THE NUTRITIONAL SUPPLY CHAIN: HUMANITARIAN FOOD AID

By

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The Nutritious Supply Chain: Optimizing Humanitarian Food Aid

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The UN World Food Programme (WFP) is the largest humanitarian agency fighting hunger worldwide, reaching around 80 million people with food assistance in 75 countries each year. To deal with the operational complexities inherent to its mandate, WFP has been developing tools to assist their decision makers with integrating the supply chain decisions across departments and functional areas. This paper describes a mixed integer linear programming model that simultaneously optimizes the food basket to be delivered, the sourcing plan, the routing plan, and the transfer modality of a long-term recovery operation for each month in a pre-defined time horizon. By connecting traditional supply chain elements to nutritional objectives, we made significant breakthroughs in the operational excellence of WFP’s most complex operations, such as Iraq and Yemen. We show how we used optimization to reduce the operational costs in Iraq by 17%, while still supplying 98% of the nutritional targets. Additionally, we show how we are using optimization in Yemen to manage the scale-up of the existing operation from three to six million beneficiaries.

Keywords: supply chain; nutrition; MILP; humanitarian logistics; WFP
JEL Codes: C61, Q18

1 Introduction

Humanitarian organizations are currently facing a large amount of high-level crises. Conflicts in Iraq, Syria, South Sudan, and Yemen have been unprecedentedly long and large in scale, and many African countries are suffering from the effects of El Niño. These crises result in rapidly deteriorating living conditions for everyone in the vicinity, threatening millions of innocents with hunger, malnutrition, and worse. For decades, humanitarian organizations such as the United Nations (UN), Médecins sans Frontières (MSF), and the International Committee of the Red Cross (ICRC) have been doing everything in their power to shield these innocents from harm.

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There are about 795 million undernourished people in the world today. This means that just over one in nine people on Earth do not have access to enough food to be healthy and lead an active life (FAO et al. (2015b)). Hunger and malnutrition are in fact the number one risk to health worldwide - greater than AIDS, malaria, and tuberculosis combined. The UN considers hunger one of the greatest solvable problems, which gave rise to the Zero Hunger Challenge (FAO et al. (2015a)). The Zero Hunger Challenge is a global initiative launched by the UN Secretary General Ban Ki-moon, and calls on everyone to do their part to eliminate hunger in our lifetimes.

One of the key players in responding to emergencies and eliminating hunger is the United Nation’s World Food Programme (WFP). WFP is the world’s largest humanitarian organization fighting hunger worldwide, with more than 14,500 employees across the globe. In emergencies they distribute food where it is needed, saving the lives of victims of war, civil conflict, and natural disasters. After the cause of an emergency has passed, WFP uses food to help communities rebuild their lives and to return a semblance of normalcy. In 2015, a total of 76.7 million people were reached directly by WFP assistance, spread over 81 countries and funded by a grand sum of 4.8 billion US dollars of donations - representing a third of the aid given in response to humanitarian emergencies in 2015 (WFP (2016)).

Delivering food to this many people in these kinds of environments requires a supply chain that is agile, adaptable, and aligned (Lee (2004)). Each year, WFP procures, transports, and distributes around 4 million metric tonnes (4 billion kilograms) of food to people in need. The poor infrastructure conditions and high levels of insecurity in conflict areas necessitate creativity and flexibility in delivering this food, and WFP has been known to employ every variety of transfer methods - from elephants and camels to airplanes and barges. On any given day WFP operates an average of 60 aircraft, 40 ships, and 5,000 trucks. By virtue of their excellent logistical performance, WFP is even mandated to lead logistics operations whenever a humanitarian agency requires a joint response from UN agencies and the humanitarian community.

There are several phases in responding to a disaster. In the literature we generally see that disaster timelines are split into four stages: mitigation, preparedness, response, and recovery (Van Wassenhove (2006); Altay and Green (2006); Ergun et al. (2011)). Mitigation focuses on the prevention of a disaster and the reduction of its intensity, for instance by setting up alert systems that warn against floods or by defining building guidelines for areas that are vulnerable to earthquakes or hurricanes. Preparedness is more concerned with setting up the appropriate resources (both physical and human), such as the building and stocking of warehouses or the training of personnel. Response starts once the disaster has occurred; it includes activities such as the delivery of food and services to those in need, evacuation of the affected region, and the collection of debris. Lastly, the recovery phase aims to return a semblance of normalcy to the affected.

Holguín-Veras et al. (2012) split up the recovery phase in short-term and long-term recovery, where short-term recovery is a transitional stage covering damage assessments, repairs, housing, etc. Long-term recovery may span multiple years and includes the rebuilding of infrastructure and distribution of medical and food supplies to prevent disease and malnutrition. This long-term recovery is one of the focus areas of WFP. Most literature on humanitarian logistics focuses on the preparedness and response side of a disaster, whereas long-term recovery is a topic that does not receive a lot of attention. In this paper we focus on this neglected phase - we develop a mathematical model for supply chains that need to provide a continuous supply of food over long periods of time (multiple months to several years).
Many researchers have characterized and discussed the challenges and opportunities of humanitarian logistics. Van Wassenhove (2006) discusses how the private sector can learn from the agility and adaptability inherent to humanitarian supply chains, and how the humanitarian sector can learn from the established Supply Chain Management (SCM) best practices in the private sector. In a follow-up paper, Van Wassenhove and Pedraza Martínez (2012) illustrate the potential of Operations Research (OR) in particular for adapting such SCM best practices to humanitarian logistics. Apte (2010) discusses research issues and potential actions surrounding the field of humanitarian logistics, and reviews analytical models from the literature to understand the state-of-the-art in humanitarian logistics. Apte mentions the sustaining of long-term developmental aid when discussing research gaps. Çelik et al. (2012) also mention that there is a gap for long-term recovery - using the term Long-Term Humanitarian Development instead. Additionally, they highlight that there is a lack of good implementation of decision support tools in humanitarian operations. Holguín-Veras et al. (2012) pinpoint research gaps that need to be filled to enhance both the efficiency of humanitarian logistics and the realism of the mathematical models designed to support it. They argue that humanitarian logistics is too broad a field to fit neatly into a single definition of operational conditions, and urge researchers to treat these different operational conditions separately.

Despite the qualitative attention for long-term recovery, there are few mathematical formulations available that cover the entire scope of a humanitarian supply chain. Most existing research is focused on (a combination of) three sub-problems, namely that of facility location (Balcik and Beamon (2008)), distribution (Haghani and Oh (1996); Özdamar and Demir (2012); Rottkemper et al. (2012)), and inventory control (Beamon and Kotleba (2006); Pérez-Rodriguez and Holguín-Veras (2015)). Humanitarian researchers have extended the traditional models for these three sub-problems with constraints, objectives, and solution methods to facilitate the special requirements of a humanitarian supply chain. These extensions include (but are not limited to) research on the appropriate objective function (Holguín-Veras et al. (2013); Gralla et al. (2014)) and modeling uncertain demand, prices, and capacities (Bozorgi-Amiri et al. (2013); Rawls and Turnquist (2012); Ben-Tal et al. (2011)). For an in-depth discussion of what is necessary to make a traditional (i.e. commercial) supply chain model work in a humanitarian context, we refer to Holguín-Veras et al. (2012).

One component of food aid that is not covered yet in the Operations Research literature is that humanitarian organizations have several methods at their disposal to deliver their aid. Whereas in the past food transfers were done exclusively in-kind (i.e. the organization buys, transports, and distributes the commodities), there is a recent trend of providing beneficiaries with cash or vouchers instead, allowing them to purchase their own commodities at local markets or selected retailers. Lentz et al. (2013) discuss the rise of these new food assistance instruments. There are a lot of interacting effects to be considered, and it is important to weigh the benefits (reduced transportation costs, increase in beneficiary’s dignity) against the dangers (the influx of cash or vouchers may distort the local economy). They state that no single tool is always and everywhere preferable, and seek to educate the reader on their appropriate use. Especially the economic repercussions of choosing one transfer modality (in-kind, cash, or vouchers) over another are notoriously hard to measure, making it difficult to select the appropriate instrument. Ryckembusch et al. (2013) discuss a new analytical tool that is able to compare the cost-effectiveness of transfer modalities. Their tool, the ‘Omega Value’, considers the trade-off between total costs (procurement, transportation, services, etc.) and the ‘Nutrient Value Score’ (NVS). The NVS is a weighted
score function that shows to what extent all nutritional requirements are met (for nutrients such as energy, protein, vitamins, etc.). The Omega Value shows the nutritional value per dollar spent, and can assist policy makers in making the right choice of food basket and transfer modality.

Carlson et al. (2003) show how mathematical models can be used to generate food baskets that satisfy all nutritional requirements (amongst other constraints). They develop a quadratic mathematical programming model that, for each age-gender group, selects the optimal food plan that meets the dietary standards, adheres to the budget constraints, and resembles the reported food consumption for that specific age-gender group (therefore making it more likely that the food plan ‘sticks’). Similarly, Chastre et al. (2007) developed linear programming routines to generate hypothetical diets using a combination of foods that will enable a family to meet their energy and nutrient requirements as recommended by the World Health Organisation (WHO) and the Food and Agriculture Organisation (FAO) at the lowest possible cost. As the software (Cost of the Diet) can identify a diet that is realistic in terms of the frequency with which foods are eaten, for example by specifying that a particular food is eaten three times a day every day, the frequency with which each food is consumed can be adjusted to reflect typical dietary patterns.

In this paper we develop a Mixed Integer Linear Programming (MILP) model that optimizes the food basket design, transfer modality selection, sourcing plan, and delivery plan\(^2\) of a long-term recovery operation for each month in a pre-defined time horizon. There are three innovations in this paper. First and foremost, we connect the composition of the food basket to be delivered to the supply chain that is necessary to deliver it. This allows us to investigate the impact of different food basket designs on the supply chain, enabling us to use food basket adjustments to drive down costs and increase the effectiveness of existing operations at WFP. Secondly, we introduce the transfer modality selection in a supply chain optimization model. This allows us to quantitatively assess whether traditional food distributions are the most cost-effective way to deliver food assistance, or if Cash & Voucher transfers are more appropriate. Thirdly, we validate and apply the optimization model in two of WFP’s most complex operations: Iraq (two million beneficiaries) and Yemen (three million beneficiaries). We show how we used optimization to reduce the operational costs in Iraq and to support Yemen in managing a scale-up of their existing operation from three to six million beneficiaries.

2 WFP’s Supply Chain

A brief discussion of WFP’s supply chain and the components of our model before defining the mathematics is prudent. We consider the demand, transfer modalities, sourcing, and logistics network.

**Demand.** WFP’s food aid depends on the context of the crisis and the health, demographics, and access to non-WFP food of the beneficiaries. The bulk of food aid is provided through General Food Distribution (GFD) - a monthly parcel that provides enough food for a standard-sized family. Additional food aid is supplied to more vulnerable beneficiaries, such as those suffering from malnutrition, young children, and pregnant and nursing women. Nutritionists track the nutrients that WFP’s food baskets provide, and make sure that they align with the needs of the different beneficiary types. Traditionally demand was defined in terms of pre-defined food baskets per beneficiary type, but we take one step back and define

\(^2\)up to but not including Last Mile Distribution (Balcik et al. (2008))
demand as nutritional requirements - allowing us to optimize the food baskets rather than using the pre-defined ones.

**Transfer modalities.** There are multiple ways of satisfying the demand - be it a pre-defined food basket or a nutritional requirement. Whereas WFP used to supply the necessary commodities itself, the last few years there has been a transition towards cash-based transfers (also known as Cash & Vouchers). Food transfers require WFP to source, store, and transport the commodities, whereas a cash-based transfer allows beneficiaries to obtain the commodities themselves from local markets. Food transfers incur a lot of logistics costs, but allow WFP a lot of flexibility in their sourcing (making use of bulk purchases, price seasonality, etc.). Cash-based transfers are more direct (so more of the donation is spent on procurement costs), but they are dependent on local market stability and are harder to track. We make a distinction between conditional (Voucher) transfers, where WFP specifies the commodities to be purchased, and non-conditional (Cash) transfers, where the beneficiary may spend the money at will.

**Sourcing.** Depending on the transfer modality, multiple sources are available. Cash-based transfers (such as e-Vouchers and direct cash transfers to debit cards) allow beneficiaries to purchase commodities at Local Markets (LM). For food transfers WFP has more purchasing options. We distinguish three supplier types: International Suppliers (IS), Regional Suppliers (RS), and Local Suppliers (LS). Local Suppliers can be found in the recipient country; Regional Suppliers can be found in neighbouring countries, where transport from the supplier to the recipient country is usually done overland. Procuring from International Suppliers involves shipping the commodities to a Discharge Port\(^3\) (DP).

**Logistics network.** The hand-over between suppliers and WFP is very flexible and dependent on the Incoterm (Ramberg (2011)). Usually WFP takes charge of the commodities at the loading port (FOB contract) or at one of its hubs (DAP contract). From Discharge Ports WFP moves commodities into the country to so-called Extended Delivery Points (EDP), which are transshipment points where commodities can be stored, packaged, consolidated, etc. From the EDPs the commodities are transported (usually by truck) to the Final Delivery Points (FDP), where they are handed over to WFP’s Cooperating Partners: local NGOs that will take care of what is called the Last Mile Distribution (Balci et al. (2008)). Note that the logistics network may vary between countries and is very context dependent; WFP may take charge of the entire delivery network (from pick-up at the supplier to last mile distribution), or it may outsource the network partially or entirely to local logistics providers or sometimes even the government. An illustrative example of WFP’s supply chain for international procurement is displayed in Figure 1.

### 3 Model

**3.1 Introduction**

In this paper we extend a capacitated, multi-commodity, multi-period network flow model with nutritional components. The first version of the model and tool were developed by a team of Industrial & Systems Engineering students from Georgia Tech (Gadepalli et al. (2014)), as part of their Senior Design project. Based on their successful prototype we have continued expanding the scope, accuracy, and applicability of the optimization model and

\(^3\)Discharge Ports are usually located inside the recipient country, but may be located in neighboring countries (for instance when the recipient country is land-locked).
Figure 1: Illustrative example of a WFP supply chain. The figure shows how commodities move from international suppliers to discharge ports (by sea), from discharge ports to extended delivery points / warehouses, and from these warehouses to final delivery points.

Figure 2: High-level overview of the modeled supply chain network.
The supply chain network is sketched as per Figure 2. The demand (or sink) nodes are the Final Delivery Points (FDPs), where demand is defined per nutrient (based on the number of beneficiaries at the FDP and their nutritional requirements).

We define a ration variable that governs the commodities flowing into an FDP, ensuring that the food WFP sends is distributable and palatable. This link between nutrients, commodities, and rations resembles the flexible bill of materials sometimes found in the manufacturing industry (Ram et al. (2006)), where the end-product is a (monthly) food basket and the number of beneficiaries in the FDP the demand for this end-product. An interesting distinction is that in the manufacturing industry the end-product is fixed and the fulfilled demand is variable, whereas here we consider the fulfilled demand fixed (100%) and make the quality of the end-product variable. So, when there is a funding shortfall we prefer to supply a less nutritious food basket to all beneficiaries rather than supplying the full food basket to fewer beneficiaries. Product design and sourcing are traditionally done separate, and there is a lot of potential to improve end-to-end performance through joint decision-making (Novak and Eppinger (2001)).

Note that the model we are using at WFP is vast and needs to be able to handle a plethora of (mathematically trivial) constraints, such as sourcing restrictions, capacity utilization, beneficiary preferences, funding allocation, etc. The model defined below is a minimum working example of that vast model, capturing the core functionality without introducing too many WFP-specific details. A brief description of all additional components included in the full model can be found in Appendix A.

### 3.2 Sets

We define multiple sub-sets for the nodes in particular to ease the definition of constraints and statistics.

\[ \mathcal{N} \] = Set of nodes \((i, j \in \mathcal{N})\)
\[ \mathcal{N}_S \] = Set of Source nodes\(^4\)
\[ \mathcal{N}_{IS} \] = Set of International Suppliers
\[ \mathcal{N}_{RS} \] = Set of Regional Suppliers
\[ \mathcal{N}_{LS} \] = Set of Local Suppliers
\[ \mathcal{N}_{LM} \] = Set of Local Markets
\[ \mathcal{N}_P \] = Set of Procurement nodes \((\mathcal{N}_{IS} \cup \mathcal{N}_{RS} \cup \mathcal{N}_{LS} \cup \mathcal{N}_{LM})\)
\[ \mathcal{N}_{DP} \] = Set of Discharge Ports
\[ \mathcal{N}_{EDP} \] = Set of Extended Delivery Points
\[ \mathcal{N}_{FDP} \] = Set of Final Delivery Points
\[ \mathcal{K} \] = Set of commodities \((k \in \mathcal{K})\)
\[ \mathcal{G} \] = Set of food groups \((g \in \mathcal{G})\)
\[ \mathcal{L} \] = Set of nutrients \((l \in \mathcal{L})\)
\[ \mathcal{B} \] = Set of beneficiary types \((b \in \mathcal{B})\)
\[ \mathcal{T} \] = Set of months \((t \in \mathcal{T})\).

Note that the suppliers \((\mathcal{N}_{IS}, \mathcal{N}_{RS}, \mathcal{N}_{LS})\) provide access to commodities that WFP ships to Final Delivery Points \((\mathcal{N}_{FDP})\) using its network of Discharge Ports \((\mathcal{N}_{DP})\) and Extended

\(^4\)There are multiple source nodes feeding each procurement node, allowing us to capture additional details about origin countries and delivery terms (not important for the minimum working example).
Delivery Points ($N_{EDP}$). Local Markets ($N_{LM}$) provide beneficiaries with direct access to commodities when they receive a Cash-based transfer.

3.3 Parameters

Due to the unique nature of long-term food distribution we require some non-conventional parameters, such as nutritional values and feeding days.

- $\alpha$ = Conversion rate from Metric Tonnes (mt) to Grams (g) ($10^6$)
- $ben$ = The beneficiary type to be optimized ($ben \in B$)
- $cap^H_{it}$ = Handling capacity (in mt) of node $i \in N_{EDP} \cup N_{DP}$ in month $t$
- $cap^P_{ikt}$ = Procurement capacity (in mt) of commodity $k$ from source $i \in N_S$ in month $t$
- $cost_{ijkt}$ = Cost (in $/mt$) of moving commodity $k$ from node $i$ to node $j$ in month $t$
- $days_b$ = Current number of feeding days per month for beneficiaries of type $b$
- $dem_{bit}$ = Number of beneficiaries of type $b$ at node $i \in N_{FDP}$ in month $t$
- $dur_{ij}$ = Duration (in days) of moving from node $i$ to node $j$
- $group_k$ = The food group that commodity $k$ belongs to ($group_k \in G$)
- $hc_i$ = Handling costs (in $/mt$) at node $i \in N_{DP} \cup N_{EDP} \cup N_{FDP}$
- $inv_{ikt}$ = Incoming arrivals (in mt) of commodity $k$ at node $i \in N_{EDP} \cup N_{DP}$ in month $t$
- $ltp_{ij}$ = Duration (proxy, in days) to supply all FDPs if we procure from source $i \in N_S$ at node $j \in N_P$
- $nutreq_{bl}$ = Nutritional requirement of beneficiaries of type $b$ for nutrient $l$
- $nutval_{kl}$ = Nutritional value per gram of commodity $k$ for nutrient $l$
- $odoc^{CV}$ = Other Direct Operational Costs rate (in %) for C&V transfers
- $odoc^F$ = Other Direct Operational Costs rate (in $/mt$) for food transfers
- $rat_{bk}$ = Current ration size (gram/person/day) of commodity $k$ for beneficiaries of type $b$
- $sc_i$ = Storage costs (in $/mt/month$) at node $i \in N_{DP} \cup N_{EDP}$.

Handling/storage capacities ($cap^H_{it}$) are only tracked for Discharge Ports (DPs) and Extended Delivery Points (EDPs), although we can easily extend it to other nodes. Basically, the suppliers take care of any handling/storage taking place at Procurement nodes (most of WFP’s contracts are FOB or DAP\(^5\)) and WFP’s cooperating partners do the same at the FDP level. Costs ($cost_{ijkt}$) are captured for all movements through the supply chain network; movements between source nodes and procurement nodes incur procurement costs, other movements are transportation costs. Costs may change over time due to seasonality and stock market movements for procurement and due to rainy seasons for transportation. We split up demand ($dem_{bit}$) per location and beneficiary type, and allow it to change over time so we can phase out or scale up operations. It is important to distinguish between beneficiary types, because their nutritional requirements are vastly different. The needs of a child are very different from a newly arrived refugee or a nursing woman for example. The currently used food baskets ($rat_{bk}$) and their (monthly) feeding days ($days_b$) are pre-defined for each beneficiary type. The model optimizes one of these baskets at a time ($ben$), and supplies the other beneficiary types with their pre-defined basket. Optimizing

\(^5\)FOB and DAP are Incoterms, a series of pre-defined commercial terms published by the International Chamber of Commerce’s (ICC). See http://www.iccwbo.org/products-and-services/trade-facilitation/incoterms-2010/the-incoterms-rules/.
all food baskets simultaneously is of course mathematically possible, but very impractical (especially when WFP does not have enough funding to supply all nutrients to all beneficiaries - whose ration should be cut?). We use \( inv_{ikt} \) to model initial inventories and incoming shipments, allowing us to easily integrate the model’s decisions with the current status of an operation. Other Direct Operational Costs (ODOC) \( (odoc^F \text{ and } odoc^{CV}) \) are surcharges per transfer modality that take care of additional costs that are incurred beyond the procurement, transport, storage, and handling of the commodities (such as milling, packaging, monitoring, reporting, etc.).

3.4 Variables

The two major variables are the ones governing commodity flows \((F_{ijkt})\) and ration sizes \((R_{kt})\), the others are mainly used to calculate statistics.

\[
\begin{align*}
F_{ijkt} &= \text{Metric tonnes of commodity } k \text{ sent from node } i \text{ to node } j \text{ in month } t \\
R_{kt} &= \text{Grams/ration of commodity } k \text{ in the food basket of month } t \\
S_{lt} &= \text{Percentage shortfall (slack variable) for nutrient } l \text{ in month } t \\
O_{lt} &= \text{Percentage overshoot (slack variable) for nutrient } l \text{ in month } t \\
SFI_{lt} &= \text{Binary indicator, 1 if there is a shortfall for nutrient } l \text{ in month } t \\
P_{ijt} &= \text{Binary indicator, 1 if food is procured from source } i \text{ at procurement node } j \text{ in month } t \\
LT_t &= \text{Maximum lead time (in days) of commodities purchased in month } t.
\end{align*}
\]

3.5 Objectives

In order to adequately track and constrain the model’s outputs we define dozens of statistics (all linear combinations of the variables). For this minimum working example we focus on just five of them:

\[
\begin{align*}
TOC &= \text{Total Operation Cost (Efficiency)} \\
NVS &= \text{Nutritional Value Score (Effectiveness)} \\
DEV &= \text{Local Expenditures (Development)} \\
ALT &= \text{Average Lead Time (Agility 1)} \\
MLT &= \text{Maximum Lead Time (Agility 2)}.
\end{align*}
\]

A multi-objective approach that allowed users to optimize any of the statistics was included in earlier versions of the model, but we discarded it for the sake of solvability. We found that the solution times are significantly higher (3-20x) when incorporating performance measures other than costs into the objective function. Because of this big difference in solution speed, it is more practical to use the other statistics as constraints (akin to a goal programming approach).
We define the five main measures as follows:

\[
TOC = \sum_{i \in N} \sum_{j,k,t} \text{cost}_{ijkt} \times F_{ijkt} \\
+ \sum_{i \notin N} \sum_{j \neq i, k, t} \text{cost}_{ijkt} \times F_{ijkt} \\
+ \sum_{i \in \text{DP} \cup \text{EDP}} \sum_{k,t} \text{sc}_i \times F_{iikt} \\
+ \sum_{i \in \text{DP} \cup \text{EDP}} \sum_{j \neq i, k, t} \text{hc}_i \times F_{ijkt} + \sum_{j \in \text{FDP}} \sum_{i,k,t} \text{hc}_i \times F_{ijkt} \\
+ \sum_{i \in \text{NLM}} \sum_{j \notin \text{NLM}, k, t} \text{odoc}^F \times F_{ijkt} \\
+ \sum_{j \in \text{NLM}} \sum_{i,k,t} \text{cost}_{ijkt} \times \text{odoc}^CV \times F_{ijkt}
\]

\[
NVS = \frac{\sum_{l,t} (1 - S_{lt})}{|\mathcal{L}| \times |T|} \times 100\% 
\]

\[
DEV = \frac{\sum_{j \in \text{NLM} \cup \text{NLS}} \sum_{i,k,t} F_{ijkt}}{\sum_{j \in \mathcal{N}_P} \sum_{i,k,t} F_{ijkt}} \times 100\%
\]

\[
ALT = \frac{\sum_{i,j,k,t} \text{dur}_{ijk} \times F_{ijkt}}{\sum_{i,j,k,t} F_{ijkt}}
\]

\[
MLT = \max_t LT_t.
\]

The optimization objective, the Total Operation Cost, consists of the following components: the procurement costs (1), the transportation costs (2), the storage costs (3), the handling costs (4), the ODOC costs for food (5), and the ODOC costs for C&V (6). For WFP the \(TOC\) measure makes the most sense, because a lower cost per beneficiary means that it is able to supply more beneficiaries from the available funding\(^6\). The other four measures are used as constraints in this paper to ensure that the resulting solutions are in line with the objectives of the operation that is being optimized.

We measure effectiveness (7) using the Nutritional Value Score (as developed by Ryckembusch et al. (2013)). We know the nutritional profile of the targeted beneficiaries and the nutritional contents of our food basket; the NVS measures how close the current food basket is to the required nutrients. It is defined as the sum of the delivered percentages for each nutrient \(l\), where we truncate the delivered nutrients at 100\% (i.e. the score does not improve if you supply more than necessary). In practice, this means that we can just sum the (reversed) shortfalls. The maximum value for this statistic is then the amount of nutrients that are being tracked (11 at WFP), which is not a very intuitive measure. We adjust the measure slightly by dividing the original NVS by the amount of nutrients. To adequately measure the NVS performance across the time horizon we also average it over the months. The NVS defined here therefore measures the average requirements supplied across all nutrients, with a maximum value of 100\% when we supply at least 100\% of the requirements for each of the tracked nutrients in each of the months in the time horizon.

\(^6\)WFP relies entirely on voluntary contributions to finance its humanitarian and development projects, most of which come from governments.
Humanitarian organizations prefer using local businesses to source and supply food, as this contributes to the development of the country. As a performance measure we consider the percentage of commodities purchased locally (8). Note that even though the ‘percentage purchased’ measure is non-linear, upper and lower bounds (goals) for this measure can be included as linear constraints.

For the lead times (which are notoriously hard to capture in linear programming models) we use two proxy measures. One is a maximum lead time proxy variable (10), which is used when WFP needs to respond to a disaster fast (i.e. they need to get a food basket inside the country within \( x \) days). In practice however, we generally apply this model to long-term recovery operations. This means that there is always food on its way to the recipient country, there are inventories in the warehouses, commodities with a long lead time are being pre-positioned, etc. Maximum lead times are of less concern in such a scenario. Additionally, if one commodity has a long lead time but the others can be supplied quickly, the maximum lead time does not reflect the agility of the supply chain well. The second proxy measure is therefore the average number of days that it takes for a metric tonne of food to arrive at its destination after being ordered (9). Note that this is again a non-linear measure that can be modeled as a linear constraint.

### 3.6 Constraints

In the implementation of the optimization model we make a distinction between constraints that always hold and optional constraints. For the minimum working example, we focus on the former. Through a graphical user interface, WFP officers may impose additional context-specific constraints such as beneficiary preferences, long-term supplier agreements, funding restrictions, etc. Most of those (optional) constraints are mathematically trivial though.

\[
\sum_j F_{ijkt} = \text{inv}_{ikt} + \sum_{(j,i,k,t^*) \in \mathcal{A}(i,k,t)} F_{jikt^*} \quad \forall i \in \mathcal{N}_T \forall k,t. \quad (11)
\]

Constraint (11) is the traditional ‘flow in = flow out’ constraint for the transshipment nodes. The parameter \( \text{inv}_{ikt} \) contains initial inventories and incoming shipments that are already underway when running the tool. \( \mathcal{A}(i,k,t) \) are pre-generated sets that contain the indices of all flow variables \( F_{jikt} \) that arrive in transshipment node \( i \) with commodity \( k \) at time \( t \), generated based on their lead times (\( \text{dur}_{ij} \)). They are currently defined as follows:

\[
\mathcal{A}(i,k,t) = \{(j, i, k, t^*) : t^* + f(\text{dur}_{ji}) = t\} \quad \forall i, k, t
\]

\[
f(t) = \left\lfloor \frac{t}{30} \right\rfloor + \mathbb{1}_{\{t \mod 30 > 20\}},
\]

so we look at the duration of each arc and transform the lead time in days to a lead time in months, using a cut-off point of 20 days. This cut-off point is very context-specific and may need to be revised when applying this algorithm to non-WFP supply chains.

\[
\sum_j F_{jikt} \times \alpha = \text{dem}_{ben, it} \times \text{days}_{ben} \times R_{kt} + \sum_{\text{b}\neq \text{ben}} \text{dem}_{b\text{it}} \times \text{days}_{b\text{t}} \times \text{rat}_{bk} \quad \forall i \in \mathcal{N}_{FDP} \forall k,t. \quad (12)
\]

Constraint (12) states that the flow into an FDP must equal its demand (amount of beneficiaries times feeding days times daily ration for commodity \( k \) plus any additional requirements
for that commodity from other beneficiary types). Note that we multiply incoming flows by \( \alpha = 10^6 \), which converts the metric tonnes values to grams (which is how food baskets are specified).

\[
F_{ijkt} \leq \text{cap}^P \times P_{ijt} \quad \forall i \in \mathcal{N}_S \quad \forall j, k, t. \quad (13)
\]

Constraint (13) specifies that the procurement flow must remain lower than its capacity. Multiplying the capacity by the binary variable \( P_{ijt} \) allows us to track maximum lead times, as follows:

\[
LT_t \geq P_{ijt} \times \text{lt}_{ij} \quad \forall i \in \mathcal{N}_S \quad \forall j, t. \quad (14)
\]

Recall that \( \text{lt}_{ij} \) is a proxy for the lead time when purchasing commodities in node \( j \) from source \( i \). We currently generate this value by applying Dijkstra’s Shortest Path Algorithm to get the fastest route to each of the FDPs and taking the maximum of those values. The lead time proxy then reflects the shortest time it takes to reach all FDPs when a commodity is procured this way. If this is the only source for this commodity, the proxy value is accurate. If multiple sources are used to supply the same commodity in some month, this proxy is an upper bound. In practice however, it is uncommon to have multiple sources for the same commodity in the same month (the sources do change over time to benefit from price seasonality).

\[
\sum_k F_{ijkt} \leq \text{cap}^T \quad \forall i, j, t. \quad (15)
\]

Constraint (15) bounds the flow between nodes, so that the flow cannot exceed the (transportation) capacity of an arc. Note that arc capacities may change over time because of hazardous conditions (security, rainy seasons, etc.).

\[
\sum_{jk} F_{jikt} \leq \text{cap}^H \quad \forall i \in \mathcal{N}_{DP} \cup \mathcal{N}_{EDP} \quad \forall t. \quad (16)
\]

Constraint (16) bounds the flow through a node (based on handling capacity rather than transportation capacity).

\[
\sum_k \text{nutval}_{kl} \times R_{kt} = \text{nutreq}_{ben,l} \times (1 - S_{lt} + O_{lt}) \quad \forall l, t. \quad (17)
\]

Constraint (17) states that the supplied nutrients must cover the requirements. To ensure that the slack variables for shortfalls (\( S_{lt} \)) and overshoots (\( O_{lt} \)) are working as intended, we need to make sure that they are never positive at the same time. For this we use the shortfall indicator:

\[
S_{lt} \leq SFI_{lt} \quad \forall l, t
\]

\[
O_{lt} \leq (1 - SFI_{lt}) \times 10 \quad \forall l, t. \quad (18)
\]

Note that \( S_{lt} \) is a continuous variable between 0 and 1, whereas the overshoot is only bounded from below (maximum nutrient intakes are not as well defined as minimum nutrient intakes).

When leaving all food basket choices up to the model, it will choose the most cost-effective way to supply all nutrients, regardless of the palatability of the resulting food basket. This may mean that a daily ration consists of half a kg of peas, that it includes large amounts of fortified food (not very palatable and with limited supply), or even 200 milliliters of oil. All these instances, and more, were found during test scenarios. Intuitively,
Table 1: The sensible food basket constraints (in grams per person per day) for each food group. These ration sizes are tailored for General Food Distribution (GFD), which is the bulk of WFP distribution.

<table>
<thead>
<tr>
<th>Food Group</th>
<th>minrat&lt;sub&gt;g&lt;/sub&gt;</th>
<th>maxrat&lt;sub&gt;g&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals &amp; Grains</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Pulses &amp; Vegetables</td>
<td>30</td>
<td>130</td>
</tr>
<tr>
<td>Oils &amp; Fats</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Mixed &amp; Blended Foods</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Meat &amp; Fish &amp; Dairy</td>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>

these solutions make no sense and are therefore not credible (despite being the cost-optimal way of delivering the nutritional requirements). Through interviews with nutrition experts and food basket designers, the ‘unwritten rules’ for food baskets were brought to light and quantified. The following constraints result in sensible food basket outputs:

\[
\begin{align*}
\sum_{k:\text{groups} = g} R_{kt} & \geq \text{minrat}_g \quad \forall g, t \\
\sum_{k:\text{groups} = g} R_{kt} & \leq \text{maxrat}_g \quad \forall g, t \\
R_{\text{Iodised Salt},t} & \geq 5 \quad \forall t \\
S_{\text{Energy},t} & \leq 0.1 \quad \forall t \\
S_{\text{Protein},t} & \leq 0.1 \quad \forall t \\
S_{\text{Fat},t} & \leq 0.1 \quad \forall t,
\end{align*}
\]

with minrat<sub>g</sub> and maxrat<sub>g</sub> values as given in Table 1. Following these constraints, the rations consist of plenty of staple foods (grains and pulses) to make two or three dishes per day, oil to satisfy fat requirements and for cooking, some fortified foods to prevent malnutrition, and iodised salt to satisfy iodine and sodium requirements. Additionally, we make sure that the three most important nutrients have at most a very small shortfall. Naturally, extra constraints should be added to capture the preferences of the targeted beneficiaries (which may differ a lot between different tribes or countries of origin). Note that these constraints are geared towards so-called General Food Distribution (GFD), which is the ration that we supply to most (if not all) targeted beneficiaries in a country. Beneficiaries with additional needs (kids, pregnant and nursing women, newly arrived refugees, etc.) receive the required supplements on top of this GFD basket. These constraints are disabled when we optimize non-GFD baskets.

Lastly, we add some non-negativity constraints:

\[
\begin{align*}
F_{ijkt} & \geq 0 \quad \forall i, j, k, t \\
R_{kt} & \geq 0 \quad \forall k, t \\
S_{lt} & \geq 0 \quad \forall l, t \\
O_{lt} & \geq 0 \quad \forall l, t \\
LT_i & \geq 0 \quad \forall t.
\end{align*}
\]
3.7 Solution approach

The mathematical model is formulated in Python, and solved using the COIN-OR solver (Saltzman (2002)). We connect to the COIN-OR solver using the PuLP module (Mitchell et al. (2011)). PuLP does not support multi-threading, so all calculations are done using a single processor at 2.5GHz. The coding language, solver, and module are all freeware, making the tool easy to implement.

The mathematical model is solved exactly, but we do a lot of pre-processing in Python to keep the problem size as small as possible. By cleaning and filtering the input data we prevent redundant variables and constraints. Additionally, we split up the constraints of the mathematical model into core constraints and situational constraints. This allows us to quickly set up new instances of the optimization model when doing scenario analyses.

Users can interact with the mathematical model through a Graphical User Interface (GUI), coded in Python (see Figure 9 in the Appendix). This GUI allows them to add operational constraints, specify goals for the key outputs, and gives them access to a range of automated analyses. Results from their analyses are automatically collected in elaborate Excel files that provide quick insights into all of the important decision variables (food basket composition, sourcing plan, delivery plan, etc.) and the resulting performance (through pivot tables, charts, etc.).

3.8 Verification and validation

When using analytics to (re)design or manage an operation, it is of paramount importance that the model is verified and validated. Seeing as many of WFP’s officers were analytically averse\(^7\), this was crucial. We developed the optimization model and tool over the course of more than two years, in close collaboration with the end users (WFP decision makers in the field). Through iterative development we were able to identify the required capabilities, model them, and ensure that they are implemented correctly.

When collaborating with WFP’s Country Offices, we ensure that we mirror their budgeted costs when imposing the current solution on the optimization model. This allows us to quickly compare the model’s calculations with theirs, which immediately highlights any components that are estimated differently or where some unmodeled costs are incurred. The latter triggers a series of in-depth discussions where we identify the unmodeled costs and find a way to introduce them into the mathematical model.

An other form of validation we use regularly is comparing the current solution to unrestricted solutions from the optimization tool, allowing us to rapidly identify operational constraints and preferences. This approach also generates strong buy-in from the local experts, because they start appreciating the scope, flexibility, and speed of the optimization tool.

3.9 Assumptions and limitations

Every optimization tool of this size comes with a list of assumptions and limitations; we highlight the most important ones.

We assume that every beneficiary (of a certain type) receives the same food basket, and that no beneficiary goes unfed. This assumption is based on the humanitarian principles of

\(^7\)There used to be a general consensus that humanitarian operations are too difficult to model and optimize.
humanity and impartiality - it would be unethical to feed only those beneficiaries that are conveniently located for instance.

We do not model the transportation network between suppliers ($N_{IS}, N_{RS}$) and loading ports. WFP floats tenders in specific countries to ensure competitive prices, which means that price forecasts are done on a country level. This means that the suppliers may differ every time WFP orders, making the cost from a supplier to the loading port difficult to estimate. Generally WFP requests FOB (Free On Board) offers, which means that the supplier takes care of the transportation up to the loading of the ship at a major port in their country.

Costs are captured using $/mt$ rates. Given WFP’s scale of economy\(^8\) and the type of contracts that it usually has with transportation companies, these linear rates are representative of the actual costs.

The current model is not robust against uncertain parameters (such as costs, lead times, and capacities). While we recognize the importance of robustness in optimizing humanitarian supply chains, the introduction of robust optimization has been put on hold until WFP improves its data and becomes more analytically mature. In parallel to the rollout of the optimization tool described in this paper, we are developing advanced forecasting algorithms for WFP’s uncertain data. In lieu of high-quality forecasts, robust optimization is moot. In the meantime we verify with WFP’s business experts that the used parameter values are the current ‘best guess’, and base our analyses on that.

The model allows for the optimization of one beneficiary type at a time (other beneficiary types will be provided with their pre-defined food basket). It is mathematically possible to optimize all food baskets simultaneously, but it would require us to weigh the nutritional requirements of one beneficiary type against those of another. We chose to avoid this controversial topic and instead optimize the food baskets individually. In practice we see that there are usually only one or two beneficiary types that receive a big food basket (so-called General Food Distribution (GFD)), other beneficiary types generally receive a single supplemental commodity (on top of the GFD ration) specifically tailored to their age or level of malnutrition. These supplemental rations rarely benefit from food basket optimization.

4 Applications

The mathematical model presented in this paper is the result of iterative development over more than two years. Through regular pilots we were able to identify what data is reliably available, what kind of analyses are the most impactful, and how the optimization tool fits in WFP’s business processes. Additionally, we use these pilots to continuously verify and validate the mathematical model underlying the tool by scheduling in-depth sessions with experts throughout the organization and by comparing the tool’s outputs to historical performance.

During the course of 2015, optimization gained a lot of traction within WFP. At present, the model is used almost weekly to provide WFP’s biggest and most complex operations with optimization support, most notably Syria (4 million beneficiaries), Ethiopia (8 million), Iraq (2 million), and Yemen (3 million). Together, these four operations account for about 17 million beneficiaries - a fifth of WFP’s average yearly workload. In this section we highlight some of the results we achieved in Iraq and Yemen in particular, and show how

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\(^8\)WFP ships around 4 billion kilograms of food every year.
different types of analyses are being used to support strategic decision making in WFP’s most complex operations.

4.1 Iraq

The humanitarian situation continues to deteriorate in Iraq amidst ongoing violence that has forced more than three million people to leave their homes. Most of them are living without access to food, water and other essentials. This is in addition to an estimated 250,000 Syrian refugees residing in the north. In total, around 4.4 million people require some sort of food assistance in Iraq (WFP (2015a)).

WFP has been operating in Iraq since 1991, and has provided food assistance in the country since April 2014 through emergency operations to assist those hundreds of thousands Iraqis forced from their homes by recent violence. In the face of further mass displacement from major Iraqi cities, such as Mosul and Ramadi, WFP scaled up activities to reach an average of 1.5 million people per month in all 18 governorates, including hard-to-reach areas. WFP is assisting people through monthly family food parcels for those with access to cooking facilities, food vouchers that can be redeemed at local shops, and ready-to-eat food known as Immediate Response Rations that provide a family of five with food for three days.

WFP’s operations in Iraq are often facing funding shortfalls, so it is vital that the operation’s design is as cost-effective as possible. In October 2015 Iraq’s Country Office requested optimization support to redesign their food basket for different levels of funding, allowing them to supply as many kilocalories as possible from the donations that they receive.

We worked intensively with their supply chain management team to gather all the necessary data and to identify operational constraints (with respect to procurement, logistics, transfer modalities, beneficiary preferences, etc.). Once we had a good grasp of the situation we ran dozens of analyses using the optimization tool to identify alternative designs that could improve the performance of the operation. Many of the solutions were pushing the envelope, so a lot of back and forth was necessary to verify the feasibility of these solutions. This intense collaboration and back and forth resulted in their supply chain management team feeling a strong sense of ownership of the final outcomes, resulting in a rapid implementation of the final recommendation.

One of the main deliverables to Iraq’s management team was Figure 3, containing our recommendations for Iraq’s Family Food Parcel (FFP) - supplied to half a million Iraqis every month. The first column represents the latest official food basket (BR4), supplying 1844 kilocalories (daily) at a cost of 13.13 USD per beneficiary per month. Each subsequent column is an optimized basket that uses different interventions (commodity swaps, ration adjustments, etc.) to improve the cost-effectiveness of the operation. Iraq officially adopted the food basket represented by the last column, supplying 1761 kilocalories (98% of the 1800 kcal target) and 69.6% NVS (1% increase) at a cost of 10.89 USD per beneficiary per month (17% reduction). Since the FFP is supplied to 500,000 beneficiaries every month, this adoption corresponds to 1.12M USD monthly savings. This means that WFP can supply the same amount of beneficiaries with a nutritious food basket in case of up to 1.12M USD funding shortfall per month, or these 17% savings can be used to supply an additional 85,000 (17%) beneficiaries with a FFP every month if funding remains at the same level. As of April 2016, the optimized food basket is being used to support 800,000 beneficiaries in Iraq, with positive feedback from the beneficiaries regarding the changes in commodities.
Figure 3: An overview of alternative food baskets for Iraq’s Family Food Parcel (FFP). We compare the kilocalories and cost per beneficiary per month of each option (as given by the acronyms on the x-axis). The acronyms show how the food basket changed compared to the original food basket (BR4). RIC=Rice, BUL=Bulgur Wheat, WHF=Wheat Flour, SRL=Split Red Lentils, WRL=Whole Red Lentils, WIB=White Beans, CHK=Chickpeas, HOB=Horse Beans, OIL=Sunflower Oil, SUG=White Sugar. A '+' or '-' denotes an increase or decrease in the current ration size. A '0' denotes a removal of the commodity, whereas the '2' denotes that we change commodity a to commodity b using the same ration size. Ration size increments are pre-defined and based on commercial packaging types for that specific commodity. The last option has been implemented in practice, resulting in a cost reduction of 17% while supplying 98% of the target kilocalories.
and ration sizes compared to the previous food basket.

4.2 Yemen

The situation in Yemen is characterized by large-scale displacement, civil conflict, food insecurity, high food prices, endemic poverty, diminishing resources, and influxes of refugees and migrants. Between mid-2014 and mid-2016, WFP aimed to provide six million people with food and cash assistance whilst also working to build communities’ resilience. In 2014, WFP conducted a Comprehensive Food Security Survey which found that 41 percent (10.6 million people) of the population is food insecure. Some five million of those are severely food insecure - unable to buy or produce the food they need - and 5.6 million people are moderately food insecure. Child malnutrition rates are among the highest in the world, with global acute malnutrition rates ranging from critical - denoting an emergency - in Al Hudaydah, Hajjah and Taizz, to poor or serious in almost all other governorates (WFP (2015b)).

WFP has been in Yemen since 1967. The organization’s main operation - a protracted relief and recovery operation (PRRO) - aims to reach six million people between mid-2014 and mid-2016 with 366,734 metric tons of food and US$74.5 million in cash and vouchers at an overall cost of US$491 million. The operation is supporting a shift from relief assistance to recovery and resilience to promote food and nutrition security. Beneficiaries include internally displaced persons and returnees, vulnerable populations in the most food insecure areas, people affected by transient crises, infants, pregnant and nursing women affected by acute and chronic malnutrition, and school-age children.

Since the start of the main operation WFP has gradually been scaling up towards the six million beneficiaries, which is proving to be a herculean task in light of the limited resources available and the escalation of conflict within Yemen. As of December 2015 they are reaching three million beneficiaries with in-kind food assistance, and aim to reach five million by February 2016. Cash-based transfers are being scaled up to one million beneficiaries in parallel, allowing WFP to reach 6 million people with life-saving assistance. In November 2015 Yemen’s management team requested optimization support for their pending scale-up from three to six million beneficiaries.

Similar to our approach in Iraq (and all other applications), we worked intensively with their management team to gather the necessary data and identify all operational constraints from a supply chain and donor/beneficiary preference perspective. We were requested to keep the commodities in the food basket as is, and focus mainly on the optimization of ration sizes. Seeing as distribution is done in active war zones, we designed the food baskets in such a way that the monthly ration for each family (of six) corresponds to an industry-standard packaging size - making distribution as fast and seamless as possible. We presented a breakdown of our recommendations in the form of a column chart similar to the one used in Iraq, but the most powerful deliverable was a Beneficiary Matrix.

The Beneficiary Matrix (Fig. 4) shows the interdependence of funding levels, nutritional targets, and beneficiary numbers. It shows decision makers how much it costs to supply different numbers of beneficiaries with the current food basket, and how alternative food baskets allow WFP to either cope with funding shortfalls (without cutting down on beneficiary numbers) or to increase the number of beneficiaries reached with the available funding (by cutting down on nutrition). For example, suppose we are supplying 4 million beneficiaries with the current food basket and we would like to scale up to 5 million. The matrix shows us that supplying 5 million beneficiaries with the current basket would cost
Figure 4: This Beneficiary Matrix (Yemen) shows the interdependence of funding levels, nutritional targets, and beneficiary numbers. Columns 2 and 3 show the performance of a food basket (column 1). We display the cost per beneficiary per month and the kilocalories (with the NVS score between brackets) as percentage of the minimum daily requirements. Columns 4 to 14 show how many beneficiaries we can supply (in million beneficiaries per month) with these food baskets under different funding scenarios (ranging from 20 to 100M USD per month). For example, the current food basket can supply 4M beneficiaries if WFP receives 55M USD per month, and 5M beneficiaries in case WFP receives 70M USD per month.

70M USD per month (15M USD (27%) more than the current cost). Alternatively, we could reach the 5 million beneficiaries by slightly reducing the nutrition levels of the food basket. In this case, we can observe that there is a food basket (WHE50 SYP10 OIL7 WSB10) that supplies 5 million beneficiaries with 80% kilocalories and 90% NVS for the same level of funding (55M USD). Insight into this trichotomy allows WFP to manage their scale-up to 6 million beneficiaries properly, and enables it to communicate clearly to donors what is required from them if WFP is to reach all people at risk within Yemen with nutritious food.

4.3 Other Applications

Our applications in Iraq and Yemen demonstrate the huge added value that optimization brings to WFP’s operations, but they show only a small breadth of the functionality that the underlying optimization model can bring to bear. In this subsection we show some other powerful analyses that can be done with the current optimization tool. These analyses allow us to explore the solution space, and by discussing the resulting insights with local supply chain teams we can come to realistic final recommendations that take into account all operational restrictions and preferences. Note that all analyses below were done with real data, but we keep the projects and countries anonymous to respect requests for confidentiality.

4.3.1 Trade-off analyses.

The mathematical model we defined has a single objective (total cost), but we tend to evaluate solutions using multiple metrics (efficiency, effectiveness, agility, and development). We use a goal programming approach to find Pareto-efficient curves for these metrics, providing
insight into what kind of outcomes are achievable and how this would affect the cost of the operation. We highlight two of these trade-off analyses in particular: one for the Nutritional Value Score (effectiveness) and one for the Cash-Based Transfer Ratio (development).

The Nutritional Value Score Trade-off curve (Fig. 5) shows the lowest cost at which WFP can attain different levels of nutrition (effectiveness). Each plot represents a solution to the mathematical model, i.e. it corresponds to an optimized food basket, sourcing plan, and delivery plan that takes into account all user-added constraints. Ideally WFP supplies 100% of the Minimum Daily Nutrient Requirements, but depending on the context (available funding, amount of beneficiaries in need, access to nutritious commodities) this may not be realistic. With this trade-off graph we show the decision makers the price tag of supplying different levels of nutrition. In Fig. 5 for instance, we can see that supplying 95% of the required nutrients reduces the cost of the operation from 10.8M USD to 8.8M USD (18.7% reduction). This means that we could still supply all beneficiaries with 95% of their requirements if our funding is 18.7% short, and alternatively that we could reach 15-20% more beneficiaries with 95% of their requirements if there is no funding shortfall.

The Cash-Based Transfer Ratio Trade-off (Fig. 6) shows the lowest cost at which WFP can attain different levels of Cash & Voucher transfers. Cash-based transfers (CBT) are very popular among WFP donors at the moment, because of the positive effects they have on local markets and the dignity of beneficiaries. In most countries CBT is more expensive than supplying the food in-kind however, so it is important to assess whether the premium price weighs up against the non-quantifiable benefits. With this graph we show the most cost-effective level of CBT, and how the cost increases as one deviates further from the
Figure 6: The Pareto-efficient curve for the Cash-Based Transfers metric. For different levels of CBT (as percentage of the total metric tonnes distributed) the optimization tool finds the cheapest food basket, sourcing plan, and delivery plan. On the y-axes we have the cost per beneficiary per month (left) and the cost of the entire operation per month (right). Note that the cost per beneficiary per month is calculated for beneficiaries that receive this food basket, whereas the operation costs also include every other activity in that country.
optimal ratio. We can observe (Fig. 6) that initially the cost decreases when increasing CBT, as the model will start supplying the most remote FDPs and the most cost-effective local commodities through conditional vouchers. Increasing CBT further means that the model has to start using less cost-effective local commodities in order to supply the required nutrients. The example shows that the optimal ratio for this project was 33%, but that we could scale up to 70% CBT with only a small increase in cost (0.9M USD; 4.4%). Decision makers have to weigh the (non-quantifiable) added value of increasing CBT for local markets and beneficiaries against this increase in cost.

4.3.2 Food basket redesign.

Whereas the trade-off analyses are most useful for strategic decision making (since they may require drastic overhauls from an existing operation), in practice we try to stay close to the current design of the operation (making any recommendations much easier to implement). We highlight two types of analyses that allow us to use slight redesigns of the current food basket to improve the performance of an operation: a commodity swap analysis and an optimization of ration sizes.

![Commodity Swap Analysis – Cereals & Grains](image)

Figure 7: This Commodity Swap Analysis shows the impact of swapping one commodity (from the Cereals & Grains food group) on nutrition and cost. The y-axes show the efficiency, with the cost per beneficiary per month on the left and the monthly operation costs on the right. On the x-axis we show the effectiveness, as percentage of the minimum daily nutrient requirements. Each plot corresponds to a unique food basket (incl. its optimal sourcing and delivery plan), with the blue circle representing the current food basket. All plots that are below and to the right of the circle are therefore strict improvements (from a cost and nutrition perspective respectively).

The Commodity Swap Analysis (Fig. 7) shows the impact of swapping one commodity in the current food basket on the performance of the operation - in this case on the supplied nutrients (effectiveness) and operation costs (efficiency). The graph shows an analysis of
cereals and grains for one of WFP’s projects. Each iteration we replace one of the cereals/grains in the current food basket with a cereal/grain that is not currently included (using the same ration size). We can observe for example that replacing the Wheat in the current basket with White Maize would increase the NVS by 0.3%-points, while reducing the cost of the operation by 4.5M USD (26.5%). Decision makers can combine these quantitative insights with context-specific constraints (such as donor and beneficiary preferences) to find the best food basket design. For instance, changing to Sorghum/Millet makes no sense if the beneficiaries have no idea how to prepare this grain, no matter how cost-effective it is.

Figure 8: This graph displays the optimal ration sizes for different levels of nutrition. On the y-axis we display the ration size in grams per person per day, while the x-axis shows different effectiveness levels (measured in kilocalories). Each column corresponds to a food basket (composed of a combination of the 9 commodities with ration sizes as given on the y-axis) and displays the total cost per month.

The Optimal Ration Size Analysis (Fig. 8) shows how the current food basket can be adjusted to become as cost-effective as possible for different performance measures (in this case we consider a nutritional target - kilocalories). When doing this type of analysis we add additional constraints that guide the composition of the food basket, to make sure that all optimized food baskets are in fact implementable. The graph shows clearly which commodities are the most cost-effective (the ones that are increased first) when it comes to supplying energy - in this case the Wheat Flour is better than the Bulgur Wheat which in turn is better than the Rice. The columns show the cost (Millions USD per month) for each of the food baskets. We regularly use this kind of analysis to help WFP decide which ration sizes to cut in case of a funding shortfall, as it helps to provide as much nutrition as possible given the available funding.
5 Evolution

Historically, WFP has had a siloed approach to managing and optimizing its supply chains. With humanitarian operations becoming increasingly complex, the need arose for cross-functional innovations that consider WFP’s operations holistically. Initial ad-hoc analyses by WFP’s Logistics & Supply Chain Development Unit showed that there was a huge potential for savings in Syria by integrating the decisions of the Procurement and Logistics teams - a thorough (cross-functional) analysis of the sourcing strategy, corridor allocation, and supply chain network design led to savings of two million USD. The analysis was performed by modeling Syria’s operation in Excel and using the built-in Excel Solver to find improvements.

From this initial analysis two things became clear. Firstly, while it was possible to optimize sourcing and delivery for a WFP operation using the Excel solver it was a very labor intense and cumbersome process. Secondly, it was noted that the sourcing and delivery solution was heavily dependent on the project design, i.e. the food basket that beneficiaries were supposed to receive and the way in which they were supposed to receive it (food, cash, or voucher). Changing even one commodity would have effects that rippled throughout the entire sourcing and delivery strategy. Integrating project design decisions into the Excel solver proved too difficult however, so WFP reached out to its partner universities to develop a model and tool that could cope with the complexity of connecting project design decisions to traditional sourcing and delivery decisions.

In 2014 students from Georgia Tech (USA) and Tilburg University (The Netherlands) developed a tractable prototype that connected the major decisions, which was then piloted in Syria during a redesign of WFP’s operation there. Through optimization we were able to identify concrete savings opportunities, and we recommended a range of food basket adjustments that led to significant savings throughout 2015 (23 million USD). Our collaborative approach to optimization, and our ability to rapidly analyze, quantify, and visualize key decisions resulted in traction for optimization initiatives. Since then we have been focusing on improving the accuracy, scope, and user-friendliness of the prototype, while institutionalizing optimization as a management tool and supporting WFP’s biggest and most complex operations with ad-hoc analyses using the model.

Moving forward, we are investing heavily on data quality and availability, enabling us to fully reap the benefits of optimization. Future work includes the development of advanced forecasting methods for local market prices, and extending the existing model with robustness against uncertainty in procurement prices and port capacities. In parallel, we are developing a similar model that enables us to optimize the use of scarce resources (mainly supplier capacities, corporate stocks, and port capacities) at global and regional planning levels, which is to facilitate WFP’s S&OP process.

6 Conclusion

Optimization has become an enabler for cross-functional collaboration at WFP. By integrating key decisions, performance measures, and operational constraints for all major components of WFP’s supply chain into one model, WFP is now able to rapidly assess the impact of major decisions (e.g. food basket design, sourcing strategy) on its overall performance. By connecting the composition of the food basket and the supply chain that is necessary to deliver it, we are able to increase the efficiency and effectiveness of WFP operations,
ensuring that WFP can supply life-saving assistance to as many people in need as possible with the available funds.

Applications in Iraq and Yemen, two of WFP’s most complex emergencies, have demonstrated the added value of optimization in managing humanitarian operations. In Yemen, optimization is enabling the supply chain management team to scale up its operation from three to six million beneficiaries through rapid evaluation of the trichotomy between beneficiary numbers, food basket quality, and available funding. This insight allows the supply chain management team to responsibly scale up the operation, while providing donors with evidence-based information about the resources necessary to reach all people in need and the impact of lack and / or untimeliness of resources on beneficiaries and operational costs. In Iraq, optimization enabled the supply chain management team to reduce the cost of general food distribution (supplying 800,000 beneficiaries with their daily nutritional needs) by more than seventeen percent, while providing additional micro-nutrients and 98% of the targeted kilocalories. Through a global rollout of the model we will be able to provide similar support to all eighty million beneficiaries currently being supported by the World Food Programme.
A All Model Constraints

In Section 3 we define a Minimum Working Example (MWE) of the model in use at WFP. For the sake of completeness, we provide a comprehensive list (in words) of all constraints that are included in the full model. Constraints that have been formalized for the MWE include a reference.

Flow preservation (11). The traditional ‘flow in = flow out’ constraint for transshipment nodes in the network flow model.

Supply demand (12). The flow into a Final Delivery Point must equal its demand.

Procurement capacity (13). The procurement flows are bounded by supplier capacities.

Arc capacity (15). The commodity movements are bounded by transportation capacities.

Node capacity (16). Commodity movements into a location are bounded by its handling/storage capacity.

Nutritional requirements (17). The optimized food basket must satisfy the nutritional requirements.

Sensible food baskets (19). The optimized food basket must be palatable.

Food basket variability. Specify whether the commodities and/or the ration sizes of the commodities may change between different months in the time horizon (user specified). Keeping everything fixed is easier to implement in practice, but not optimal.

In-kind commodity donations. Specify if any in-kind donations are expected (including timing and size), and how they should be handled/spent (user specified). The way in-kind contributions are handled differs a lot between donating countries, some hand over surplus commodities at one of our ports, whereas others allow us to specify the commodities and delivery location ourselves (up to a certain budget).

Transfer modality restrictions. Specify to what extent C&V may be used as a transfer modality, and whether the tool should take a cash or voucher approach (user specified). May be specified at country, commodity, and/or FDP level. Vouchers are conditional, so we can track their nutritional value. Cash is non-conditional, so we need some additional assumptions about expenditure patterns to track the nutritional value. Some of the cash is also lost to non-food items, so the voucher approach is preferred.

Expenditure patterns. Specify how beneficiaries usually spend non-conditional (cash) contributions (user specified). This allows us to estimate the contribution of a cash contribution to the nutritional value score. Expenditure patterns are based on market research in the recipient country and extensive beneficiary surveys.

Sourcing restrictions. Specify which sources should be excluded or included, and to what extent (user specified). Specifications may be general (buy 10% of the required metric tonnes from international markets) or highly specific (buy 50mt of 5% Broken Rice (medium-grain) in India to be delivered DAP in Damascus (Syria) in January). This is also used to exclude origin countries when donors do not want us to spend money in countries on which they have a trade embargo.
Food basket restrictions. Specify which commodities or food groups should be included/excluded, to what extent nutritional objectives should be met, and whether Genetically Modified Organisms (GMO) are allowed (user specified). Beneficiary preferences differ a lot, even within a single recipient country (e.g. when beneficiaries are of different tribes or when there are refugees from multiple origin countries). Governments and donors also have a lot of say in what is and is not allowed to be in the food basket.

Logistics restrictions. Specify which routes should be used/avoided, how incoming shipments should be allocated to ports/warehouses, and how much of the available capacity a country is allowed to utilize (user specified). Most of WFP’s capacity is shared between countries (especially for land-locked countries) and even with other UN agencies, so if one or more of these are not modeled the available capacity should not be utilized fully. Additionally, allocating shipments to multiple ports improves the robustness of the solution.

Solution restrictions. Specify upper and lower bounds for any of the tracked statistics (user specified). Currently the tool tracks the value of 29 statistics in each month of the time horizon, in addition to their total and average value (so 29 × (T+2) outputs that can be bounded and therefore used as a goal). The most important ones were already discussed: Total Operation Cost, Nutritional Value Score, Lead Time (Max and Average), and Local Expenditures.

B GUI

![Figure 9: A screenshot of the Graphical User Interface that was developed for the model.](image)
References


