Case study: World Food Programme

15.093: Optimization methods

Dimitris Bertsimas

Alexandre Jacquillat

Massachusetts Institute of Technology

Sloan School of Management

Acknowledgments

informs
http://pubsonline.informs.org/journal/ijoo

INFORMS JOURNAL ON OPTIMIZATION
Vol. 3, No. 2, Spring 2021, pp. 200–226
ISSN 2572-1484 (print), ISSN 2575-1492 (online)

The Nutritious Supply Chain: Optimizing Humanitarian Food Assistance

Koen Peters,[a,b] Sérgio Silva,[a] Rui Gonçalves,[a] Mirjana Kavelj,[a] Hein Fleuren,[b] Dick den Hertog,[c] Ozlem Ergun,[d] Mallory Freeman[e]

[a] Supply Chain Planning and Optimization Unit, World Food Programme, 00148 Rome, Italy; [b] Department of Econometrics and Operations Research, Tilburg University, 5000 LE Tilburg, Netherlands; [c] Amsterdam Business School, University of Amsterdam, 1018 TV Amsterdam, Netherlands; [d] Department of Mechanical and Industrial Engineering, Northeastern University, Boston, Massachusetts 02115; [e] Advanced Technology Group, United Parcel Service, Atlanta, Georgia 30328

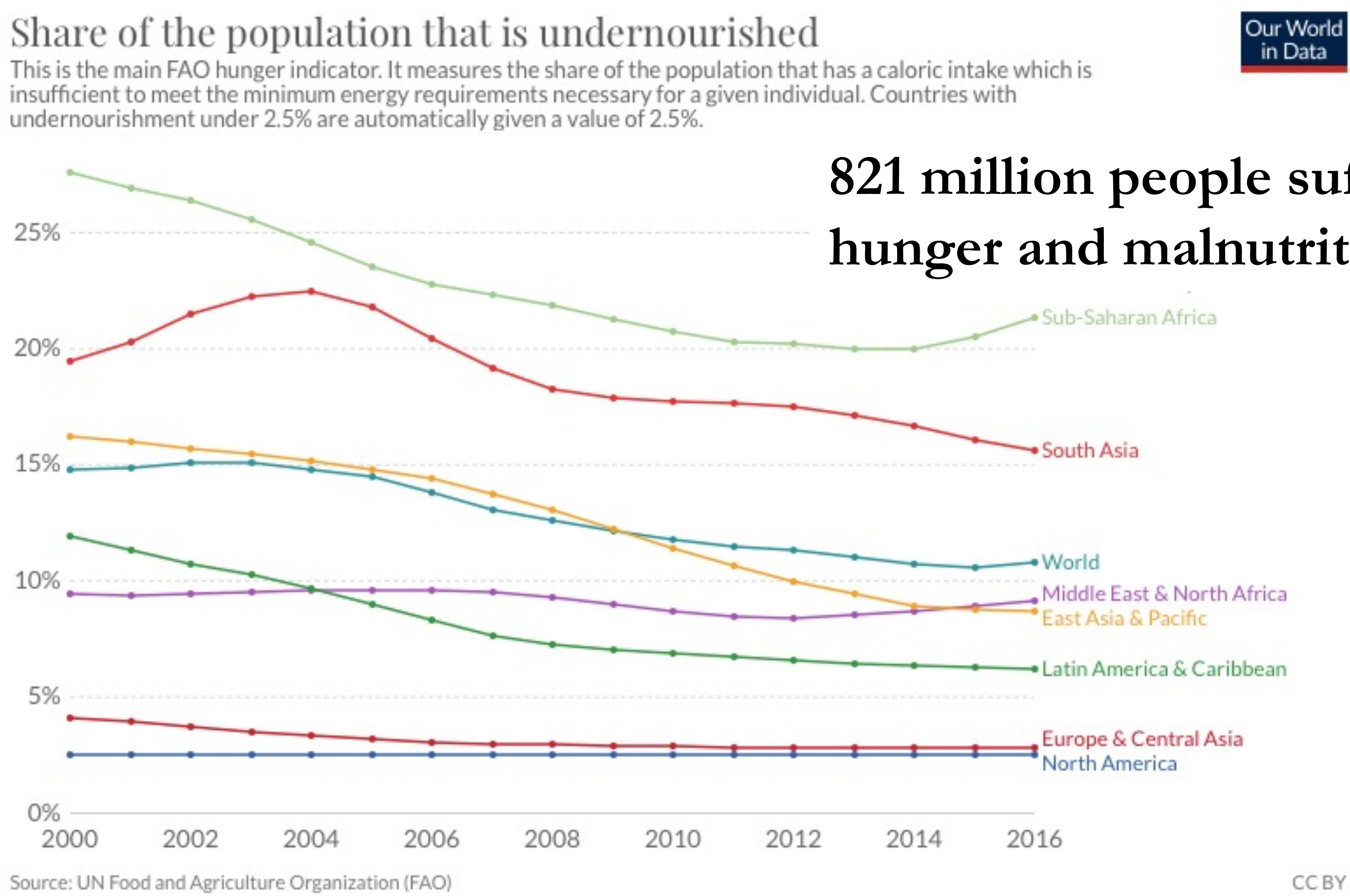
Contact: koen.peters@wfp.org, https://orcid.org/0000-0002-9685-1808 (KP); sergio.silva@wfp.org (SS); rui.goncalves@wfp.org (RG); mirjana.kavelj@wfp.org (MK); h.fleuren@tilburguniversity.edu, https://orcid.org/0000-0002-8902-0555 (HF); d.denhertog@tilburguniversity.edu, https://orcid.org/0000-0002-1829-855X (DDH); o.ergun@northeastern.edu, https://orcid.org/0000-0002-3420-3338 (OE); malloryfreeman@ups.com (MF)

Received: May 21, 2020
Revised: September 24, 2020
Accepted: October 30, 2020
Published Online in Articles in Advance: April 1, 2021

https://doi.org/10.1287/ijoo.2019.0047

Abstract. The World Food Programme (WFP) is the largest humanitarian agency fighting hunger worldwide, reaching approximately 90 million people with food assistance across 80 countries each year. To deal with the operational complexities inherent in its mandate, WFP has been developing tools to assist its decision makers with integrating 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 delivery plan, and the transfer modality of a long-term recovery

World hunger



821 million people suffer from hunger and malnutrition

UN sustainable development goals

Multiple causes of hunger

War & conflict

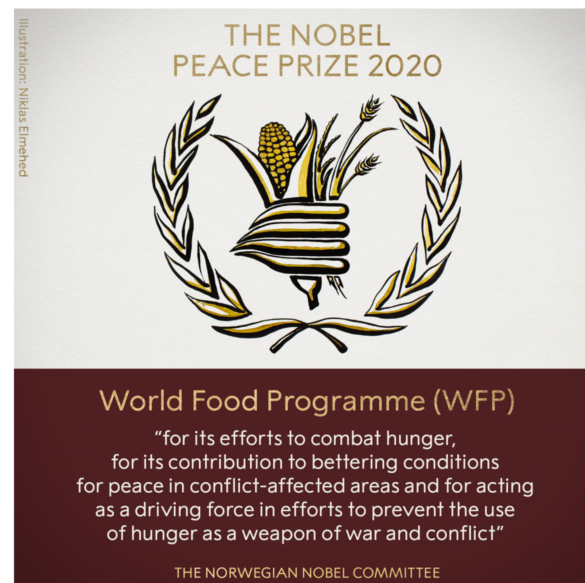
Poor nutrition

Poverty

Climate change

There's a silver lining. Or is there?

- The fact is: We have enough food globally!
- But we have a food transportation issue
- United Nations World Food Programme
  - 80M beneficiaries annually our of the 821M potential beneficiaries
  - Every day: operations of 40 shipments, 5,000 trucks, 70 aircraft

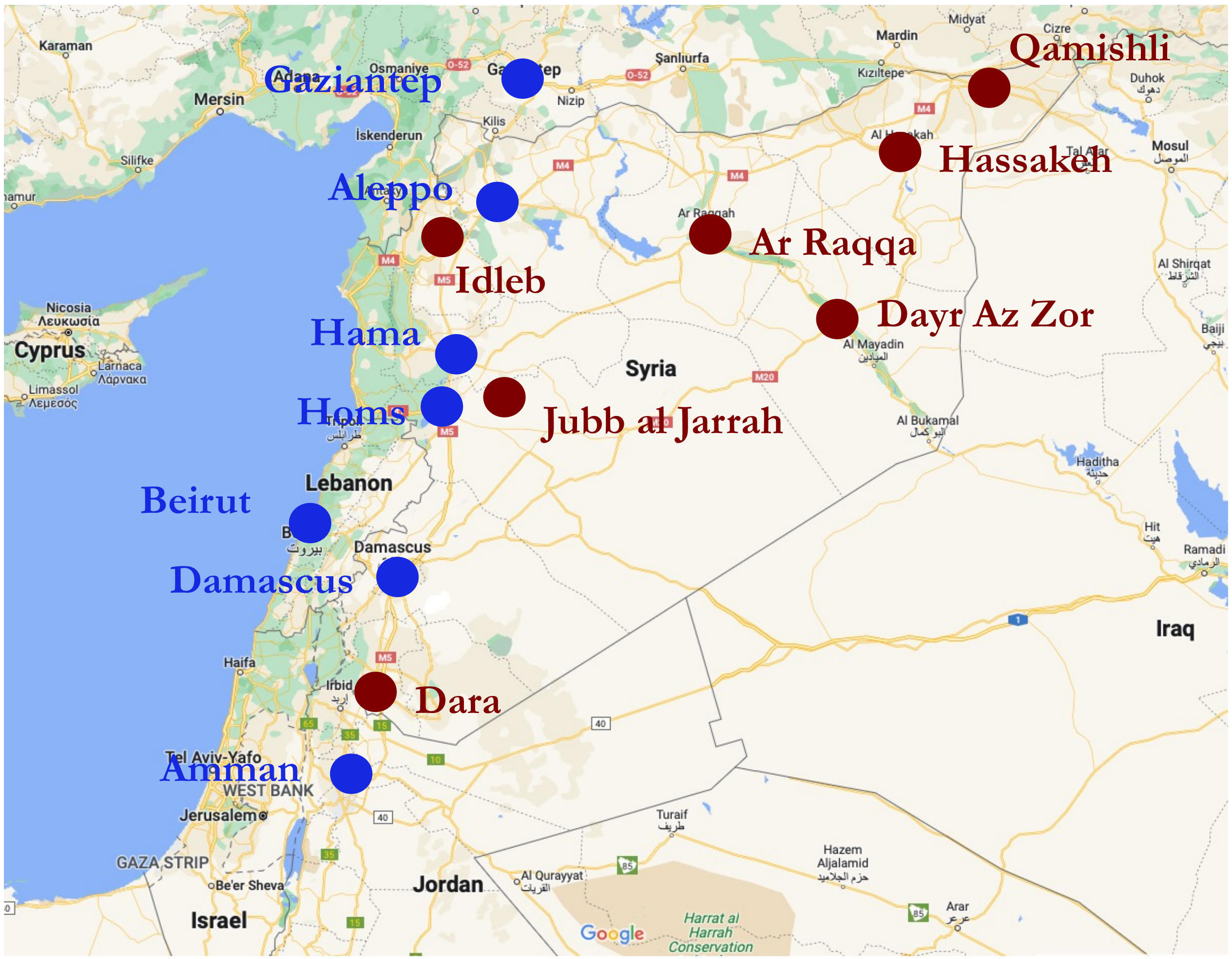


(Simplified) WFP Data

WFP's supply chain

Network: Syria 2016

Supply nodes



Demand nodes

Data: Procurement costs

- Prices in each domestic location and international prices for each of 14 commodities (beans, bulgur, cheese, fish, meat, etc.)
  →Information at the node level (for each source node)
- Detailed information for Syrian locations; costs from regional estimates for international locations

Procurement costs ($ per kg)														
Supply	**Beans**	**Bulgur**	**Cheese**	**Chickpeas**	**Dates**	**Fish**	**Lentils**	**Meat**	**Milk**	**Oil**	**Rice**	**Salt**	**Sugar**	**Flour**
Aleppo	1.08	0.51	2.86	0.97	1.84	4.10	0.83	5.29	0.50	1.27	0.95	0.32	0.63	0.49
Amman	0.8	0.45	15	0.55	0.5	0.9	0.5	1.2	1.2	1.4	0.575	0.8	1	0.3
Beirut	0.8	0.45	15	0.55	0.5	0.9	0.5	1.2	1.2	1.4	0.575	0.8	1	0.3
Damascus	1.31	1.01	2.95	1.85	2.31	5.1	1.21	6.18	0.55	2.04	1.39	0.66	1.24	0.85
Gaziantep	0.8	0.45	15	0.55	0.5	0.9	0.5	1.2	1.2	1.4	0.575	0.8	1	0.3
Hama	1.31	0.64	2.70	1.35	2.02	4.75	1.00	6.31	0.48	1.35	0.99	0.30	0.59	0.49
Homs	1.26	0.61	2.55	1.31	1.93	4.46	0.99	6.45	0.47	1.35	0.98	0.31	0.58	0.47

Data: demand and transportation costs

- Transport costs: distance (in meters, from Google API) and unit transportation costs (in $ per km per kg) (arc-level information)
- Demand from demographic information

Transportation Costs ($/kg)		Demand Nodes						
		Ar Raqqa	Dara	Dayr Az Zor	Hassakeh	Idleb	Jubb al Jarrah	Qamishli
Supply Nodes	**Aleppo**	0.42	—	—	0.74	0.13	—	0.85
	Amman	1.29	0.20	1.30	1.67	1.05	0.90	1.83
	Beirut	0.931	0.43	1.10	1.36	0.67	0.56	1.47
	Damascus	—	0.22	0.91	—	—	—	—
	Gaziantep	0.59	1.16	0.86	0.79	0.37	0.70	0.90
	Hama	0.54	—	0.82	0.98	0.21	0.20	1.08
	Homs	—	—	—	—	0.31	0.19	—

Targeted population						
Ar Raqqa	**Dara**	**Dayr Az Zor**	**Hassakeh**	**Idleb**	**Jubb al Jarrah**	**Qamishli**
10,000	20,000	25,000	5,000	10,000	2,000	5,000

Data: Food & nutrition

- Nutritional information from World Health Organization

Nutritional value per 100 g of food											
Food item	Energy (kcal)	Protein (g)	Fat (g)	Calcium (mg)	Iron (mg)	Vitamin A (ug)	Thiamine B1 (mg)	Riboflavin B2 (mg)	Nicacin B3 (mg)	Folate (ug)	Iodine (ug)
Beans	335	20	1.2	143	8.2	0	0.5	0.22	2.1	180	0
Bulgur	350	11	1.5	23	7.8	0	0.3	0.1	5.5	38	0
Cheese	355	22.5	28	630	0.2	120	0.03	0.45	0.2	0	0
Fish	305	22	24	330	2.7	0	0.4	0.3	6.5	16	0
Meat	220	21	15	14	4.1	0	0.2	0.23	3.2	2	0
Dates	245	2	0.5	32	1.2	0	0.09	0.1	2.2	13	0
…	…	…	…	…	…	…	…	…	…	…	…

Daily nutritional requirements per person										
Energy (kcal)	Protein (g)	Fat (g)	Calcium (mg)	Iron (mg)	Vitamin A (ug)	Thiamine B1 (mg)	Riboflavin B2 (mg)	Nicacin B3 (mg)	Folate (ug)	Iodine (ug)
2100	52.5	89.25	1100	22	500	0.9	1.4	12	160	150

Optimization of WFP Operations

Model 1: Network flows

Sets

$i, j = 1, \cdots, n$: nodes

$\mathcal{N}_S$: source nodes

$\mathcal{N}_I$: intermediate nodes

$\mathcal{N}_T$: terminal nodes

Parameters

c_{ij} : unit transportation cost

S_i : supply capacity, $i \in \mathcal{N}_S$

D_j : demand, $j \in \mathcal{N}_T$

Decisions

x_{ij} = shipment amount

Formulation

$$
\begin{aligned}
\min \quad & \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \\
\text{s.t.} \quad & \sum_{j=1}^{n} x_{ij} \leq S_i, && \forall i \in \mathcal{N}_S \\
& \sum_{i=1}^{n} x_{ij} = \sum_{i=1}^{n} x_{ji}, && \forall j \in \mathcal{N}_I \\
& \sum_{i=1}^{n} x_{ij} \geq D_j, && \forall j \in \mathcal{N}_T \\
& x \geq 0
\end{aligned}
$$

minimize transport costs

in each source node

in each intermediate node

in each terminal node

what comes out…

what comes in…

… meets the capacity

… meets the demand

Issue: multiple food items (commodities), not a single one

Model 2: Multicommodity flows

Sets

$i, j = 1, \cdots, n$: nodes

$\mathcal{N}_S$: source nodes

$\mathcal{N}_I$: intermediate nodes

$\mathcal{N}_T$: terminal nodes

$k = 1, \cdots, m$: commodities

Parameters

c_{ijk} : unit transportation cost

S_{ik} : supply capacity, $i \in \mathcal{N}_S$

D_{jk} : demand, $j \in \mathcal{N}_T$

Decisions

x_{ijk} = shipment amount

Formulation

minimizing transport costs, summed over all commodities

$$
\begin{aligned}
\min \quad & \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{m} c_{ijk} x_{ijk} \\
\text{s.t.} \quad & \sum_{j=1}^{n} x_{ijk} \leq S_{ik}, && \forall i \in \mathcal{N}_S, \ \forall k = 1, \cdots, m \\
& \sum_{i=1}^{n} x_{ijk} = \sum_{i=1}^{n} x_{jik}, && \forall j \in \mathcal{N}_I, \ \forall k = 1, \cdots, m \\
& \sum_{i=1}^{n} x_{ijk} \geq D_{jk}, && \forall j \in \mathcal{N}_T, \ \forall k = 1, \cdots, m \\
& x \geq 0
\end{aligned}
$$

constraints hold for each commodity

Issue: “demand” in nutritional requirements, not in food items

Full model: inputs

Sets: elements defining all parameters and decision variables

$i, j = 1, \cdots, n$: nodes in the network

$\mathcal{N}_S$: subset of source nodes (suppliers)

$\mathcal{N}_I$: subset of intermediate nodes (ports, warehouses)

$\mathcal{N}_T$: subset of terminal nodes (beneficiaries)

$k = 1, \cdots, m$: commodities

$l = 1, \cdots, q$: nutrients

Make sure to carefully define the first-level sets (and second-level subsets if relevant)

Parameters: Model inputs—obtained from the data

p_{ik} : procurement cost of commodity k in source node $i \in \mathcal{N}_S$ (in \$/kg)

t_{ij} : transport cost from node i to node j (in \$/kg)

h_j : handling cost at node $j \in \mathcal{N}_I \cup \mathcal{N}_T$ (in \$/kg)

D_j : number of beneficiaries at node $j \in \mathcal{N}_T$

min_l : minimum requirements of a beneficiary for nutrient l

V_{kl} : nutritional value of commodity k for nutrient l (per kg)

Make sure to carefully define which parameters depend on which sets

Full model: formulation

Decision variables: Unknown quantities—subject to optimization

x_{ijk} = amount of commodity k sent from node i to node j (kg)

r_{jk} = ration size of commodity k in node $j \in \mathcal{N}$ (kg)

Again, define which variables depend on which sets

Model formulation: Objective and constraints

procurement + transport + handling costs

$$
\begin{aligned}
\min \quad & \sum_{i\in\mathcal{N}_S}\sum_{j=1}^{n}\sum_{k=1}^{m} p_{ik}x_{ijk} + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{m} t_{ij}x_{ijk} + \sum_{i=1}^{n}\sum_{j\in\mathcal{N}_I\cup\mathcal{N}_T}\sum_{k=1}^{m} h_j x_{ijk} \\
\text{s.t.} \quad & \sum_{i=1}^{n} x_{ijk} = \sum_{i=1}^{n} x_{jik} \qquad \forall j \in \mathcal{N}_I, \forall k = 1,\cdots,m \\
& \sum_{i=1}^{n} x_{ijk} \geq D_j r_{jk}, \qquad \forall j \in \mathcal{N}_T, \forall k = 1,\cdots,m \\
& \sum_{k=1}^{m} V_{kl} r_{jk} \geq min_l, \qquad \forall j \in \mathcal{N}_T, \forall l = 1,\cdots,q \\
& x \geq 0, \; r \geq 0
\end{aligned}
$$

in each intermediate node

in each terminal node

for each commodity

for each nutrient

what comes in…

… comes out

… meets the ration

the nutritional value…

meets the requirements

Model components

Supply chain optimization

Multicommodity flow model

Food basket optimization

Diet model

Art and science of optimization formulations

Model extensions?

- A multi-period model:
  - Time variations in food prices and availability
  - Time variations in beneficiary nutritional demand, etc.
  - Lead times in food shipments
- Different beneficiaries with different requirements:
  - Adults, children, pregnant women, etc.
  - Palate restrictions, cultural preferences, etc.
- Financing: cash, commodity vouchers, value vouchers, etc.
- Capacity restrictions and uncertainty on transport quantities
- Equity across communities? How to even capture it?
- Anything else?

Results

Optimal cost

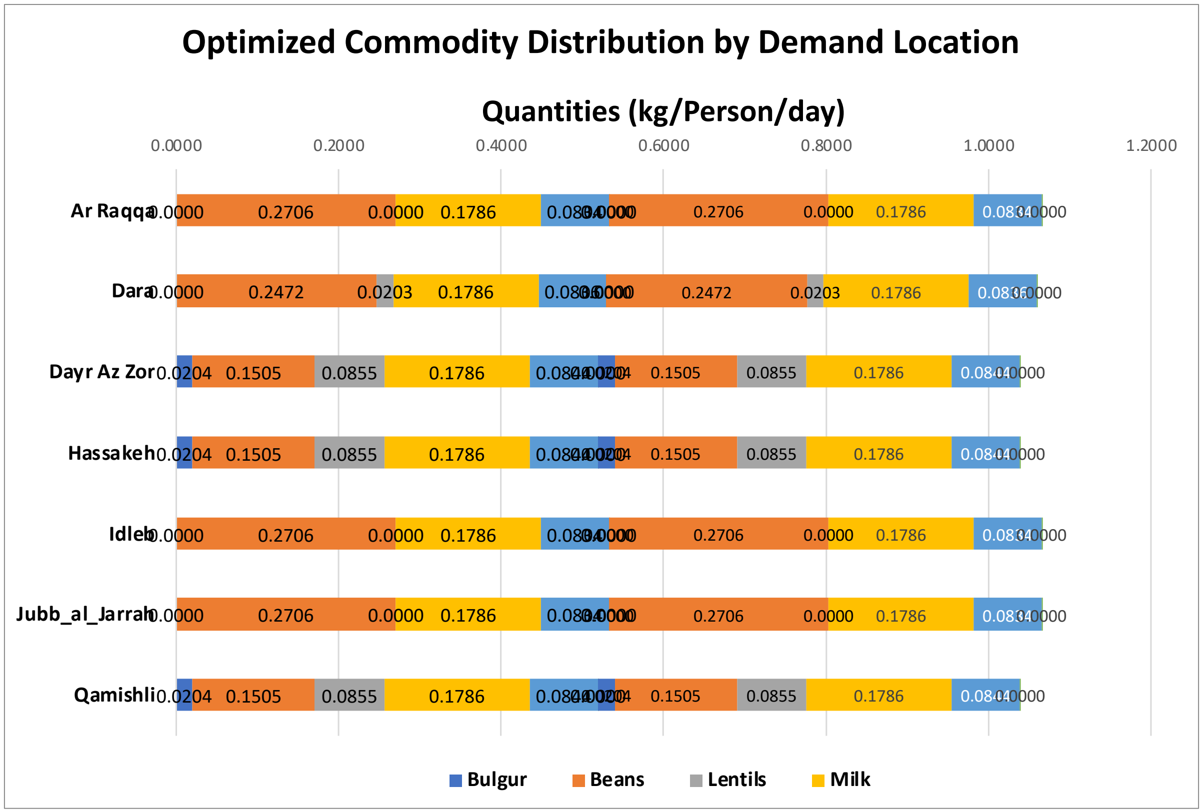
Commodity	Procurement	Transport
Beans	$1,544	$41,569
Bulgur	$6,690	$309,470
Cheese	$0	$0
Fish	$0	$0
Meat	$0	$0
Dates	$0	$0
Milk	$6,971	$367,924
Salt	$1	$31
Lentils	$4,810	$174,230
Chickpeas	$0	$0
Rice	$0	$0
Sugar	$0	$0
Oil	$8,664	$172,943
Wheat flour	$0	$0

Location	Procurement	Transport	Cost/person
Ar Raqqa	$3,663	$65,132	$6.88
Hassakeh	$3,663	$203,901	$20.76
Dara	$6,882	$32,177	$1.95
Dayr_Az_Zor	$10,239	$624,918	$25.41
Qamishli	$1,832	$133,874	$27.14
Jubb al-Jarrah	$736	$2,877	$1.81
Idleb	$1,665	$3,288	$0.99

- Significant cost disparities across commodities & locations
- Breakdown gives a “dashboard” of optimal cost/performance

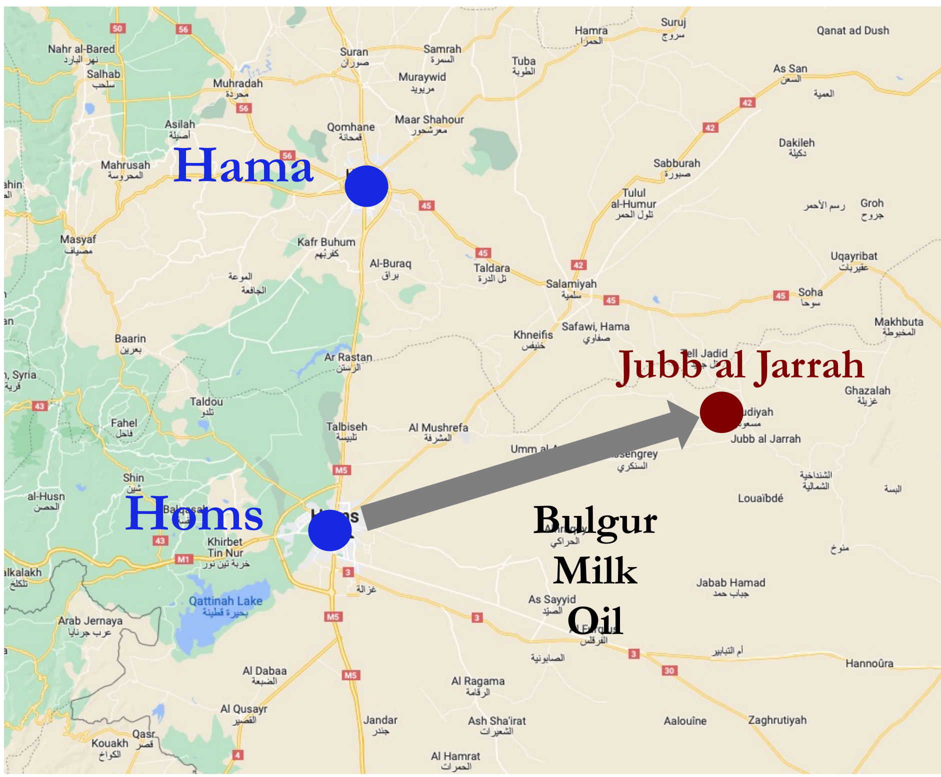
Food basket composition

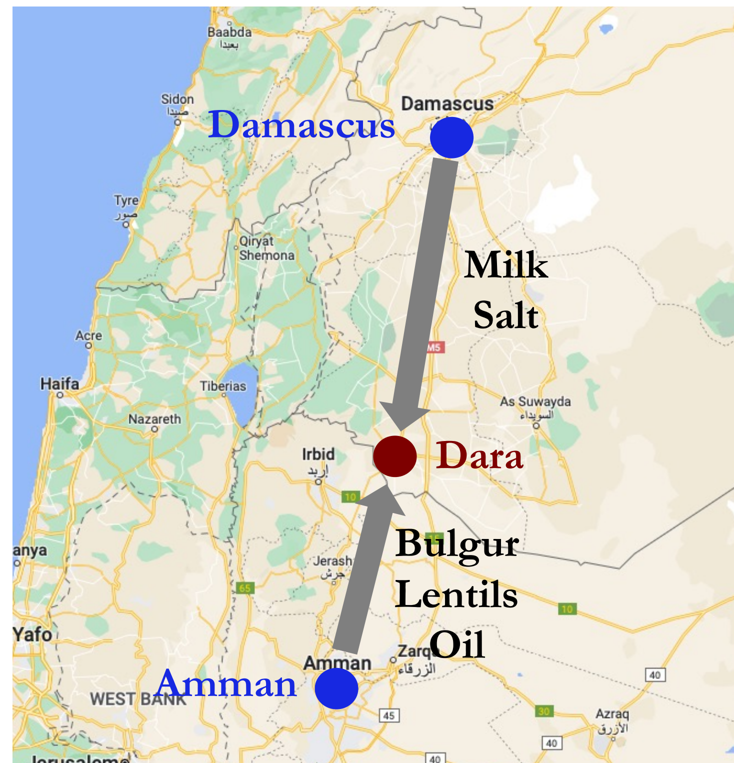
- Main food basket comprises beans, bulgur, lentils, milk, oil & salt
- In a couple of locations, beans and lentils are replaced by bulgur



Food supply chain

- Most demand nodes sourced from a single supply node
  - Near-sourcing strategy—transportation costs exceed procurement costs
- Still, some variations in sourcing strategy across commodities

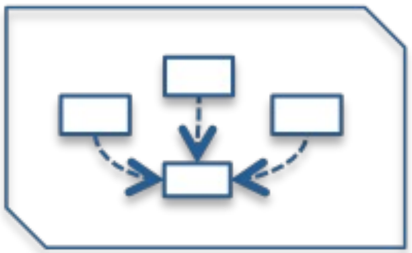




Deployment

Deployment challenges

Technological challenges


Data Management


Accessibility


Synchronisation


Data quality

Practical challenges

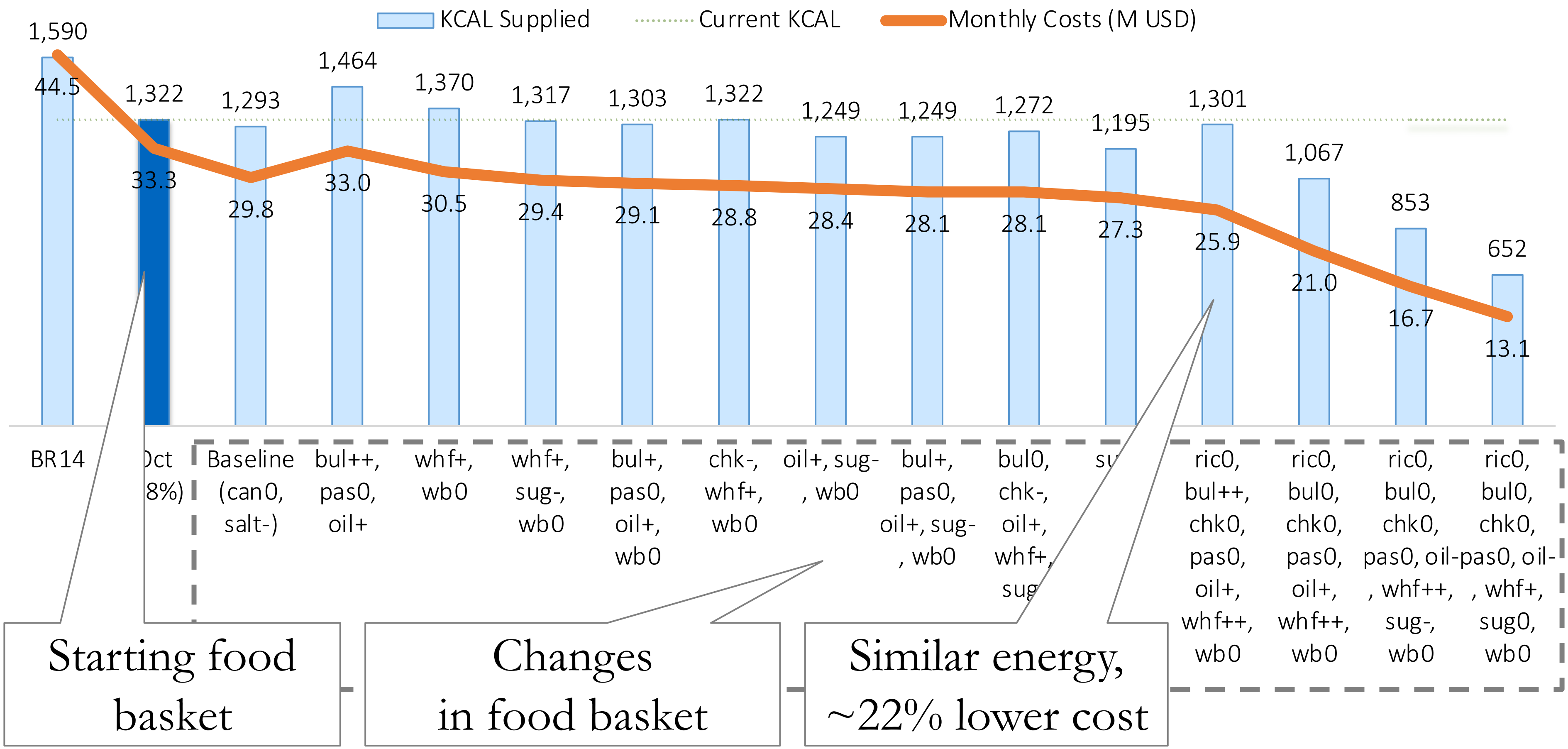

Scalability


Financing


Disruption response


Re-optimization

Application to Syria in 2016

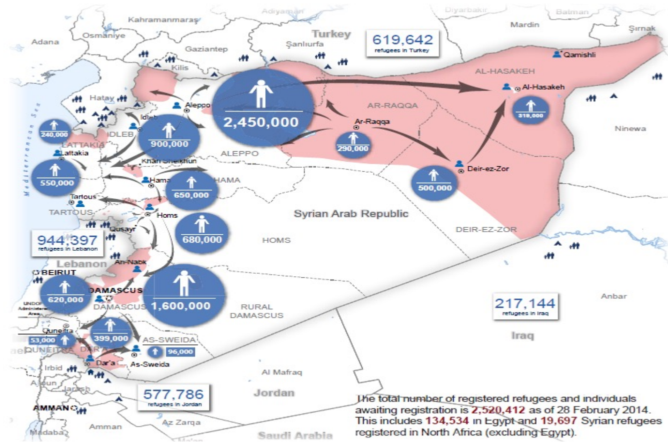


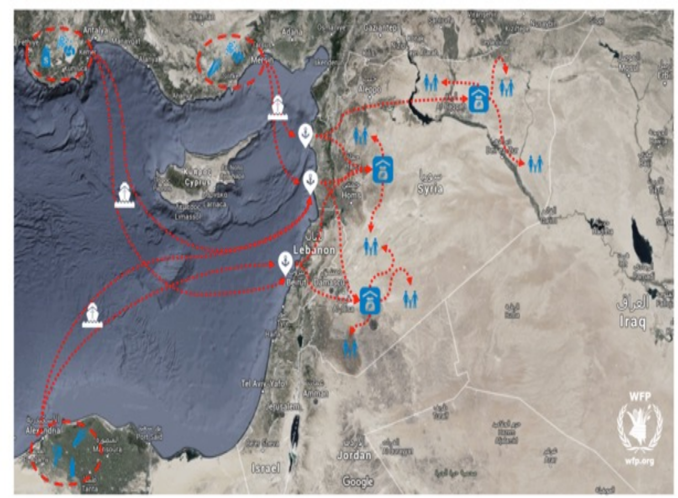
Application to Syria in 2016

- The current food basket gives 95.8% of daily nutritional value
- Identification of food baskets with:
  - 96.0% nutritional value at 74% of costs
  - 97.5% nutritional value at 85% of costs
- The first option was chosen by WFP

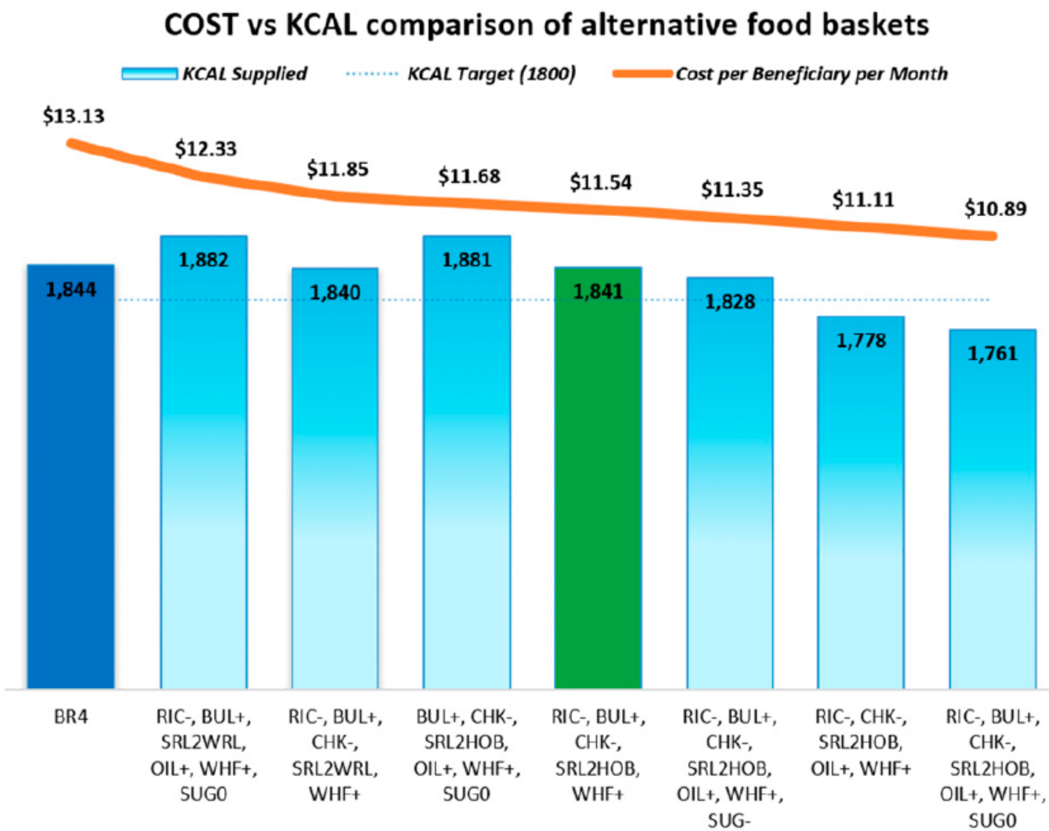
→Considerable savings for similar nutritional impact

→Impact: from 4 million beneficiaries to 5 million beneficiaries





Application to Iraq in 2015



- Scale of operations: 500,000 beneficiaries or $6.57M per month
- 17% cost reduction: $1.12M/month or 85,000 more beneficiaries

Application to Yemen - 2016

Food basket options | Cost & nutrition per basket | Monthly funding level & number of beneficiaries (millions)

Basket Name	USD per Beneficiary	kcal (NVS)	20M USD	30M USD	40M USD	45M USD	50M USD	55M USD	60M USD	70M USD	80M USD	90M USD	100M USD
WHF75 SYP10 WSB10 OIL06	$ 15.32	107% (96%)	1.3	2.0	2.6	2.9	3.3	3.6	3.9	4.6	5.2	5.9	6.5
WHG75 SYP10 WSB10 OIL06	$ 13.89	100% (95%)	1.4	2.2	2.9	3.2	3.6	4.0	4.3	5.0	5.8	6.5	7.2
WHG75 SYP10 WSB05 OIL05	$ 12.87	93% (89%)	1.6	2.3	3.1	3.5	3.9	4.3	4.7	5.4	6.2	7.0	7.8
WHF50 SYP10 WSB10 OIL05	$ 11.65	81% (90%)	1.7	2.6	3.4	3.9	4.3	4.7	5.2	6.0	6.9	7.7	8.6
WHF50 SYP10 WSB05 OIL06	$ 11.03	78% (85%)	1.8	2.7	3.6	4.1	4.5	5.0	5.4	6.3	7.3	8.2	9.1
WHG50 SYP10 WSB10 OIL06	$ 10.90	78% (89%)	1.8	2.8	3.7	4.1	4.6	5.0	5.5	6.4	7.3	8.3	9.2
WHG50 SYP05 WSB10 OIL06	$ 10.10	74% (87%)	2.0	3.0	4.0	4.5	5.0	5.4	5.9	6.9	7.9	8.9	9.9
WHG50 SYP10 WSB05 OIL05	$ 9.88	71% (83%)	2.0	3.0	4.0	[illegible].6	5.1	5.6	6.1	7.1	8.1	9.1	10.1

$20 million cost savings with 87% of nutritional value

2 million extra beneficiaries with 83% of nutritional value

Conclusion

Analytics for a better world

Optimizing radio-therapy treatment

Optimizing decarbonization

Optimizing dikes for flood prevention

Optimizing college admission systems

Optimizing UN WFP's supply chain

Optimizing public school bus systems