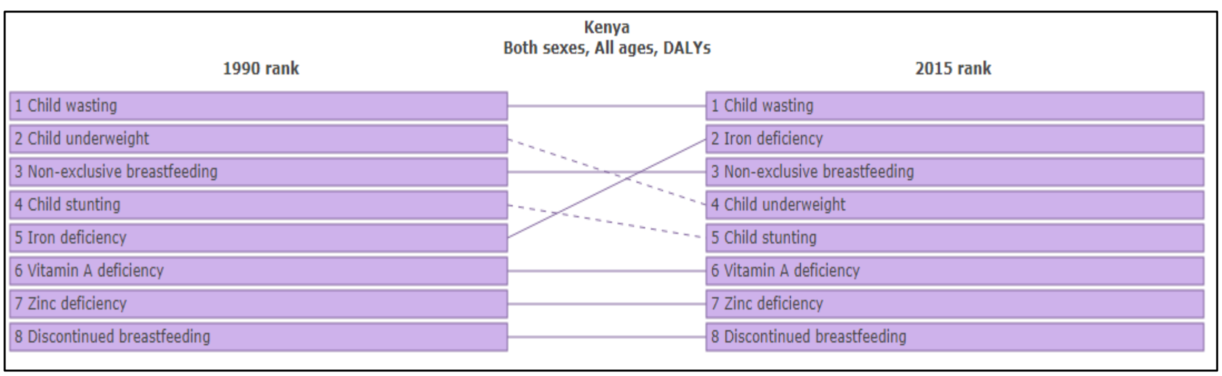



Figure 5 Major nutritional risk factors in Kenya.

Table 6 Nutrient values ($\theta_{ik}$) for 1 kg of fortified and regular maize meal and goat meat and daily requirements for the nutrients ($\Theta_k$)

Source: NutVal 4.1 Ration Calculator (2014)

| Nutrient | Maize meal (WFP) | Maize meal (regular) | Goat meat[2] | Daily Requirement |
|---|---|---|---|---|
| Calories (kcal) | 3700 | 3700 | 1116 | 2100 |
| Vitamin A (µg) | 1648 | 110 | 4968 | 550 |
| Iron (mg) | 26 | 11 | 30.4 | 32 |
| Zinc (mg) | 37.2 | 6.6 | 40 | 12.4 |

Now, we need to estimate the avoided malnutrition treatment costs as a result of WFP's aid program ($\tau_k$) using current malnutrition statistics for Kenya. One way to accurately reflect the effect of a food aid program on nutrition is to calculate the DALYs caused by nutrition deficiency. The DALY concept was developed by the World Health Organization (WHO) and is widely used in cost-effectiveness analyses of different treatments (Edejer *et al.*, 2003). One DALY is considered to be one year lost from a healthy life. The DALY caused by a condition is the sum of the years lost due to premature mortality and those lost due to disability. In other words, this metric counts the extra years that could have been lived (depending on the country's life expectancy) and the years that could have been lived without disability. Each condition has a weight between 0 (healthy) and 1 (dead). For example, the weight for caloric deficiencies is 0.053, and that for diabetes is 0.015. Multiplying these weights by the life expectancy gives the years with disability. Table 7 gives the DALY contribution of the nutrition-related risk factors and their shares in Kenya's total risk factors.

[2]For the goat meat, we used a composition of 900 g of raw meat and 100 g of raw goat liver since they are commonly sold together.

Table 7 DALY contribution of each risk factor in Kenya

| Risk Factor | Total DALY Loss ($DALY_k$) | Share |
|---|---|---|
| Wasting | 1564108 | 7.96% |
| Low Weight | 466505.9 | 2.38% |
| Stunting | 313613.9 | 1.60% |
| Iron Deficiency | 677243.8 | 3.43% |
| Vitamin A Deficiency | 144568.3 | 0.74% |
| Zinc Deficiency | 78670.85 | 0.40% |

As explained previously, the first three groups are linked to the calorie deficiency, so we have combined the DALY losses of these three conditions. The micronutrient deficiencies are modeled separately. Given subnational or regional data, WFP can directly use the number in the nutrient-deficient population, but we have access only to national-level aggregated DALY data. We divide the total number of DALYs caused by deficiency $k$, represented as $DALY_k$, by the number of extreme poor (those in the bottom 20% of the wealth group) to determine the DALY burden of an individual. We multiply this number by the cost of treating that deficiency ($tr_k$). This is an intuitive definition since in the literature treatment costs are usually reported as money spent per DALYs saved. The resulting figure provides an estimate of $\tau_k$, the avoided malnutrition treatment cost for nutrient $k$ per person. Treatment costs ($tr_k$) depend on the local context and the available treatments. Cost-effectiveness analyses for malnutrition treatment in SSA report cost savings ranging from \$26 to \$1344 per DALY averted (Bachmann, 2010; Puett *et al.*, 2013). We instead used a benchmark approach. According to a World Bank report (World Bank, 1993), a treatment in low- and middle-income countries is considered "attractive" in terms of cost-effectiveness if it costs less than \$150/DALY averted. Shillcutt *et al.* (2009) suggest that this figure should be regularly adjusted for inflation. We converted \$150 in 1993 to 2016 dollars and obtained \$250/DALY, and we used this value for all nutrient treatments.

$$\tau_k = \frac{DALY_k tr_k}{pop_{<20}}$$

### 1.4. Cost Parameters

In this section, we discuss the cost structures for a possible cash and voucher program for food distribution in Garissa as well as the current cost structure for in-kind distribution. For cash, we based the analysis on WFP's current cash interventions for refugees. For vouchers, we used data from a program in Garissa operated by Action Against Hunger.

### 1.4.1. In-kind

WFP Kenya has operated in the region for the last couple of decades and mainly focuses on in-kind distribution. Thus, the infrastructure is already in place, and the costs associated with the initial investment can be considered sunk costs. As explained earlier, WFP pays transportation costs per metric tonne, and no other fixed costs are associated with these operations. Similarly, WFP dynamically arranges its storage capacity on a regular basis and achieves almost a pay-per-tonnage cost for this as well. As a result, we can calculate an overall cost estimate per metric tonne of in-kind aid distributed.

WFP procures food commodities or receives donations and packages them (procurement costs), then transports the food to the Mombasa port (external transportation costs). The food is stored there or elsewhere (storage and handling costs). Finally, it is transported to the Garissa EDP (primary transportation costs) and then to the FDPs (secondary transportation costs). Meanwhile, the staff overseeing these operations incur operational costs. Table 8 lists values for these costs derived from WFP's reports and logistics office.

Table 8 Costs of in-kind aid distribution by WFP in Garissa, Kenya

| Cost | |
|---|---|
| Procurement cost | \$323.1/tonne |
| External transportation cost | \$75.4/tonne |
| Storage and handling cost | \$177/tonne |
| Operational costs | \$142.6/tonne |
| Primary transportation | \$48.4/tonne |
| Secondary transportation | \$6.83/tonne if distance <10 km |
| | \$0.28/tonne/km if distance >10 km |

### 1.4.2. Cash

In Kenya the main mechanism for cash transfer is M-Pesa, a mobile money transfer system. It allows users to deposit, withdraw, and transfer money in exchange for goods and services via SMS (Saylor, 2012). The user needs a SIM card, and the retailer needs a mobile device to complete the transaction. M-Pesa was initiated in 2007 by

Safaricom, Kenya's largest mobile provider. As of 2014, M-Pesa transactions accounted for KSh 2.1 trillion, half of Kenya's GDP (Safaricom, 2016). In short, M-Pesa is a branchless banking service for people who do not have bank accounts. A study examining the long-term effects found that M-Pesa lifted 2% of extremely poor households out of poverty just by providing financial services (Suri and Jack, 2016). The effects are stronger for female-headed households: their food consumption increased more than that for male-headed households, and 185,000 women were transferred from farming activities to better-paying occupations, usually retailing their own goods.

M-Pesa allows WFP to distribute cash cheaply. WFP started to distribute cash in cooperation with M-Pesa in 2015 in Kakuma and Dadaab refugee camps; the program was called Bamba Chakula[3]. Beneficiaries received 10% of their in-kind rations as cash via M-Pesa, and in 2016 this increased to 50% (WFP, 2016). Follow-up studies revealed that 97% of beneficiaries redeemed their cash accounts regularly. Safaricom provides the necessary SIM cards, and the transactions cost 1% to 3% of the cash transfer values (The Complementarity Initiative and World Food Programme, 2015). We assumed that a similar program is available, with no fixed costs and a variable cost of on average 2% per transaction.

#### 1.4.3. Vouchers

WFP does not currently have a voucher program in Kenya. We used cost data from the voucher program of Action Against Hunger, assuming that the WFP's potential voucher program would have similar costs.

The fixed costs are incurred by program employees in the field. They must find reliable retailers, sign contracts with them, and regularly check that all is well. If problems arise at the contracted retailers, the beneficiaries go hungry. Also, retailers may not honour the face-value of the vouchers or may exchange vouchers for unauthorized items (WFP, 2014). This is forbidden in the WFP contracts, and the beneficiaries are warned about such practices. However, prevention of this behavior requires regular monitoring and thus higher operational costs.

The voucher variable costs are less straightforward than those for cash. Vouchers must be printed and distributed, and each contracted retailer receives a payment from WFP at the end of each month with an associated transaction

[3]Bamba Chakula means "Get your food" in Swahili.

cost. Table 9 gives the costs reported in an external evaluation of the Action Against Hunger program (Dunn, 2009):

Table 9 Costs of Action Against Hunger voucher program in Garissa, Kenya

| Cost | |
|---|---|
| Operational cost (contracting & monitoring) | \$124138/market/year |
| Printing cost | \$0.23/voucher |
| Market payment transaction cost | \$6.30/market/month |

## 2. Sensitivity Analysis Results for Program Budget

In this section, we provide details of our sensitivity analysis on the available budget and objective function weights, as described in Section 5.1. When WFP distributes only in-kind aid, the program has a limited nutritional contribution and makes no contribution to the local economy. Given the current market prices, if WFP desires better results on the latter objectives, it must increase the budget. We investigate the impact of increases. To do this, we add a budget constraint to the FAIMS model. We first set the budget, *B*, to the total program cost value obtained under the cost minimization problem (*B* = \$18,177,208). Then, we increase it in 10% increments ($\varsigma \in \{0, 10, \ldots, 100\}$) and find the new solutions.

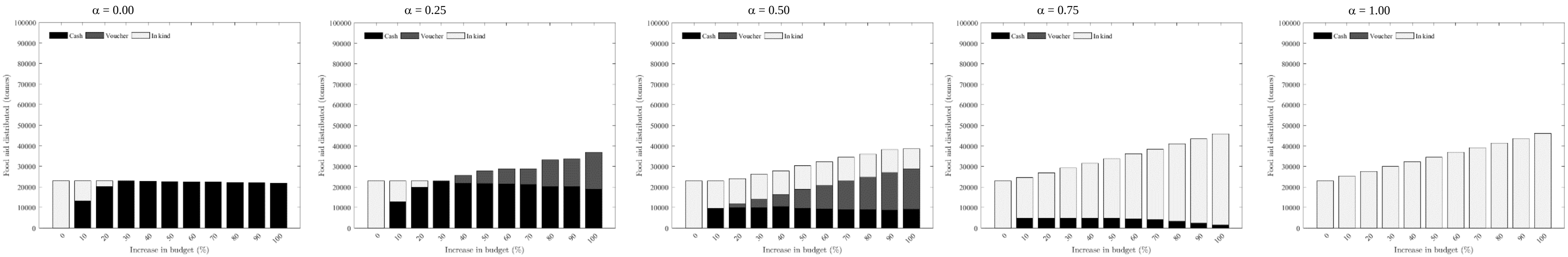
**Model 2: FAIMS with budget constraint**

$$\max \quad \alpha \text{ Objective 1} + \beta \text{ Objective 2}$$

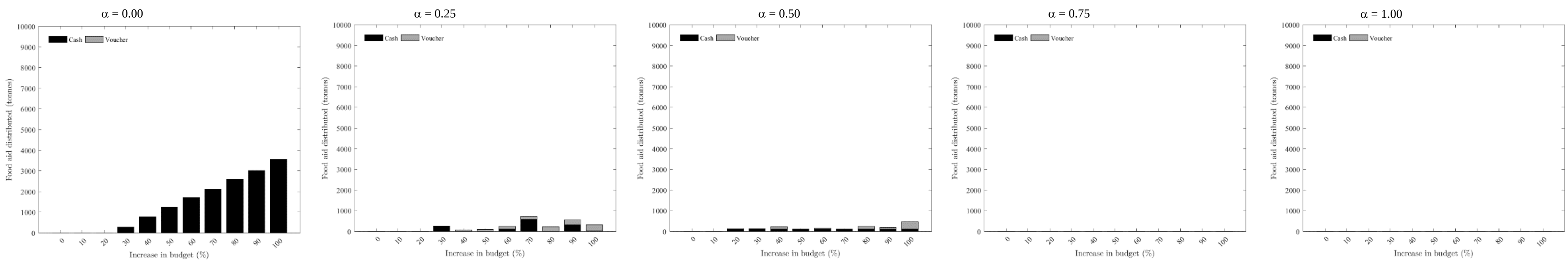
*s.t.*

$$\text{Objective 3} \leq B\,(1+\varsigma\%)$$

$$(2) - (18)$$




(a) Basic food aid




(b) Tasty food aid

Figure 6 Amount and type of aid distributed as program budget increases.

These two objectives together represent the contribution of the program to the community. We use multi-criteria optimization to combine objectives 1 and 2, adapting the reference point method (Clímaco *et al.*, 2006) for generic multi-criteria problems. We generate alternative optimal program designs by altering the budget ($\varsigma$) and weight parameters ($\alpha$, $\beta$=1-$\alpha$). We set $\alpha$ = {0, 0.25, 0.5, 0.75, 1}. Figures 8a and 8b show the basic and tasty food consumption and the aid types distributed for these parameter settings.

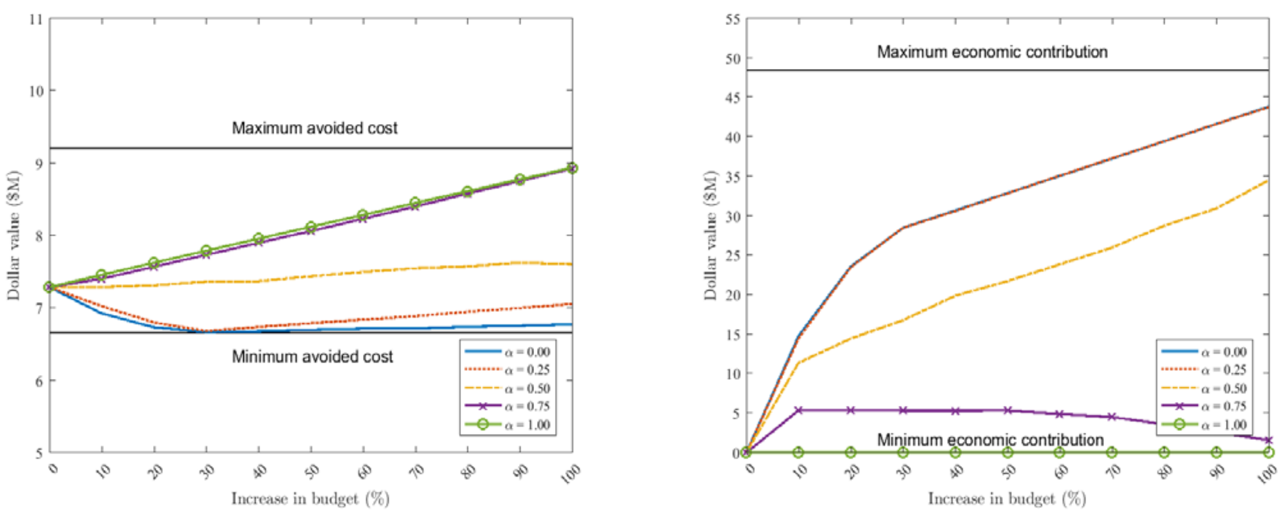
The leftmost graphs of Figures 8a and 8b are obtained for the scenario with $\alpha$=0, $\beta$=1 and represent the case where the emphasis is on the economic impact. Conversely, the rightmost graphs with $\alpha$=1, $\beta$=0 represent the case where the emphasis is on the nutrition objective. The first column of each graph corresponds to the optimal solution for the original budget, and the remaining columns correspond to the solutions for the increased budgets.

In the first scenario, $\alpha$ = 0, all the in-kind distribution is replaced by cash distribution after a 30% budget increase, and after that point the amount remains almost stable, whereas the amount of tasty food consumed starts to increase steadily. As $\alpha$ increases, and nutrition is emphasized more, we observe a significant increase in basic food consumption and a decline in tasty food consumption. In terms of modalities, we observe higher in-kind distribution amounts as $\alpha$ increases. Although we observe more cash and voucher distribution for $\alpha$=0 and 0.25 as the budget increases, this behavior is not observed for higher $\alpha$ values. Interestingly, for $\alpha$=0.5, all three aid types are distributed at the same time. No beneficiaries receive cash and vouchers simultaneously, but many households receive in-kind aid as a supplement to cash/vouchers.

When $\alpha$ reaches 0.75, in-kind aid starts to dominate. As we increase the budget by 10%, cash distribution increases significantly compared to the base case, but it decreases again as the budget expands further. This is because it is not possible to achieve significant malnutrition gains with a small budget increase. On the other hand, distributing some of the calories using cash yields a notable jump from zero in the economic component of the objective function.

Finally, for α=1, the optimal solution indicates in-kind distribution throughout the budget scale. The most important conclusion to be drawn from these graphs is this final scenario. The rightmost graphs show that an in-kind program is optimal not only from a cost perspective as in the base case but also from a nutritional perspective.

Figure 9 indicates how the budget and the WFP's goals affect the aid program. It is worth noting how the two objectives respond to these factors. As the budget and α increase, the avoided malnutrition treatment cost and the contribution to the economy change as shown in Figures 9a and 9b. The lines parallel to the x-axis indicate the upper and lower bounds on the objectives. In Figure 9a, we observe that when WFP emphasizes nutrition (α=0.75, 1), the objective value increases almost linearly with the budget. If WFP values both objectives equally (α=0.5), nutrition still increases slightly. For lower α values (α=0, 0.25), the nutrition objective decreases with budget increase since WFP transforms its operations from in-kind to cash as seen in Figure 8a, and the beneficiaries start to consume local maize instead of the fortified alternative. After cash-only distribution starts (at a 30% budget increase), and consumption starts to rise, nutrition also increases slowly. However, even a 100% budget increase cannot restore the base-case nutrition levels.

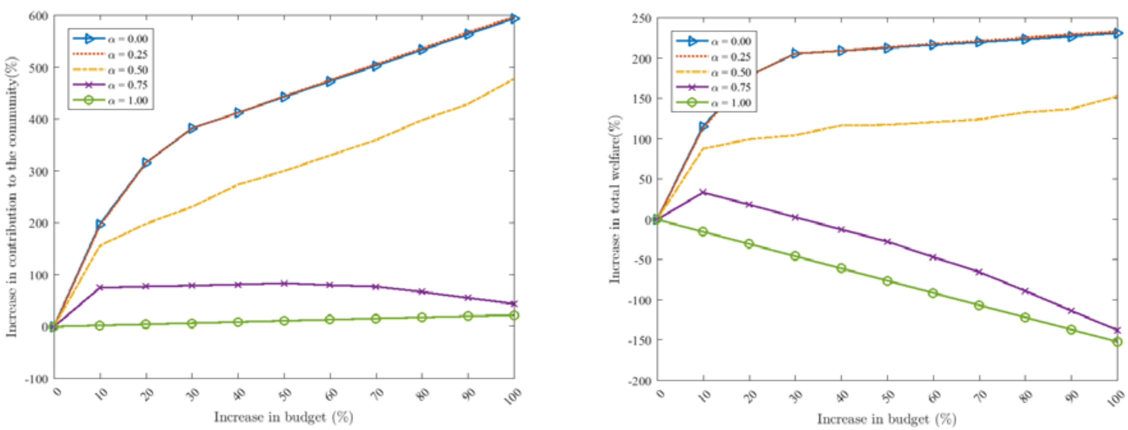



(a) Avoided malnutrition treatment cost

(b) Contribution to local economy

Figure 9 Objective values as budget and α increase.

In Figure 9b, the effect of α (=1-β) on the contribution to the economy is in the opposite direction, as expected. For lower values of α (α=0, 0.25), i.e., higher values of β, this contribution first grows quickly as WFP distributes less in-kind and more cash. After the completion of the switch to cash, the contribution continues to grow linearly, in parallel with the budget increase. Assigning equal weights does not inhibit this growth. However, if WFP emphasizes nutrition, then we observe a limited (α=0.75) or zero (α=1) contribution. It is clear from these graphs that the objective values are sensitive to the weight changes. However, from a policy evaluation perspective, investigating only the modality distributions or the objective function values does not indicate whether or not WFP should increase the program budget, and if so, by how much. Each of these three objective functions are in monetary terms, so an overall combination of the costs and benefits can be calculated.



(a) Contribution of aid program to community (b) Total welfare

Figure 10 Contribution to community and total welfare changes as budget increases.

Figure 10a shows by how much objectives 1 and 2 are changed relative to the base case. These two objectives measure the contribution of the program to the community, since they reflect the well-being of beneficiaries and non-beneficiaries simultaneously. The contribution to the community grows with extra budget regardless of the α value. The overall growth is much faster when the emphasis is on the economic contribution rather than nutrition because of the different upper bounds: economic contribution can increase to \$45 million, while avoided malnutrition cannot go beyond \$9.1 million.

On the other hand, WFP pays to achieve these contributions to the community. If we take the program costs into account, we obtain the change in the total welfare generated by the program by combining all three objectives to reflect the perspectives of the three stakeholders. Figure 10b represents the change in the total welfare for all $\alpha$ values. Choosing an $\alpha$ too high, i.e., 1, does not contribute to the total welfare since it overemphasizes nutrition, which has a limited monetary contribution in comparison to the other two objectives. On the other hand, a 10% budget increase improves the total welfare significantly for $\alpha \leq 0.75$. Furthermore, a 20% increase can be considered if WFP chooses $\alpha \leq 0.5$. However, an increase beyond 30% is not worthwhile, regardless of the $\alpha$ value. To summarize, a budget increase can give significant improvements (up to 200%) in total welfare, as long as WFP assigns a nonzero weight to the economic contribution. However, the total welfare function flattens or decreases beyond an increase of 30%.

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