Towards an online OR toolkit for humanitarian logistics

Dissertation
zur Erlangung des Doktorgrades
der Wirtschaftswissenschaftlichen Fakultät
der Georg-August-Universität Göttingen

vorgelegt von

Dipl.-Wirtsch.-Ing. Henning Gösling
geboren in Osnabrück

Göttingen, 2015

Prüfungsausschuss

Erstprüferin: Prof. Dr. Jutta Geldermann
Weitere Prüfer: Prof. Dr. Michael Wolff
Prof. Dr. Brigitte Werners

Tag der mündlichen Prüfung: 29.09.2015

Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter an der Professur für Produktion und Logistik der Georg-August-Universität Göttingen. In dieser Zeit wurde ich von vielen Menschen unterstützt und begleitet; und an dieser Stelle möchte ich die Gelegenheit nutzen, diesen Menschen zu danken.

Ganz besonders bedanke ich mich bei Frau Prof. Dr. Jutta Geldermann für die Betreuung der Arbeit und die damit einhergehende fachliche Unterstützung. Herrn Prof. Dr. Michael Wolff danke ich für die Begutachtung meiner Arbeit. Frau Prof. Dr. Brigitte Werners danke ich für die Teilnahme an der Prüfungskommission.

Dank gilt meinen Kollegen an der Professur für die ausgesprochen angenehme Arbeitsatmosphäre. Dazu beigetragen hat insbesondere mein Bürokollege Herr Fabian Renatus. Herzlich danken möchte ich ebenfalls meinen (ehemaligen) Kollegen Dr. Katharina Amann, Beatriz Beyer, Francesco Castellani, PD Dr. Anke Daub, Dr. Jan Friedrich, Matthias Garbs, Dr. Martina Hesse, Ingo Karschin, Dr. Lars-Peter Lauven, Nils Lerche, Tobias Lühn, Dr. Heti Mulyati, Meike Schmehl, Genoveva Schmidtmann, Tim Schröder, Katharina Stahlecker, Sadegh Taskhiri, Dr. Harald Uhlemair, Dr. Susanne Wiedenmann und Dr. Sumetee Wongsak. Herrn Dr. Tim Dabringhausen danke ich für das gewissenhafte Gegenlesen der Arbeit.

Mein tiefer Dank gilt meiner Familie für die uneingeschränkte Unterstützung auf meinem bisherigen Lebensweg. Meiner Freundin Svenja danke ich ganz besonders für die unvergesslichen gemeinsamen Momente aus denen ich die Kraft zog, um mich dieser Arbeit zu stellen.

Table of content

List of figures

List of tables

List of abbreviations

EM-DAT	Emergency Event Database
IFRC	International Federation of Red Cross and Red Crescent Societies
IP	Integer program
ISCRAM	Information Systems for Crisis Response and Management Association
LDC	Local distribution center
LP	Linear program
MILP	Mixed integer linear program
MMS	Model management system
NGO	Non-governmental organization
NLP	Non-linear program
NRC	Norwegian Refugee Council
OR	Operations Research
PAHO	Pan American Health Organization
UML	Unified Modeling Language
UN	United Nations
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
WFP	World Food Programme

List of sets, parameters and variables

Superscripted letters in the notation are only used for additionally labelling of parameters and variables. Subscripted, italic letters in the notation are used as indices.

Sets:

A	Coverage levels
B	Set of settlements
G	Set of locations
I	Set of locations where stationary warehouses can be erected
M	Set of locations where LDCs can be/ are erected
O	Set of locations where supply facilities are erected
P	Set of locations where transshipment facilities can be/ are erected
Q	Set of locations where demand facilities are erected
R	Set of relief item types
S	Set of scenarios
T	Set of time periods
U	Set of facility sizes
V	Set of vehicle depots
W	Set of transportation modes
Z	Set of transportation vehicle types
Ψ	Set of transportation vehicles
Θ	Set of routes

A_r	Set of coverage levels for relief item type r
$I_{a_r s}$	Set of locations providing coverage of level a_r for the demand location in scenario s
M_ϑ	Set of locations visited on route ϑ
Z_w	Set of transportation vehicle types defined for transportation mode w

Parameters:

big	Big number
bgt^{P}	Budget in the disaster preparedness (P) phase
bgt^{R}	Budget in the disaster response (R) phase
c_r^{a}	Costs for the acquisition (a) of a unit of relief item type r
c_{ir}^{ah}	Costs for the acquisition and holding (ah) of a unit of relief item type r at location i
c_{bmu}^{c}	Costs for the collection (c) of a relief item unit coming from location b at location m where a LDC of size u is erected
c_{ghz}^{d}	Costs for driving (d) a transportation vehicle of type z from location g to location h per unit of length
$c_{\psi\vartheta}^{\mathrm{d}}$	Costs for driving (d) the transportation vehicle ψ on route ϑ
c_r^{h}	Costs for the holding (h) of an unused unit of relief item type r
c_{ir}^{h}	Costs for the holding (h) of a unit of relief item type r at location i

c_{ghz}^{t}	Costs for the transportation (t) of a relief item unit with transportation vehicle type *z* from location *g* to location *h* per unit of length
c_{ijrs}^{t}	Costs for the transportation (t) of a unit of relief item type *r* from location *i* to location *j* in scenario *s*
c_{iprs}^{t}	Costs for the transportation (t) of a unit of relief item type *r* from location *i* to location *p* in scenario *s*
c_{irs}^{t}	Costs for the transportation (t) of a unit of relief item type *r* from location *i* to the demand location in scenario *s*
c_{omu}^{t}	Costs for the transportation (t) of a relief item unit from location *o* to location *m* where a LDC of size *u* is erected
c_{pqrs}^{t}	Costs for the transportation (t) of a unit of relief item type *r* from location *p* to location *q* in scenario *s*
c_{mrt}^{u}	Costs for a unit of unsatisfied (u) demand for relief item type *r* at location m in time period *t*
c_{r}^{u}	Costs for a unit of unsatisfied (u) demand for relief item type *r*
C_{i}^{s}	Costs for setting up (s) a stationary warehouse at location *i*
C_{iu}^{s}	Costs for setting up (s) a stationary warehouse of size *u* at location *i*
C_{ps}^{s}	Costs for setting up (s) a transshipment facility at location *p* in scenario *s*
$CapB_{m}$	Capacity available to service beneficiaries at location *m* where a LDC can be erected
$CapD_{m}$	Capacity available to distribute relief items at location *m* where a LDC can be erected

$CapD_{mu}$	Capacity available to distribute relief items at location m if a LDC is erected with size u
$CapH_{ps}$	Capacity available to handle relief items at location p where a transshipment facility can be erected in scenario s
$capH_r$	Capacity necessary to handle a unit of relief item type r
$CapT_{ijs}$	Capacity available to transfer relief items on arc between location i and location j in scenario s
crs_{gh}	Probability of completely crossing the arc between location g and location h
cvy	Maximum number of transportation vehicles in a convoy
d_{bm}	Distance between location b and location m
d_{gh}	Distance between location g and location h
d_{ij}	Distance between location i and location j
d_{mn}	Distance between location m and location n
dmd_b	Units of relief items demanded at location b
dmd_g	Units of relief items demanded at location g
dmd_{irs}	Units of relief item type r demanded at location i in scenario s
dmd_{mr}	Units of relief item type r demanded at location m
dmd_{mrt}	Units of relief item type r demanded at location m in time period t
dmd_{rs}	Units of relief item type r demanded in scenario s

dmd_{qrs}	Units of relief item type r demanded at location q in scenario s
dMx	Upper distance limit
dMx_a	Upper distance limit of coverage level a
dMx_r	Upper distance limit to transfer relief item type r
dsd_{irs}	Percentage of relief item type r usable at location i in scenario s
ld_r	Load by a unit of relief item type r
Ld_z	Maximum load of a transportation vehicle of type z
Ld_{z_w}	Maximum load of a transportation vehicle of type z_w
Ld_ψ	Maximum load of transportation vehicle ψ
Nf	Number of facilities to be erected
$NfMx_u$	Maximum number of facilities with size u to be erected
Nr	Number of relief items to be distributed
Nv_{gz}	Number of transportation vehicles of type z available at location g
Nv_{gz_wt}	Number of transportation vehicles of type z_w added to the fleet at location g at the beginning of time period t
Ppl_m	Population at location m
prb_s	Probability of occurrence of scenario s
prt_g	0 if location g is a priority location, 1 otherwise

rnk_{gh}	Probability of being ransacked on arc between location g and location h
$rnkCvy_{gh}$	Probability of not being ransacked on arc between location g and location h if the number of vehicles going over it is the maximum size of a convoy
shr_{a}	Maximum percentage of relief item demand at a settlement to be satisfied from LDCs providing coverage level a
sMx_{gh}	Upper speed limit between location g and location h
sMx_{z}	Upper speed limit of a transportation vehicle of type z
$SpcW_{i}$	Storage space available to store relief items at location i where a stationary warehouse can be erected
$SpcW_{u}$	Storage space available to store relief items in a stationary warehouse with size u
$spcW_{r}$	Storage space used by a unit of relief item type r
spl	Units of relief items available
spl_{g}	Units of relief items available at location g
spl_{rt}	Units of relief item type r available at the beginning of time period t
$splDmd_{grt}$	Units of relief item type r available or demanded at the beginning of time period t at location g; positive for supply and negative for demand
t_{irs}^{s}	Time for satisfying (s) demand for relief item type r at demand location in scenario s from location i
t_{ghw}^{t}	Time for transferring (t) relief items from location g to location h using transportation mode w; 0 for a non-existent arc

t_{ips}^{t}	Time for transferring (t) relief items from location *i* to location *p* in scenario *s*
$t_{\psi\vartheta}^{\mathrm{t}}$	Time for transferring (t) relief items on route ϑ using transportation vehicle ψ
TrC	Target total costs
$TrCrs$	Target probability of completely crossing all used arcs
$TrMnCrs$	Target minimum probability of completely crossing a used arc
$TrMxR$	Target maximum probability of being ransacked on a used arc
$TrMxRt$	Target maximum reaching time
$TrMxU$	Target maximum percentage of unfulfilled demand
TrP	Target percentage of fulfilled demand at priority node
TrR	Target probability of not being ransacked on all used arcs
tMn_{a_r}	Lower time limit defining coverage level a_r
tMx	Upper time limit
tMx_{a_r}	Upper time limit defining coverage level a_r
use_{ghz}	0 if arc between location *g* and location *h* cannot be used by a transportation vehicle of type *z*, 1 otherwise
ω^{C}	Weight for total costs (C)
ω^{Crs}	Weight for probability of completely crossing all used arcs (Crs)
ω^{MnCrs}	Weight for minimum probability of crossing a used arc (MnCrs)
ω^{MxR}	Weight for maximum probability of being ransacked on a used arc (MxR)

ω^{MxRt}	Weight for maximum reaching time (MxRt)
ω^{MxU}	Weight for maximum percentage of unfulfilled demand (MxU)
ω^{P}	Weight for percentage of fulfilled demand at priority node (P)
ω^{R}	Weight for probability of not being ransacked on all used arcs (R)
ω_r	Importance factor of relief item type r
ω_{a_r}	Importance factor of coverage level a_r
γ	Collective probability of occurrence of scenarios in the reliability set

Variables:

C	Total costs
Crs	Probability of completely crossing all used arcs
DC	Deviation: total costs from target value
$DCrs$	Deviation: probability of completely crossing all used arcs from target value
$DMnCrs$	Deviation: minimum probability of crossing a used arc from target value
$DMxR$	Deviation: maximum probability of being ransacked on a used arc from target value
$DMxRt$	Deviation: maximum reaching time from target value
$DMxU$	Deviation: maximum percentage of unfulfilled demand from target value
DP	Deviation: percentage of fulfilled demand at priority location from target value
DR	Deviation: probability of not being ransacked from target value
$MnCrs$	Minimum probability of crossing a used arc

MxR	Maximum probability of being ransacked on a used arc
$MxRt$	Maximum reaching time
$MxSC_{rt}$	Maximum shortage costs due to unsatisfied demand for relief item type *r* in time period *t*
MxU	Maximum percentage of unfulfilled demand
P	Percentage of fulfilled demand at priority location
R	Probability of not being ransacked on all used arcs
rt_g	Reaching time of location *g*
x_{bm}^{c}	Relief items collected (c) from a LDC at location *m* by beneficiaries from settlement *b*
x_{ghz}^{d}	Transportation vehicles of type *z* driving (d) from location *g* to location *h*
$x_{ghz_w t}^{\mathrm{d}}$	Transportation vehicles of type z_w driving (d) from location *g* to location *h* at the beginning of time period *t*
x_{gz}^{d}	Transportation vehicles of type *z* driving (d) to location *g* as their final destination
x_{irs}^{h}	Relief items of type *r* held (h) in the stationary warehouse at location *i* in scenario *s*
x_{ir}^{p}	Relief items of type *r* prepositioned (p) in stationary warehouse at location *i*
x_{mrt}^{p}	Relief items of type *r* prepositioned (p) in LDC at location *m* in time period *t*
x_{g}^{s}	Relief items staying (s) at location *g* at the end of the operation

x_{gh}^{t}	Relief items transferred (t) from location *g* to location *h*
x_{ghz}^{t}	Relief items transferred (t) by a transportation vehicle of type *z* from location *g* to location *h*
x_{ghrwt}^{t}	Relief items of type *r* transferred (t) by transportation mode *w* from location *g* to location *h* at the beginning of time period *t*
x_{ijrs}^{t}	Relief items of type *r* transferred (t) from location *i* and location *j* in scenario *s*
x_{iprs}^{t}	Relief items of type *r* transferred (t) from stationary warehouse at location *i* to transshipment facility at location *p* in scenario *s*
x_{m}^{t}	Relief items transferred (t) to LDC at location *m*
x_{omu}^{t}	Relief items transferred (t) from supply facility at location *o* to LDC at location *m* with size *u*
x_{pqrs}^{t}	Relief items of type *r* transferred (t) from transshipment facility at location *p* to demand facility at location *q* in scenario *s*
$x_{\psi\vartheta mrt}^{\mathrm{t}}$	Relief items of type *r* transferred (t) by transportation vehicle ψ on route ϑ to LDC at location *m* in time period *t*
x_{grt}^{u}	Relief item demand of type *r* unsatisfied (u) at location *g* at the beginning of time period *t*
x_{irs}^{u}	Relief item demand of type *r* unsatisfied (u) at location *i* in scenario *s*
x_{qrs}^{u}	Relief item demand of type *r* unsatisfied (u) at demand facility at location *q* in scenario *s*
$x_{gz_wt}^{\mathrm{w}}$	Transportation vehicles of type z_w waiting (w) at location *g* at the beginning of time period *t*

y_{bmu}	1 if the demand for relief items at location *b* is satisfied by LDC at location *m* with size *u*
y_{gh}	1 if any transportation vehicle drives from location *g* to location *h*, 0 otherwise
y_{ghz}	1 if any transportation vehicle of type *z* drives from location *g* to location *h*, 0 otherwise
y_{gz}	1 if any transportation vehicle of type *z* has location *g* as its final destination, 0 otherwise
y_i	1 if a stationary warehouse is located at location *i*, 0 otherwise
y_{ips}	1 if a transshipment facility is located at location *p* and assigned to stationary warehouse at location *i* in scenario *s*, 0 otherwise
y_{iu}	1 if a stationary warehouse is located at location *i* and has a size *u*, 0 otherwise
y_m	1 if a LDC is located at location *m*, 0 otherwise
y_{mn}	1 if the population of location *n* is served by a LDC at location *m*, 0 otherwise
y_{mu}	1 if a LDC is located at location *m* with size *u*, 0 otherwise
y_{pqrs}	1 if the demand for relief item type *r* at location *q* is satisfied by transshipment facility at location *p* in scenario *s*, 0 otherwise
$y_{\psi\vartheta t}$	1 if transportation vehicle ψ uses route ϑ in time period *t*, 0 otherwise
α_{irs}	Percentage of demand for relief item type *r* satisfied from the stationary warehouse at location *i* in scenario *s*

β_{mrt}	Percentage of demand for relief item type r unsatisfied at location m in time period t
γ_s	1 if scenario s is included in reliability set, 0 otherwise

1 Introduction

Disasters – whether caused by nature or human activity – occur all over the world. Between 1970 and 2010 natural disasters alone killed 3.3 million people, an annual average of 82,500 deaths worldwide in a typical year (World Bank, 2010, p. 23). When a disaster strikes, the distribution of relief items becomes essential for survivors, if the disaster has destroyed the infrastructure and markets that had allowed sellers and buyers to transact supplies (Holguín-Veras et al., 2013). Humanitarian logistics networks then organize the distribution of relief items in the affected areas. The International Federation of Red Cross and Red Crescent Societies (IFRC), for example, provided 255,000 blankets, 34,000 tents, and 120,000 plastic sheets to survivors of an earthquake that hit the west coast of India in 2001 (van Wassenhove, 2006). The important role of humanitarian logistics was publicly acknowledged in the aftermath of the Asian tsunami in 2004 – and Operations Research (OR) was identified as an academic field that can have a positive impact on the design and management of humanitarian logistics networks (Kovács and Spens, 2007; Nikbakhsh and Zanjirani Farahani, 2011; van Wassenhove, 2006).

Since then, OR for humanitarian logistics has received increasing interest from academics and various models have been published in scientific journals. According to a recent review by Anaya-Arenas et al. (2014), the number of contributions to this field becomes larger each day and continues to grow. All published contributions should support practitioners to make decisions about the configuration of a humanitarian logistics network before and after a disaster strikes. The following list presents a selection of publications, published in scientific journals and sorted by alphabetical order:

- “A multi-criteria optimization model for humanitarian aid distribution” (Vitoriano et al., 2011)
- “A two-echelon stochastic facility location model for humanitarian relief logistics” (Döyen et al., 2012)
- “Emergency logistics planning in natural disasters” (Özdamar et al., 2004)
- “Facility location in humanitarian relief” (Balcik and Beamon, 2008)
- “Facility location under demand uncertainty: Response to a large-scale bioterror attack” (Murali et al., 2012)
- “Last mile distribution in humanitarian relief” (Balcik et al., 2008)
- “Modeling and optimizing the public-health infrastructure for emergency response” (Lee et al., 2009a)
- “Optimizing hurricane disaster relief goods distribution: model development and application with respect to planning strategies” (Horner and Downs, 2010)

- “Pre-positioning planning for emergency response with service quality constraints” (Rawls and Turnquist, 2011)

However, Kovács and Spens (2007) stated that humanitarian organizations have insufficient knowledge about the latest methods and techniques and Altay and Green (2006) pointed out that even the best available OR models for disaster management (including those for humanitarian logistics) are often not adopted due to various reasons including time, limited staff availability, and limited funding. More recently, Ortuño et al. (2013) conclude that available OR models for humanitarian logistics are generally not incorporated into the decision-making processes of humanitarian organizations. They mention a gap between academic results and practitioner needs. Galindo and Batta (2013b) see a reason for this gap in the lack of research developed in conjunction with humanitarian organizations and claim that academics have to get closer to humanitarian organizations in order to understand the organizations’ needs, their most urgent problems, and their actual budget constraints. A gap between academic results and practitioner needs was also identified on a panel at the 2013 conference of the Information Systems for Crisis Response and Management Association (ISCRAM) in Baden-Baden, Germany (Schulenberg, 2014). Consequently, the practitioners’ effort that comes with the identification and application of available OR models for humanitarian logistics needs to be reduced and the collaboration process between academics as the developers of OR models and practitioners as the end-user of OR models needs to be supported in order to propagate the use of OR in the field of humanitarian logistics.

The present work starts with an overview on disasters and disaster management with humanitarian logistics as an essential part of disaster management (chapter 2). Hereafter, the field of humanitarian logistics is analyzed in detail, i.e. the actors, the general shape of a humanitarian logistics network, the decisions that comprise the setup and running of a humanitarian logistics network, and the performance measures necessary to decide between a good and a bad configuration of a humanitarian logistics network. In chapter 3, the general characteristics of an organizational problem are defined, OR methodologies commonly used in the field of disaster management are presented, and an overview is given on available OR models for humanitarian logistics. The review builds on available reviews of OR models in the field of disaster management (Altay and Green, 2006; Galindo and Batta, 2013b) and humanitarian logistics (Anaya-Arenas et al., 2014; Caunhye et al., 2012; LaTorre et al., 2012; Özdamar and Alp Ertem, 2015).

The primary idea of this thesis is to develop an online OR toolkit for humanitarian logistics to reduce the effort which comes with the identification and application of available OR models as well as to enhance collaboration between academics and practitioners. Naturally, shaping the toolkit’s structure is a major challenge towards a complete, ready-to-use toolkit. The development of the toolkit’s structure should be the main contribution of the present work (section

3.4). Nine different OR models (those listed on pp. 1f) are arranged and characterized according to this structure in chapter 4 in order to show that the proposed structure can indeed integrate available OR models that are captured in different mathematical formulations with different notations and focus on different classes of problems. An exemplary path through the toolkit is presented in chapter 5 in order to show how the proposed structure can be used to guide a toolkit-user to a suitable OR model and to show how the proposed structure can be used to support the application of OR models (thereby supporting the setup and running of a humanitarian logistics network). Chapter 6 presents final conclusions and an outlook.

It is important to emphasize that the contribution of this thesis is *not* a complete, ready-to-use online OR toolkit for humanitarian logistics. Instead, a possible structure of such a toolkit is presented. A ready-to-use toolkit should be a platform whereto available models can be assigned and where practitioners can collaborate with academics as the model developers – whereby academics could help practitioners to apply their models while practitioners could provide feedback on the models' usefulness for their particular use cases. Such a platform should also help academics to identify open research questions and to reduce the risk of redundant or useless model building.

Currently, such an online platform, where academics can share their developed OR models for humanitarian logistics does not exist. Even more, such an online platform for sharing OR models does not yet exist for any other particular field of application. Hence, how the structure of an OR toolkit for humanitarian logistics will be derived in the present work could be an example of how structures of future OR toolkits for other fields of application could be shaped. There are several OR handbooks, such as the "Handbook of healthcare operations management" by Denton (2013), the "Handbook of operations research for homeland security" by Herrmann (2013), or the "Handbook of OR/MS models in hazardous materials transportation" by Batta and Kwon (2013), that do go in the same direction as an OR toolkit in the sense of the present work: they are collections of chapters about OR models, mostly written by academics, for a certain field of application. However, the reviewed OR handbooks (Barnhart and Smith, 2012; Batta and Kwon, 2013; Bookbinder, 2013; Denton, 2013; Herrmann, 2013; Kovacevic et al., 2013) generally do not arrange their chapters based on a pre-defined detailed framework. Moreover, each chapter has a different internal structure and a chapter's focus can be the presentation of a single OR model or a review of a collection of available OR models. Therefore, an online OR toolkit – to which available models are assigned, which allows for the updating of the included models, where each included OR model is described in a consistent and well-defined form, and which allows for the interaction between model developer and model user – could be seen as a possible advancement of OR handbooks. This work should be a step forward towards such an online OR toolkit – towards an online OR toolkit with a focus on humanitarian logistics.

2 Humanitarian logistics

A disaster, as defined by the IFRC, is a sudden event that seriously disrupts the functioning of a community and causes human, material, economic, or environmental losses that exceed a community's ability to cope using its own resources (IFRC, n.d.e). An overview on the short-term effects of disasters is given in a handbook of the Pan American Health Organization (PAHO, 2001, pp. 3ff). The PAHO distinguishes between deaths, severe injuries, communicable diseases, damage to health facilities, damage to water supply systems, lack of food, and large population displacements. These short-term effects can have a lasting impact on the well-being of individuals; especially on the well-being of elder people, women, and children. A temporary lack of food, for example, can permanently stunt growth and can lower the cognitive abilities among children younger than three (World Bank, 2010, pp. 41ff).

The risk for a community that a potentially damaging event becomes a disaster rises with the vulnerability of that community. A potentially damaging event is also called a "hazard". Hazards can be differentiated into natural and man-made hazards. Man-made hazards are events caused by humans and occur in or close to human settlements. These events comprise deliberate conflicts, transport accidents, and industrial accidents. Natural hazards are naturally occurring physical phenomena caused either by geophysical, hydrological, climatological, meteorological, or biological events. Hazardous geophysical events include earthquakes, landslides, tsunamis, and volcanic activities; hazardous hydrological events include avalanches and floods; hazardous climatological events include extreme temperatures, droughts, and wildfires; hazardous meteorological events include cyclones as well as storms and wave surges; and hazardous biological events include disease epidemics as well as insect and animal plagues (IFRC, n.d.d).

Figure 2.1 illustrates the locations of earthquakes above magnitude six on the Richter scale for 1950 to 2010, storm tracks for 1975 to 2007, and droughts based on a standardized precipitation index. The world's geophysical hazard hotspots tend to cluster along fault boundaries characterized by mountainous terrain. Hazards primarily driven by hydro-meteorological processes strongly affect the eastern coastal regions of the major continents as well as some interior regions of North and South America, Europe, and Asia (Dilley, 2005, p. 2). For example, in November 2013 the tropical storm named "Haiyan" hit the eastern coast of the Philippines; over 6,000 people were killed and 14 million people were affected, including 4 million people who remained displaced from their homes (reliefweb, n.d.b).

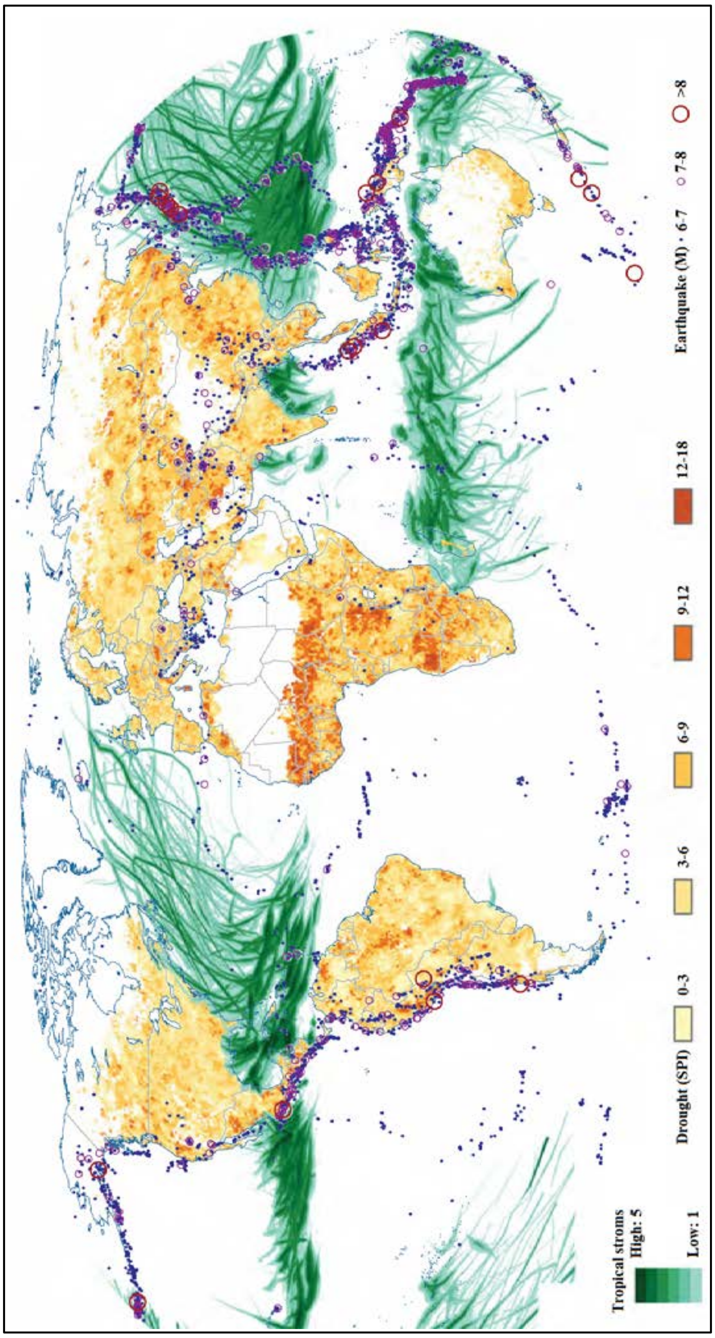


Figure 2.1. Earthquakes, storms, and droughts on a global scale (adapted from World Bank, 2010, p. 33)

Table 2.1 outlines the different types of hazards which could cause disasters. Detailed profiles of the different types of hazards can be found on the website of the IFRC (IFRC, n.d.d). Data is stored in the online Emergency Event Database (EM-DAT) about hazards that actually became a disaster. This database contains data on more than 18,000 disasters (EM-DAT, n.d.c). A disaster, to be included in the EM-DAT, must have one of the following outcomes: 10 or more people reported killed, 100 or more people reported affected, declaration of a state of emergency, and/ or call for international assistance (EM-DAT, n.d.b).

Table 2.1 Types of hazards (IFRC, n.d.d; Penuel and Statler, 2011, p. 87)

Category	**Sub-category**	**Sub-sub-category**
Natural hazards	Geophysical hazards	Earthquakes Landslides Tsunami Volcanic activity
	Hydrological hazards	Avalanches Floods
	Climatological hazards	Extreme temperatures Drought Wildfires
	Meteorological hazards	Cyclones Storms/ wave surges
	Biological hazards	Disease epidemics Insect/ animal plagues
Man-made hazards	Technological hazards	Transportation accident Accident release Explosions Pollution
	Sociological hazards	Civil disobediences Terrorism

Disaster mitigation focuses on reducing the risk that hazards become disasters by preventing the occupation of high risk areas, by building barrier constructions, and by passing specific building codes. Disaster preparedness focuses on developing capacities to cope with disasters when they occur. Disaster response comprises the evacuation of people out of a disaster area, the provision of physical and medical health services, the building of emergency shelters, and the distribution of food, blankets, etc. among beneficiaries. Disaster recovery refers to those measures which help to rebuild a community in the aftermath of a disaster by providing material or financial assistance to individuals and governments. In total, disaster management includes four steps, mitigation, preparedness, response, and recovery. These four steps comprise the so-called disaster management cycle shown in Figure 2.2. The phases can be seen in terms of a cycle that links recovery back to mitigation. Thus, ideally, recovery includes a learning element for further disasters to come (Altay and Green, 2006; Kovács and Spens, 2009; Tomasini and van Wassenhove, 2009, pp. 44ff).

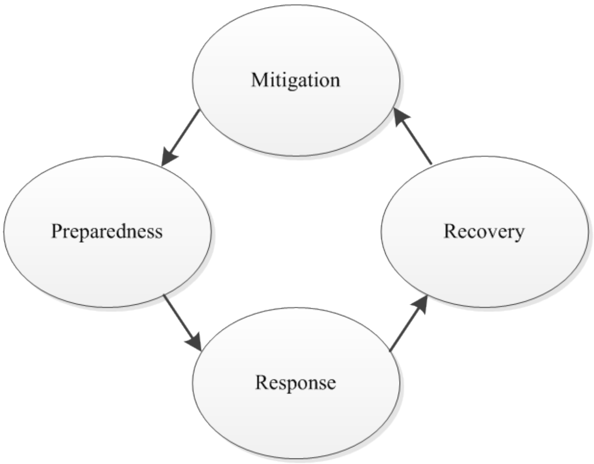


Figure 2.2. Disaster management cycle (adapted from Tomasini and van Wassenhove, 2009, p. 45)

The focus of the present work is on the logistical processes that are necessary to assist beneficiaries in response to disasters. In the aftermath of the Haiti earthquake in 2010, for example, the IFRC provided 172,700 households with emergency shelter materials, 80,000 households with a hygiene kit at least three times, 195,160 households with food assistance, 317,480 people with daily access to drinking water, and 265,400 people with access to sanitation facilities (IFRC, 2010). After the storm named "Sandy" hit the eastern cost of the US in 2012, the American Red Cross, within three months, provided shelter for more than 74,000 overnight stays, served more than 17.5 million meals and snacks, and distributed more than 7 million non-food items (American Red Cross, 2013).

A catalogue of 2,400 standard relief items, called the "Emergency Items Catalogue", is hosted by the IFRC. Listed relief items are categorized and are specified by a description, a shipping weight and volume, a price, and an amount of demand one unit is able to cover. Different kinds of relief items are often combined to kits. So-called "Emergency Response Units" consist of trained personnel and kits (IFRC, n.d.a). The provision with different types of relief items is necessary due to the many effects disasters can have (PAHO, 2001, pp. 3ff; Sphere Project, 2011):

- severe injuries, communicable diseases, and damage to health facilities require the provision with health care items;
- damage to water supply requires the provision with drinking water;

- lack of food requires the provision with religiously, culturally, and traditionally appropriate food; and
- the displacement of population requires the provision with shelter, non-food items (e.g. clothes and bedding), and sanitation systems.

Some types of relief items are distributed once at the beginning of the disaster response phase (e.g. tents and blankets) while other relief items are handed out regularly during the disaster response phase (e.g. food, water, and medicine) (Balcik et al., 2008). The provision of beneficiaries with relief items is encompassed by the term “post-disaster humanitarian logistics” (Holguín-Veras et al., 2012), by “humanitarian logistics in disaster relief operations” (Kovács and Spens, 2007), or more generally by “humanitarian logistics” (IFRC, n.d.c). The term “humanitarian logistics” can also comprise the logistics processes that are necessary to distribute relief items as part of a continuous aid work to assist the development of a region (Kovács and Spens, 2007). From hereon, the term “humanitarian logistics” will only refer to logistics operations in disaster relief.

Actors that organize and realize relief item flows in humanitarian logistics networks can be specialized military and non-military institutions, non-governmental organizations (NGOs), United Nations (UN) agencies or private sector companies (e.g. freight forwarders and clearing agents). Network coordination is often in the hands of local or national disaster response agencies (a list of national disaster management authorities can be found on reliefweb, n.d.a) or – when the impact of the disaster overwhelms national capacity and a request for humanitarian assistance goes out to the international community – in the hands of UN agencies, international organizations, and international NGOs (PAHO, 2001, pp. 21ff). In order to improve partnerships between humanitarian actors during international responses to disasters, the UN Emergency Response Coordinator introduced a reform in 2005 which, among other measures, included the formation of groups of organizations (called “clusters”), organized by sectors, which work together to improve the humanitarian response. One of these groups is called the “Logistics Cluster” which is headed by the World Food Programme (WFP) and is responsible for the inter-organizational coordination of the logistics activities during international humanitarian responses (Logistics Cluster, n.d.).

Governmental and private donors are the primary funders of humanitarian logistics networks, and each are influenced by different factors. While private donation levels are strongly impacted by the amount and type of news coverage (Wakolbinger and Toyasaki, 2011, p. 37), governmental donation levels can depend on various factors including political, ideological, religious, economic, and security factors (Harmer and Cotterrell, 2005). Often, a country’s ministry of foreign affairs acts as the coordinating department for external assistance (Harmer and Cotterrell, 2005). The size of funds received by an organization determines the scope of the humanitarian logistics network the organization is able to set up and run – for example, the American Red Cross collected US$308 million following storm “Sandy” in the year 2012 (American Red Cross, 2013). Large amounts of donations provide humanitarian organizations with the opportunity to take advantage of economies of scale and leverage in negotiating with suppliers. Some organizations have financial resources which they can use to pre-finance their operations before receiving donations (e.g. the IFRC has a so-called “Disaster Relief Emergency Fund”). However, organizations that do not have the financial resources to pre-finance their operations need to wait until they receive the donations before they can respond. In the case of earmarked funds, donors put conditions on their gifts, selecting what activities to fund within the recipient organization. This can reduce the organization’s efficiency since it might be forced to allocate too much money and resources to specific disaster areas. Too many funds allocated to one area not only take away funds that could be used in other areas in need, but they can also lead to increased prices (Wakolbinger and Toyasaki, 2011, p. 38).

2.1 Characteristics of humanitarian logistics

Commercial and humanitarian logistics operations are both necessary for the distribution of goods (Arnold, 2008; Holguín-Veras et al., 2012). However, while commercial supply chains are generally permanent structures, large parts of humanitarian logistics networks can only be set up after a disaster strikes. These temporary networks have to be interlaced into a region where transport corridors may be broken, unsafe, or unsecure, where failed communication systems remove the logical links between the actors, and where the locations of beneficiaries are dynamic or unknown (Holguín-Veras et al., 2012; Kovács and Spens, 2007; Nikbakhsh and Zanjirani Farahani, 2011). The Haiti earthquake in 2010, for example, caused serious damages of the airport and port of Port-au-Prince as well as of many streets and was followed by frequent power cuts and corresponding communication outages (IFRC, 2010). Due to disaster-related disruptions in transportation and communication systems, it is not possible to set up one temporary network that realizes all the flows of relief items in a disaster area. Instead, a multitude of poorly coordinated decision-makers set up their own networks. This results in a multitude of independent supply chains that may overlap and battle for scarce resources. For example, professional and volunteer workers are often scarce in disaster situations due to fatalities or injuries of their own or of their family members. Furthermore, during disaster response the temporary humanitarian logistics networks are often clogged with inappropriate, unusable material donations – a phenomenon which is referred to as “material convergence” and can have adverse effects not only on the actual disaster response but also on the local economy. Humanitarian organizations do not refuse these relief items for fear of upsetting donors which could negatively impact future funding (Holguín-Veras et al., 2012; Gösling and Geldermann, 2014a; Gösling and Geldermann, 2014b).

In a typical disaster response, prepositioned relief items together with donations and those acquired from local or global private companies arrive in temporary warehouses in bigger cities of the affected region. The corresponding transportation processes between stationary warehouses, donors, or companies on the one hand, and the temporary warehouses on the other hand are long-haul operations. Obviously, they can be performed by different modes of transportation (road, rail air, and/ or water). From temporary warehouses the relief items are distributed to the beneficiaries. Beneficiaries can pick up the relief items at designated facilities: local distribution centers (LDCs). LDCs are often built into existing public infrastructure such as schools and are removed once the emergency has passed. In camps for displaced people (e.g. evacuations centers, transitional sites, tent cities, and spontaneous settlements) LDCs provide relief items in regular cycles. If beneficiaries are supplied with relief items over a longer period of time, replenishment orders are initiated within the logistics network. In order to make use of advantages of different modes of transportation or of cargo consolidations, transportation processes between donors, companies, stationary warehouses, temporary warehouses, and LDCs might be separated by handling points. Transportation processes within the disaster area are mostly performed by trucks (sometimes helicopters and boats are used instead). In hostile environments, vehicles travel together as a convoy or are accompanied by armed escorts. In stationary vehicle depots, transportation vehicles wait for the next disaster response (Anaya-Arenas et al., 2014; Balcik et al., 2010; Horner and Downs, 2010; IFRC, n.d.b; Nikbakhsh and Zanjirani Farahani, 2011; PAHO, 2001; PedrazaMartinez et al., 2011).

In certain cases – such as before the landfall of a hurricane – organizations can set up the temporary part of a humanitarian logistics network before the onset of a potential disaster (Horner and Downs, 2010; Kovács and Spens, 2009). In most cases, however, the characteristics of the temporary part of the humanitarian logistics network depend on the results of an initial rapid assessment conducted after the onset of a disaster. In the assessment process, information about the specific needs, available resources, and social, cultural, and environmental characteristics of the disaster area are collected from secondary data analysis and community level assessments (IASC, 2012). The gathering of information is conducted by a large number of humanitarian actors and the schemas for the data sets are generally not standardized across the different actors nor are the mechanisms for sharing the data. Since 2011, the UN Office for the Coordination of Humanitarian Affairs (UNOCHA) is undertaking an initiative to build a common data exchange language – the Humanitarian Exchange Language – to address this problem (UNOCHA, 2011a). Its alpha version was released in October 2014 (HIF, 2014).

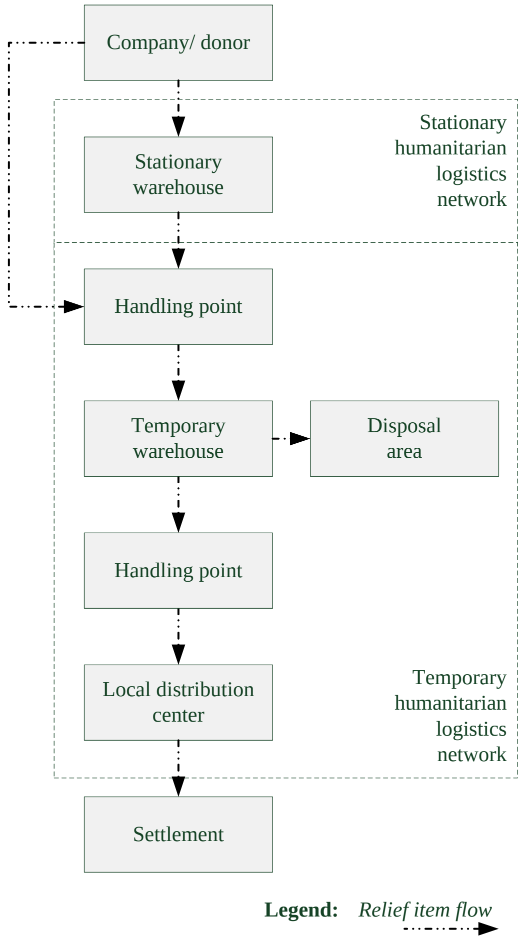


Figure 2.3. Structure of a humanitarian logistics network

A simple version of a humanitarian logistics network is shown in Figure 2.3. Arcs with a solid black arrow represent the flows of relief items from a stationary warehouse, a donor, and a commercial company via handling points and a temporary warehouse to a LDC or – in the case of non-necessary relief items – to a disposal area. Alternatively, the necessary processes to realize the relief item flows from the producers/ donors of relief items to the beneficiaries are illustrated in Figure 2.4 as an activity diagram using the Unified Modeling Language (UML).

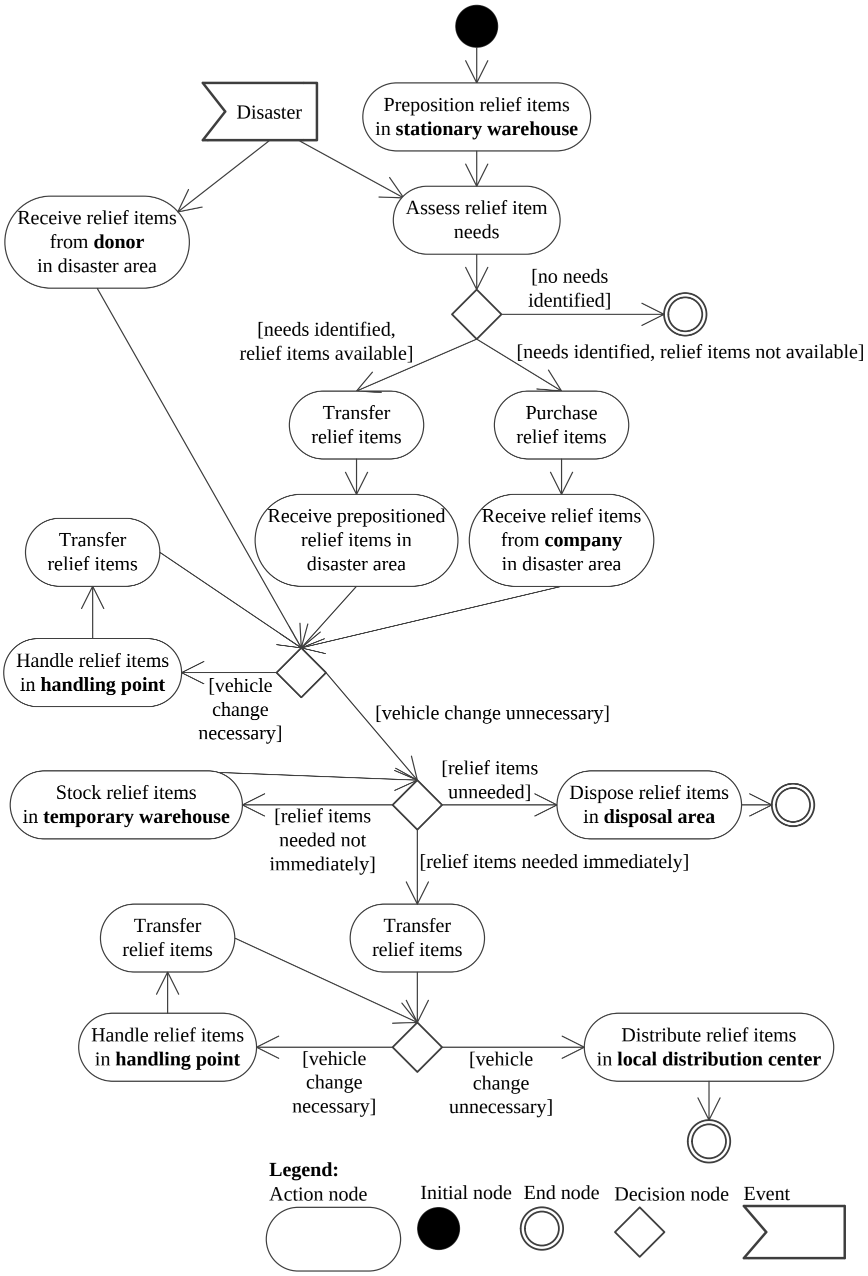


Figure 2.4. UML activity diagram depicting the processes within an humanitarian logistics network

2.2 Tasks in humanitarian logistics

Setting up and running a humanitarian logistics network comprises several tasks which can either be assigned to the disaster preparedness phase or the disaster response phase of the disaster management cycle (Tomasini and van Wassenhove, 2009, p. 44). In contrast, in commercial logistics tasks can be assigned to either strategic, tactical, or operational levels (Rushton et al., 2006, p. 21). In the disaster preparedness phase, the characteristics of stationary warehouses (locations, storage spaces, workers, equipment, relief item stocks, and suppliers) and vehicle depots (locations, storage spaces, workers, equipment, transportation vehicle stocks, and suppliers) need to be determined. Moreover, facilities are chosen that might be used during a future disaster response as a temporary facility (temporary warehouse, handling point, or LDC). Lastly, humanitarian organizations can establish agreements with suppliers of relief items during the disaster preparedness phase so that these suppliers hold certain amounts of emergency stocks for organizations. After a disaster strikes, the permanent part of the humanitarian logistics network is extended by a temporary part that has to be interlaced into the disaster area. How the network is integrated into the disaster environment depends on the results of the assessments conducted by the humanitarian organizations. As part of the assessments, decisions about the members, routes, and schedules of the responsible assessment teams have to be made. The assessment phase merges with the deployment phase. During the deployment phase of the relief mission, decisions have to be made about the characteristics of temporary warehouses, handling points, and LDCs (locations, storage spaces, workers, equipment, suppliers, and relief item stocks) and about the characteristics of the disposal points for non-priority donations (locations, storage spaces, workers, and equipment). In the sustainment phase of the relief mission, the transportation activities between the opened facilities are determined (modes of transportation, transportation vehicle types, relief item loads, routes, schedules, and drivers) together with the suppliers, sizes, and schedules of replenishment orders for relief items. The relief mission ends with the reconfiguration phase, in which operations are reduced and finally terminated (Anaya-Arenas et al., 2014; Balcik and Beamon, 2008; Holguín-Veras et al., 2012; Görmez et al., 2010; Gösling and Geldermann, 2014a; Gösling and Geldermann, 2014b; IASC, 2012; Nikbakhsh and Zanjirani Farahani, 2011; PAHO, 2001; PedrazaMartinez et al., 2011; Rushton et al., 2006, p. 21).

Table 2.2 gives an overview on the tasks in the field of humanitarian logistics. Choices can be made by a single actor or – if communication systems are still intact – by several actors in a coordinated way (Tomasini and van Wassenhove, 2009, pp. 65ff). Moreover, decision-makers must choose when to make operational decisions in the disaster response phase, since postponing a decision may result in additional information about a problem’s characteristics (Pauwels et al., 2000).

Table 2.2. Tasks in humanitarian logistics (adapted from Gösling and Geldermann, 2014a)

Tasks in the disaster preparedness phase	Tasks in the disaster response phase
Specification of…	Specification of…
• stationary warehouses (locations, storage spaces, equipment, workers, suppliers, and relief item stocks) • guaranteed relief item stocks (suppliers and amounts) • vehicle depots (locations, storage spaces, suppliers, workers, equipment, and vehicle stocks) • facilities that can be used temporarily during disaster response (locations)	• community level assessment teams (members, routes, and schedules) • temporary warehouses, handling points, and LDCs (locations, storage spaces, equipment, workers, suppliers, and relief item stocks) • staging areas for non-priority donations (locations, storage spaces, equipment, and workers) • transportation activities (modes of transportation, vehicle types, loads, routes, schedules, and drivers) • replenishment orders for relief items (suppliers, sizes, and schedules)

2.3 Humanitarian logistics performance

Making decisions in the field of humanitarian logistics results in a specific configuration of the permanent and temporary parts of a humanitarian logistics network. Much like in commercial logistics, each network configuration requires a case-specific amount of inputs and produces both desired and non-desired outputs. In the following, inputs of a humanitarian logistics network are broken down into the necessary logistics resources and the acquired relief items; and the outputs of a humanitarian logistics network are broken down into the network's effects on the beneficiaries, on the society, on the ecosystem, and on the responsible organization's finance and workforce (Beamon and Balcik, 2008; Gösling and Geldermann, 2014a; Gösling and Geldermann, 2014b; Tomasini and van Wassenhove, 2009, pp. 9ff; Rushton et al., 2006, pp. 481ff). For an organization responsible for setting up and running a humanitarian logistics network, the inputs and outputs can be used to evaluate and compare alternative configurations – hence, these inputs and outputs can be defined as the "key dimensions" for measuring a specific network's performance (Neely et al., 1995).

The procured types of relief items can be characterized by their quantity and quality. Resources (i.e. facilities, men, and machines) needed to build up and run a humanitarian logistics network can be differentiated into those necessary for warehousing, transportating, handling, distributing, and coordinating. Regardless of their function, resources can be specified by a capacity, i.e. the potential to realize specific processes in a well-defined time-interval (e.g. given in distributed relief items per hour) and a storage space where specific items can wait to be processed (e.g. given in m^2 or m^3). Broadly speaking, warehousing resources have a storage space for relief items and a capacity to place and remove items from this storage space; distribution resources have a capacity to hand over relief items to beneficiaries; transportation resources have a capacity to realize the flow of relief items between facilities; handling resources have a capacity to change relief items from one transportation resource to another; and coordination resources have a capacity to orchestrate all these warehousing, distribution, transportation, and handling resources (Arnold, 2008, p. 58; Gösling and Geldermann, 2014b; PAHO, 2001; Rushton et al., 2006, pp. 255ff).

The setup and running of a humanitarian logistics network have several effects. The effect on beneficiaries can be defined as a network's delivery service. The delivery service can be broken down to the delivered relief item quantity, the delivered relief item quality, the delivery time, the delivery service information[1], and the quality of the LDCs where beneficiaries pick up relief items. The quality of a LDC can be further differentiated into the distance between a LDC and the settlement of beneficiaries, the number of beneficiaries assigned to a LDC, and a LDC's convenience, safety, and security for beneficiaries (Beamon and Balcik, 2008; IFRC, 2008, p. 106; Gösling and Geldermann, 2014b; Tomasini and van Wassenhove, 2009, pp. 9ff).

General social effects of a logistics network are related to accidents, workforce satisfaction, workforce safety and security, workforce diversity, and supplier diversity (Carter and Jennings, 2002). A social effect, unique to a humanitarian logistics network, is caused by the beneficiaries' participation in the distribution activities since this contributes to their psychological and social well-being (Sphere Project, 2011, p. 56). Ecological effects of a logistics network can be differentiated into waste, noise pollution, water pollution, air pollution, and nature conservation (Rushton et al., 2006, pp. 577f). Finally, financial effects of a logistics network on the responsible humanitarian organization depend on the satisfaction of the donors with the network's output and on the acquisition of new donors due to media attention, sometimes known as the "CNN-effect" (Olsen et al., 2003). The CNN-effect can lead an organization to choose a response to enhance organizational reputation rather than the situation of beneficiaries (Maxwell et al., 2012). However, humanitarian organizations generally attach the greatest weight to their delivery service. This perspective is known as the "Rule of Rescue"; individuals identified as being in immediate danger are provided with relief items even if doing so requires a disproportionately large amount of logistical resources (Holguín-Veras et al., 2013).

---

[1] Delivery service information is crucial during a humanitarian response because people need accurate and updated information about actions taken on their behalf (e.g. where and when relief items are distributed). Common ways of sharing information include noticeboards, public meetings, newspapers, and radio broadcasts (Sphere Project (2011, p. 57)).

Table 2.3. Critical dimensions and metrics in humanitarian logistics (adapted from Gösling and Geldermann, 2014a)

Dimension	Sub-dimension	Sub-sub-dimension	Metrics	
Inputs	Relief items	Relief item quantity	Utilization	Efficiency Flexibility
		Relief item quality		
	Logistics resources	Coordination		
		Warehousing		
		Transportation		
		Handling		
		Distribution		
Outputs	Delivery service	Distributed relief item quantity	Effectiveness Impartiality Non-discrimination	
		Distributed relief item quality		
		Delivery time		
		Beneficiaries' distance to LDC		
		Beneficiaries assigned to LDC		
		LDC safety & security		
		LDC convenience		
		Delivery service information		
	Social effects	Workforce satisfaction		
		Workforce safety & security		
		Workforce diversity		
		Supplier diversity		
		Beneficiaries participation		
		Accidents		
	Ecological effects	Waste		
		Pollution		
		Nature conservation		
	Financial effects	Donor satisfaction		
		Media attention		

The performance of a particular humanitarian logistics network in the critical dimensions can be measured using metrics (Beamon and Balcik, 2008; Caplice and Sheffi, 1994; Neely et al., 1995; Nikbakhsh and Zanjirani Farahani, 2011;

Schulz and Heigh, 2009). In the following, six types of metrics are differentiated: utilization metrics, effectiveness metrics, impartiality metrics, non-discrimination metrics, efficiency metrics, and flexibility metrics (Gösling and Geldermann, 2014a; Gösling and Geldermann, 2014b).

Utilization metrics measure the usage of inputs, either reported as an absolute value (e.g. inventories, costs, capacity) or as a ratio between an actual amount of inputs and a norm value (Beamon and Balcik, 2008; Caplice and Sheffi, 1994). Effectiveness metrics measure the output quality, either reported as an absolute value or as a ratio between an actual amount of outputs and a norm value (Beamon and Balcik, 2008; Caplice and Sheffi, 1994). Norm values for measuring the effectiveness of a configuration's delivery service are presented in the Sphere Project handbook (Sphere Project, 2011) and the handbook of the Norwegian Refugee Council (NRC, 2008). In the Sphere Project handbook, minimum relief item quantities are specified for water supply and sanitation, food, shelter and non-food items, and medical supplies. For example, the minimum requirements for water supply and nutrition are defined as 15 liters of water and 2,100 kcal per day and person (Sphere Project, 2011, p. 181). In the NRC handbook, norm values are specified to measure a LDC's characteristics. For example, the maximum walking distance between beneficiaries and a LDC is defined to be 5 km and the maximum number of people per LDC is defined to be 20,000 (NRC, 2008, p. 396). Additionally, the NRC proposes that, for convenience reasons, LDCs are not too close to congested areas such as open markets, clinics, or religious buildings and should have enough shelter for queuing during delays or rain. Furthermore, for security reasons, the NRC proposes that no military and police checkpoints lie between the beneficiaries' settlements and LDCs (NRC, 2008, p. 396).

A humanitarian assistance has to follow the principles of non-discrimination and impartiality. Impartiality metrics measure if assistance is provided solely on the basis of need. Non-discrimination metrics measure if no one is discriminated against on any grounds of status, including age, gender, race, colour, ethnicity, sexual orientation, language, religion, disability, health status, political or other opinion, national or social origin (Sphere Project, 2011, p. 22; Tomasini and van Wassenhove, 2009, p. 22). Humanitarian assistance can be corrupted in several ways: by elites that bribe those conducting the need assessments in order to inflate needs to favor specific groups; by powerful individuals within the community that manipulate the beneficiary lists; by suppliers that bribe an organization to accept sub-standard goods; or by an organization's staff urging beneficiaries to bribe them in order to maintain their place in a distribution line or receive goods (Maxwell et al., 2012). In conflict situations, those who control the distribution of relief items tend to provide them to victims who support them, victims who could be won over to their side, or those expected to remain neutral (World Bank, 2010, pp. 49f).

Efficiency metrics measure the ratio of actual outputs to actual inputs (Beamon and Balcik, 2008; Caplice and Sheffi, 1994). Finally, flexibility metrics measure the transformational efficiency of a configuration over time, reported as the quantity of additional inputs necessary to adapt to changes in the disaster environment or as the number of different disaster environments a network can serve without additional inputs (Beamon and Balcik, 2008).

In Table 2.3 (p. 16) those critical dimensions and metrics are outlined which could be used in the field of humanitarian logistics. Objectives describe the desired outcome for a metric (Ackoff, 1978, p. 19); hence, if a metric is to be minimized ("negative objective") or if a metric is to be maximized ("positive objective"). The term "norm" refers to any value selected by a humanitarian organization to be used in comparison against an actual value. Norm values can be expected targets or fixed requirements and can be determined based on standards, historical values, or values from related organizations (Caplice and Sheffi, 1994).

The overarching goal of this thesis is to build a structure of an online OR toolkit for humanitarian logistics wherein available OR models are arranged and characterized. Structuring and characterizing these models requires a thorough understanding of humanitarian logistics, especially of the central components of humanitarian logistics networks, the tasks that are necessary to build and run such a network, and the critical dimensions/ metrics to evaluate a certain network's performance. The aim of this chapter was to provide for this understanding of the field of humanitarian logistics.

3 OR for humanitarian logistics

Structuring and characterizing OR models for humanitarian logistics requires a deeper understanding, not only of the field of humanitarian logistics (see chapter 2), but also of the field of OR. Therefore, this chapter starts with general descriptions of OR models, of the components of organizational problems, and of commonly used OR methodologies for capturing and solving problems in the field of disaster management. Following this, a review is given on the available OR models, published in scientific journals, for tasks in the field of humanitarian logistics. In the final section of this chapter, the concept of an online OR toolkit for humanitarian logistics is presented and a structure for such a toolkit is developed. Based on this structure, nine available OR models for humanitarian logistics are arranged and characterized in section 4.

An OR model is a conceptual representation of an organization's real or proposed decision problem. It is developed through a modeling phase in which the properties of a problem are converted into mathematical representations. Several techniques exist to transform a problem into a mathematical representation and to support a decision-maker in finding an advantageous solution (Hillier and Lieberman, 2010, pp. 2f; Law and Kelton, 1982, pp. 1f; Williams, 2013, pp. 3f; Zimmermann, 2005, pp. 1f). However, even if a decision-maker has already decided what to do, an OR model still provides several benefits: the psychological comfort of having a formal analysis to corroborate unaided intuition, to help the communication process, to justify conclusions to others, or to convince others of the reasonableness of the proposed solution. Moreover, there is always the possibility that an OR model will broaden a decision-maker's vision and uncover new insights that result in a different solution to the one preferred by the decision-maker beforehand (Keeney and Raiffa, 1993, p. 9).

Whether an OR model incorporates all relevant characteristics of a problem is determined in the model validation phase. An OR model is transformed into a computerized model during the implementation phase. Solutions for the problem are obtained by applying the computerized model in the experimentation phase (Sargent, 2005). The transformation into a computerized model and the conduct of experiments are supported by software tools called "modeling environments" (e.g. Microsoft Excel, CPLEX Optimization Studio). A model management system (MMS) is a software tool that facilitates not only the development and experimentation of new computerized models but also the storage, selection, adaption, combination, and updating of available computerized models (Muhanna and Pick, 1994). Computerized model verification is defined as assuring that the model's implementation correctly represents the mathematical model. Operational validation is defined as determining whether the computerized model's solution is applicable for the intended problem and has a sufficient accuracy. Data validation is defined as ensuring that the data necessary for model building, model evaluation and testing, and conducting experiments is adequate and correct (Sargent, 2005).

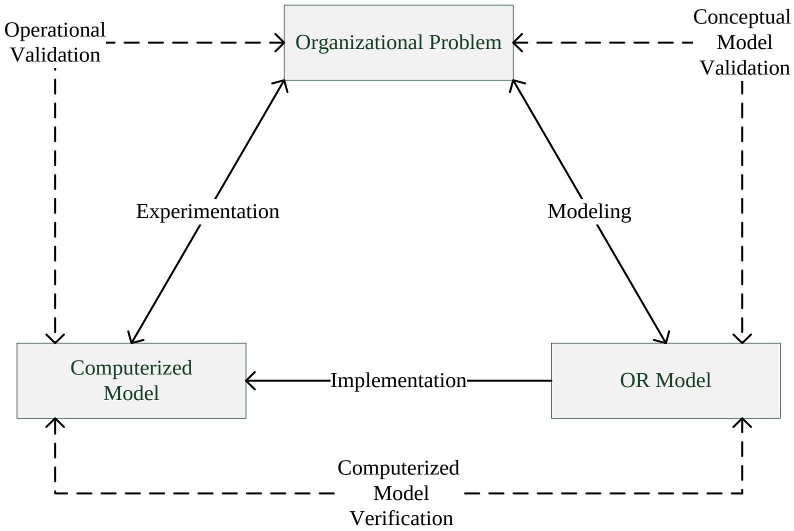


Figure 3.1. Model development process (adapted from Sargent, 2005)

Figure 3.1 gives an overview on the processes necessary to find a solution for a problem using an OR model. As shown in Figure 3.1, it is not implied that the steps are conducted in a specific order, or that one step must be completed before another is begun. As it is pointed out by Ackoff (1956), there is usually a continuous interplay between these steps during the research; that is, there is usually considerable recycling of each step through the preceding step.

3.1 Structure of a problem

As a conceptual representation of an organization's problem, an OR model attempts to capture all the problem components. Simon and Newell (1958) define a problem that can be captured by an OR model as a "well-structured problem". In the present section, the different components of a problem are identified by going through the definitions of several authors. This results into an original characterization framework for organizational problems. Based on this framework, OR models with a focus on different types of organizational problems and developed with different OR methodologies can be characterized in a consistent way. This framework can therefore be of use in the online OR toolkit for humanitarian logistics for a consistent characterization of the included models.

Greeno (1976) defines the main components of a problem as: an environment wherein the problem occurs, a set of rules for combining the elements in the environment, a set of available resources which can transform the elements in the environment, and a target or a requirement. Ackoff (1978, p. 17) determines the main components of a problem as: a decision-maker's objectives, the possible courses of action using available resources, an environment wherein the problem takes place, and interactions between objectives, resources, and the environment. Checkland and Poulter (2010, pp. 202ff) state the main components of a problematic situation as a system and its elements, a changing environment, possible actions of the system's elements to adapt to the changing environment, communication channels between the system and the environment, and metrics to evaluate the actions. Russell et al. (2010, pp. 40ff) define the main properties of a task as an environment in which the task takes place, metrics to evaluate the tasks performance, available resources to perform actions, and available sources of information to characterize the environment.

Duncan (1972) distinguishes between two types of environments from an organizational point of view. The internal environment consists of the physical and social factors within the boundaries of the organization that are taken directly into consideration in the decision-making process; that is, the organization's personnel, its technical resources, and interdependences of organizational units in carrying out their activities. In contrast, the external environment consists of physical and social factors outside the boundaries of the organization that are taken directly into consideration in the decision-making process; that is, its customers, suppliers, and competitors as well as social-political and technological aspects.

Table 3.1. Components of an organizational problem

Category	Sub-category (with properties)
Environment	Elements in environment - Static vs. dynamic - Deterministic vs. stochastic
Organization	Available resources of the organization - Static vs. dynamic - Deterministic vs. stochastic - Single vs. discrete vs. continuous Use and interaction of resources and environment Critical dimensions, metrics, objectives, targets, and requirements

The scheme in Table 3.1 is built on the problem characterizations of Ackoff (1978), Checkland and Poulter (2010), Greeno (1976), and Russell et al. (2010), as well as the distinction between internal and external environments of Duncan (1972). The scheme can be of use to (1) specify the properties of an organizational problem before starting the modeling phase and to (2) specify an organizational problem that has already been transformed into an OR model by making conclusions from the mathematical representation to the properties of the problem. In that case, another column should be introduced in the framework to indicate the mathematical representations of an OR model which capture certain aspects of a problem. In an OR model the elements, attributes, and attributes' values can be stated explicitly or implicitly. "Implicitly" means that they are postulated in terms of other elements, attributes, or attributes' values (Geoffrion, 1987).

According to Table 3.1, an organizational problem can be characterized by the specific environment in which it takes place. External environments can be comprised of several elements (e.g. other humanitarian organizations, beneficiaries, suppliers, transport infrastructure, society, ecosystem etc.). Complex external environments have a large number of elements and a high degree of sophistication of these elements (Sharfman and Dean, 1991). In the special case of an environment that hosts more than one decision-making entity (e.g. two humanitarian organizations that operate either in competition or in collaboration with each other), the corresponding environment can be called "multi-organizational". Limited availability of resources leads to competitiveness or even hostility in a multi-organizational environment (Sharfman and Dean, 1991). According to Russell et al. (2010, pp. 41ff), it is possible to characterize the elements in a task environment in more detail. A first distinction can be made between static and dynamic elements. If an element's attribute can change while the organization is deliberating about the actions it can be called "dynamic" (e.g. the location of beneficiaries during the disaster response); otherwise, it can be called "static" (e.g. the distance of a road). A second distinction can be made between deterministic and stochastic elements. If the next state of an element is completely determined by the current state and the actions executed by the organization, it can be called "deterministic"; otherwise, it is "stochastic". Elements in an environment appear to be stochastic if the environment is only partly observable – that is, if an organization's information sources are not able to cover all the elements' actual states.

A problem can also be characterized by an organization's available personnel and technical resources (internal environment); by the allowed interactions between resources and elements in the environment; and by an organization's critical dimensions (e.g. time and quality), metrics to capture these dimensions as well as objectives, targets, and requirements for these dimensions respectively for these metrics. Just as the elements in the environment, the resources of an organization can be characterized as being dynamic or static as well as deterministic or stochastic. Moreover, an organization's resources can be characterized by the number of states they are able to adopt. Indeed, the determination of the states of all or some of an organization's resources is the ultimate problem captured in an OR model. The problem can be called a discrete problem, if the resources can adopt a finite number of different states; otherwise, it is referred to as a continuous problem (Russell et al., 2010, p. 44).

3.2 OR methodologies

A possible way to structure an online OR toolkit is by sorting inserted OR models according to their underlying methodology. Different methodologies have been developed in order to transform problems with a discrete or continuous number of alternative solutions into an OR model (Bradley et al., 1977, pp. 3ff; Hillier and Lieberman, 2010). Three OR methodologies that are often used in the field of disaster management are (Galindo and Batta, 2013b):

- mathematical programming, a methodology that provides approaches to model a problem with a continuous and/ or a discrete number of possible alternative solutions and to select the most advantageous alternative;
- decision analysis, a methodology that provides approaches to model a problem with a discrete number of possible alternative solutions and to select the most advantageous alternative; and
- simulation, a methodology that provides approaches to model and evaluate one or more possible solutions to a problem.

A mathematical program is able to capture a problem with a continuous and/ or a discrete number of alternative solutions in terms of mathematical symbols and expressions. It consists of variables, parameters, and functions. A decision variable represents the value of a certain attribute of an organizational resource (e.g. the number of aid workers at a LDC). Decision variables are the values to be determined by the program while parameters are the values which have already been determined. A parameter represents the value of a certain attribute of an organization's resource (e.g. maximum velocity of a transportation vehicle) or the value of a certain attribute of an environmental element (e.g. condition of a roadway). The allowed use of resources and their allowed interaction with each other and the environment are captured by the functions of a mathematical program. However, functions can also be used to determine the consequences of the use and interaction of resources on the organization's performance (e.g. on the transportation costs). One of the program's functions – the objective function – is optimized, i.e. minimized or maximized. Constraints are functions that are restricted to specific values ("right-hand sides"). Depending on the type of environment in which the organization operates and depending on the type of resources the organization has at hand, the corresponding mathematical program can include dynamic and/ or stochastic parameters. The corresponding programs are called "dynamic programs" and "stochastic programs", respectively. In the case of competitive multi-organizational environments, mathematical programs can make use of certain game theory concepts (Hillier and Lieberman, 2010, p. 11; Williams, 2013, pp. 5ff).

The use of a linear program (LP) requires that the objective function and the constraints involve only linear expressions. An integer program (IP) contains integer decision variables; and if it solely consists of integer decision variables it is a pure integer program and if there are both, continuous together with integer variables it is said to be a mixed integer program. The class of mixed integer linear programs (MILP) contains integer variables and involves only linear expressions. Non-linearities in the objective function or constraints result in a non-linear program (NLP) (Williams, 2013, pp. 5ff). A set of mathematical rules for solving a particular class of mathematical programs (i.e. finding values for the decision variables so that the objective function is optimized while considering the constraints) is known as an algorithm. The algorithms typically in use for solving LP models are based on the revised simplex algorithm; those for solving IP models are often based on branch and bound, implicit enumeration, and cutting plane algorithms; and those for solving NLP models are often based on separable programming, linear approximation, quadratic programming, unconstraint minimization and maximization, and one-dimensional optimization algorithms (Bradley et al., 1977; Williams, 2013, p. 11). Table 3.2 lists some available modeling environments which support the computerization and experimentation of mathematical programs. Some of these modeling environments are fixed to specific packages of solvers (e.g. CPLEX Optimization Studio) while others are not (e.g. GAMS). Solvers are algorithms that are programmed into a set of computer routines for solving the corresponding type of mathematical program assuming the program is presented in a specific format (Williams, 2013, p. 11).

Table 3.2. Available modeling environments for mathematical programming

Name	URL	State
AIMMS	www.aimms.com	commercial
CPLEX Studio	www.ilog.com	commercial
GAMS	www.gams.com	commercial

A decision analysis model is able to capture a decision problem with a discrete number of alternative solutions in terms of a pay-off table. For each possible decision (e.g. a certain configuration of the humanitarian organization’s temporary warehouses within the disaster area) the corresponding impacts on the environment and on the organization itself are entered into the table. The pay-off table must be adapted in the case of certain characteristics of the decision problem, e.g. in the case of competitive or stochastic environments. An algorithm in the field of decision analysis is a set of mathematical rules for determining the best solution based on the values given in the pay-off table (Hillier and Lieberman, 2010, p. 674). Table 3.3 lists some available modeling environments which support the computerization and experimentation of decision analysis models.

Table 3.3. Available modeling environments for decision analysis

Name	URL	State
D-Sight	www.d-sight.com	commercial
Visual PROMETHEE	www.promethee-gaia.net	commercial
WebHipre	hipre.aalto.fi/	free

A simulation model captures and evaluates one possible solution to a problem in terms of mathematical symbols and expressions. The solution under consideration corresponds to an already fixed configuration of the controlled variables (i.e. the values of certain attributes of an organization's resources). The allowed use of an organization's resources, the interaction with each other, as well as the interaction with the environment are captured by mathematical functions. Consequences on the environment and the organization itself (i.e. on the performance metrics) are also captured by mathematical functions. Depending on the characteristics of the environment and the organization's resources, the corresponding simulation model can include dynamic and/ or stochastic parameters. If the simulation model includes dynamic parameters that change their values only at discrete events, it is called a discrete-event simulation. In continuous simulation models, the values of dynamic parameters change continuously. Simulations in stochastic and static environments are called "Monte-Carlo-Simulations" (Law and Kelton, 1982, pp. 2ff). Table 3.4 lists some available modeling environments which support the computerization and experimentation of simulation models.

Table 3.4. Available modeling environments for simulation

Name	URL	State
Arena	www.arenasimulation.com	commercial
ExtendSim	www.extendsim.com	commercial
Simulink	www.mathworks.com/products/simulink	commercial

3.3 OR models for humanitarian logistics

An online OR toolkit for humanitarian logistics would naturally build on existing OR models for this particular field of application. Reviews on OR methodologies that were used in disaster management were published by Altay and Green (2006), Galindo and Batta (2013b) and Ortuño et al. (2013). Additionally, four reviews have been found that give an overview on available mathematical programs supporting the setup and running of a humanitarian logistics network: Anaya-Arenas et al. (2014), Caunhye et al. (2012), LaTorre et al. (2012), and Özdamar and Alp Ertem (2015). All four reviews include mathematical programs supporting decisions about the routing of transportation vehicles during disaster response.

Furthermore, Caunhye et al. (2012) list mathematical programs that can support the specification of stationary warehouses. In the review of Anaya-Arenas et al. (2014) mathematical programs are classified into those for stationary and temporary facility planning, for transportation and rescue activities, for both locating and routing, and for so-called “other important topics”. Reviews on OR models for humanitarian logistics based on simulation or decision analysis have not been found. Moreover, only one article (Roh et al., 2015) containing a decision analysis model with an explicit focus on humanitarian logistics has been found when going through the existing reviews on OR models for disaster management (Altay and Green, 2006; Galindo and Batta, 2013b; Ortuño et al., 2011) and additionally searching the scientific databases Google Scholar, Science Direct, and Web of Science (as of February 2015).[2] Again, only one simulation model (Mulyono and Ishida, 2014) with an explicit focus on humanitarian logistics has been found when going through the existing reviews and additionally searching the scientific databases Google Scholar, Science Direct, and Web of Science (as of February 2015).[3] Two articles mention that simulation models were used to evaluate the performance of particular humanitarian logistics networks in Thailand (Tatham et al., 2010) and South Sudan (Beamon and Kotleba, 2006). However, these publications lack the necessary information to reproduce the simulation models.

In the following, a review of existing mathematical programs for humanitarian logistics will be presented, building on the available reviews of Altay and Green (2006), Anaya-Arenas et al. (2014), Caunhye et al. (2012), Galindo and Batta (2013b), LaTorre et al. (2012), Ortuño et al. (2013), and Özdamar and Alp Ertem (2015), as well as on an additional literature search in relevant scientific databases. Only models published in peer-reviewed academic journals were included. Hence, conference papers, dissertations, governmental reports, NGO reports, and practitioner reports were excluded from the review. The result of the review is shown in Table 3.5. In it, mathematical programs are assigned to the tasks they support. The different tasks were identified based on the framework outlined in Table 2.2 (p. 14). Some parts of Table 3.5 cannot be filled – in other words, there were no programs found in peer-reviewed scientific journals for certain problems in the field of humanitarian logistics.

---

[2] The search terms used were “decision analysis”, “humanitarian”, and “logistics”. All hits were scanned found by the search engines of Science Direct and Web of Science. The first 100 hits found by the search engine Google Scholar were scanned.

[3] The search terms used were “simulation”, “humanitarian”, and “logistics”. All hits were scanned found by the search engines of Science Direct and Web of Science. The first 100 hits found by the search engine Google Scholar were scanned.

Table 3.5. Review of mathematical programs for humanitarian logistics

Phase	Problem	Models
Disaster preparedness phase	Specification of stationary warehouses	Balcik and Beamon (2008) Barzinpour and Esmaeili (2014) Bozorgi-Amiri et al. (2013) Campbell and Jones (2011) Chang et al. (2007) Davis et al. (2013) Döyen et al. (2012) Görmez et al. (2010) Jia et al. (2007a) Li et al. (2011) Mete and Zabinsky (2010) Rawls and Turnquist (2011) Rawls and Turnquist (2012) Salmerón and Apte (2010) Yang et al. (2014) Yushimito et al. (2012)
	Specification of guaranteed stocks at suppliers	-
	Specification of vehicle depots	-
	Specification of facilities that can be used during disaster response	-
Disaster response phase	Specification of community level assessment activities	-
	Specification of temporary warehouses and handling points	Afshar and Haghani (2012) Galindo and Batta (2013a) Lin et al. (2012) Rath and Gutjahr (2014) Rottkemper et al. (2011) Tzeng et al. (2007) Wang et al. (2014)
	Specification of LDCs	Horner and Downs (2010) Jia et al. (2007b) Lee et al. (2009a) Lee et al. (2009b) Murali et al. (2012)
	Specification of staging areas for non-priority donations	-
	Specification of replenishment orders for relief items	Alp Ertem and Buyurgan (2011) Beamon and Kotleba (2006) Consuelos Salas et al. (2012) Das and Hanaoka (2014) Falasca and Zobel (2011) McCoy and Brandeau (2011)
	Specification of transportation activities	Adıvar and Mert (2010) Afshar and Haghani (2012) Angelis et al. (2007)

Balcik et al. (2008)
Barbarosoğlu et al. (2002)
Barbarosoğlu and Arda (2004)
Berkoune et al. (2012)
Camacho-Vallejo et al. (2014)
Campbell et al. (2008)
Gu (2011)
Haghani and Oh (1996)
Hu (2011)
Huang et al. (2012)
Huang et al. (2015)
Lin et al. (2011)
Lin et al. (2012)
Najafi et al. (2013)
Naji-Azimi et al. (2012)
Nolz et al. (2011)
Ortuño et al. (2011)
Özdamar (2011)
Özdamar and Demir (2012)
Özdamar et al. (2004)
Rath and Gutjahr (2014)
Shen et al. (2009)
Suzuki (2012)
Vitoriano et al. (2009)
Vitoriano et al. (2011)
Wang et al. (2014)
Wohlgemuth et al. (2012)
Yan and Shih (2009)
Ye and Liu (2014)
Yi and Özdamar (2007)

Regarding the disaster preparedness phase, only mathematical programs for the planning of stationary warehouses were identified; namely the programs published by Balcik and Beamon (2008), Barzinpour and Esmaeili (2014), Bozorgi-Amiri et al. (2013), Campbell and Jones (2011), Chang et al. (2007), Davis et al. (2013), Döyen et al. (2012), Görmez et al. (2010), Jia et al. (2007a), Li et al. (2011), Mete and Zabinsky (2010), Rawls and Turnquist (2011), Rawls and Turnquist (2012), Salmerón and Apte (2010), Yang et al. (2014), and Yushimito et al. (2012). All mathematical programs belong to the functional class of facility location models. A classification scheme for facility location models in general was presented by Klose and Drexl (2005). Classification schemes for facility location models focusing on humanitarian logistics can be found in the reviews of Anaya-Arenas et al. (2014) and Caunhye et al. (2012).

Several mathematical programs were identified for decision problems in the disaster response phase. The specification of temporary warehouses and/ or handling points was targeted by the programs of Afshar and Haghani (2012), Galindo and Batta (2013a), Lin et al. (2012), Rath and Gutjahr (2014), Rottkemper et al. (2011), Tzeng et al. (2007), and Wang et al. (2014) and the specification of LDCs was targeted by the programs of Horner and Downs (2010), Jia et al. (2007b), Lee et al. (2009a), Lee et al. (2009b), and Murali et al. (2012). Again, all of the mathematical programs belong to the class of facility location models.

Choices about the suppliers, sizes, and dates of replenishment orders during the relief operations are supported by the models of Alp Ertem and Buyurgan (2011), Beamon and Kotleba (2006), Consuelos Salas et al. (2012), Das and Hanaoka (2014), Falasca and Zobel (2011), and McCoy and Brandeau (2011). These models belong to the functional class of inventory models and can be seen as rather special applications of mathematical programming (or other OR methodologies) where the formulation can be exploited to simplify computations or to characterize the form of the optimal inventory policy (Veinott, 1966). A classification scheme for inventory models in general was developed by Silver (1981). More specific classification schemes that can be used for inventory models with a focus on humanitarian logistics have not been found.

Mathematical programs supporting the specification of transportation vehicle operations during a disaster response were developed by Adıvar and Mert (2010), Afshar and Haghani (2012)*, Angelis et al. (2007), Balcik et al. (2008), Barbarosoğlu et al. (2002), Barbarosoğlu and Arda (2004), Berkoune et al. (2012), Camacho-Vallejo et al. (2014), Campbell et al. (2008), Gu (2011), Haghani and Oh (1996), Hu (2011), Huang et al. (2012), Huang et al. (2015), Lin et al. (2011), Lin et al. (2012)*, Najafi et al. (2013), Naji-Azimi et al. (2012), Nolz et al. (2011), Ortuño et al. (2011), Özdamar (2011), Özdamar and Demir (2012), Özdamar et al. (2004), Rath and Gutjahr (2014)*, Shen et al. (2009), Suzuki (2012), Vitoriano et al. (2009), Vitoriano et al. (2011), Wang et al. (2014)*, Wohlgemuth et al. (2012), Yan and Shih (2009), Ye and Liu (2014), and Yi and Özdamar (2007).[4] These programs belong to the functional class of transportation models. These models can be further differentiated into those focusing on long-haul transportation and those focusing on pre-haul and end-haul transportation. Long-haul (intercity) transportations are transportation operations which are mainly concerned with the movement of goods over relatively long distances, between terminals or cities. Goods may be moved by rail, truck, ship, or any combination of modes. Mathematical programs capturing these long-haul transportation problems are known as "network flow planning models" if they only support the decisions on the movements of loads; and "service network design models" if they also support the decisions on the modes and types of transportation vehicles used for the movements of loads. Supplementary to long-haul transportations are pre-haul and end-haul transportations, i.e. the local movements between terminals and customers respectively beneficiaries. Vehicle routes usually start and end at the same depot and are composed of several pickup and delivery operations or a combination of both. Vehicle routing models capture these pre- and end-haul transportations (Crainic, 1998; Crainic and Laporte, 1997; SteadieSeifi et al., 2014). A classification scheme for vehicle routing and scheduling models was developed by Bodin and Golden

---

[4] The programs marked with a star (*) also support the specification of some sort of facility within the humanitarian logistics network.

(1981). Classification schemes for transportation models with a focus on humanitarian logistics can be found in the reviews of Anaya-Arenas et al. (2014), Caunhye et al. (2012), LaTorre et al. (2012), and Özdamar and Alp Ertem (2015).

Table 3.6. Available classification schemes for characterizing problems captured in mathematical programs (for humanitarian logistics)

Classifications scheme	Categories$^+$
Anaya-Arenas et al. (2014) for facility location models	Type of parameters, number of sources, number of different items, capacity limits, resource allocation, number of objectives, types of objectives
Anaya-Arenas et al. (2014) for transportation models	Type of parameters, number of vehicle depots, number of transportation modes, fleet composition, number of different items, capacity limits, number of objectives, types of objectives
Bodin and Golden (1981) for vehicle routing models	Type of demand, type of network, location of demands, type of service times, vehicle route-times, number of vehicle depots, number of vehicles, fleet composition, capacity limits, vehicle operations, other constraints, type of costs, type of objective
Caunhye et al. (2012) for facility location models	Type of parameters, number of stages, capacity limits, other constraints, other decisions, number of objectives, types of objectives, requirements
Caunhye et al. (2012) for transportation models	Type of parameters, number of stages, capacity limits, other constraints, other decisions, number of objectives, types of objectives, requirements
Klose and Drexl (2005) for facility location models	Type of parameters, type of topography, number of stages, number of different items, capacity limits, demand elasticity, type of item delivery, type of objective
LaTorre et al. (2012) for transportation models	Type of demand, type of supply, type of travel time, number of vehicle depots, fleet composition, number of different items, types of objectives
Özdamar and Alp Ertem (2015) for transportation models	Type of model, types of constraints, types of objectives
Silver (1981) for inventory models	Type of demand, type of supply, number of stocking points, number of different items, shelf-life considerations, discounts, stock-out consequences, types of constraints, type of costs, types of objectives

$^+$The labelling and orders of the presented categories can, for the sake of clarity, vary from the original labelling and orders in the publications.

Table 3.6 gives an overview of the classification schemes developed by Bodin and Golden (1981), Klose and Drexl (2005), and Silver (1981) as well as of the used categories in the reviews of Anaya-Arenas et al. (2014), Caunhye et al. (2012), LaTorre et al. (2012), and Özdamar and Alp Ertem (2015). Clearly, these classification schemes can only be useful for characterizing certain types of mathematical programs that are included in the online OR toolkit for humanitarian logistics.

3.4 Online OR toolkit for humanitarian logistics

As it is outlined in Table 3.5 (pp. 27f), there are several OR models available for the support of problems occurring in the field of humanitarian logistics during the disaster preparedness and disaster response phases. The aim of this work is to develop a structure for a so-called “online OR toolkit for humanitarian logistics”. The online toolkit should help academics store their OR models, allow practitioners to find, adapt, apply, and combine available OR models, allow practitioners to make contact with academics (as the OR model developers) in order to give feedback on a model’s usefulness for a specific use case, and help academics update or remove their OR models in response to practitioners’ comments. In this sense, a complete online OR toolkit for humanitarian logistics could be regarded as a software tool that comprises several functions of a model management system (MMS). As noted before, a MMS can support the development of new computerized models as well as the storage, selection, adaption, application, combination, and update of available computerized models. The online OR toolkit can also be regarded as a web-based electronic marketplace for decision technologies as envisioned by Bhargava et al. (1997). Customer operations on this kind of market could range from searching and gathering information about available OR models (similar to yellow pages) to executing available OR models directly through their web browsers. Provider operations on this market comprise the registration, update, and withdrawal of OR models (Bhargava et al., 1997).

Before describing the proposed structure of an online OR toolkit for humanitarian logistics, some remarks are made about the general usefulness of OR models for decisions in the field of humanitarian logistics. According to some authors, applying analytical tools to support decision-making can help reduce stress by managing information flow and enhancing the decision-maker’s cognitive process (Dai et al., 1994; Wallace and Balogh, 1985). Since humanitarian practitioners are under pressure after the onset of a disaster to demonstrate their effectiveness – also due to 24-hour media scrutiny (ELRHA, n.d., pp. 7f) – it could be concluded that OR models are generally useful for humanitarian logistics practitioners. However, in his review on the impact of stress on disaster response, Paton (2003) states that naturalistic decision-making, where the decision-maker recognizes the type of situation encountered and from previous experiences selects an appropriate course of action, has a greater stress resilience than an analytical approach. Indeed, this naturalistic decision-making ability can only be developed through experiences. High staff turnover in humanitarian organizations (Tomasini and van Wassenhove, 2009, p. 129) and the relative infrequency of disasters (Altay and Green, 2006; Wallace and Balogh, 1985) can impede practitioners in the field of humanitarian logistics from accumulating experiences. Therefore, an OR model could at least be seen as a tool for rather inexperienced practitioners in the field of humanitarian logistics.

Furthermore, the dependency on computer technology can be seen as a limitation for the use of OR models because disasters are often associated with power outages. Therefore, if a decision-maker wants to use OR models during a disaster response, the field office should be equipped with reliable back-up capacities for power supply (e.g. generators, solar panels, batteries). However, guides of humanitarian organizations, e.g. the field guide of the WFP (WFP, 2002, p. 281), require field offices to have reliable power supplies which should allow decision-makers to make use of computer technology and thereby of OR models also during a disaster response.

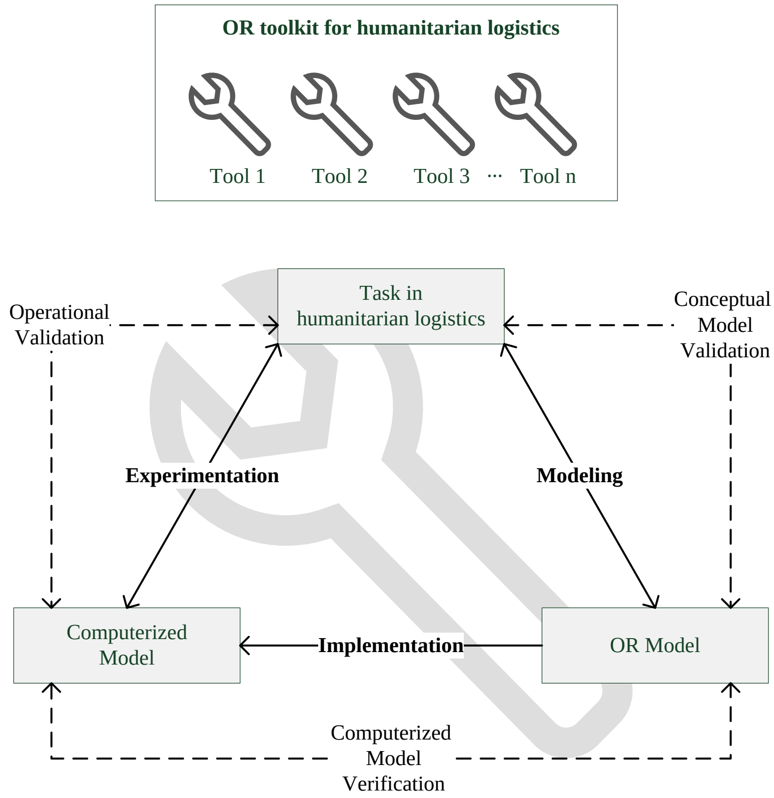


Figure 3.2. Functions of a tool in the online OR toolkit for humanitarian logistics

Other than electricity, there are further – more general – requirements for the use of OR models by a humanitarian logistics practitioner or a team of practitioners. The practitioner (or the team) must come across a decision-making approach that has not proven to be reasonably productive in the past, must work in a climate favorable to innovation, must be convinced of the usefulness of OR models for decision problems in humanitarian logistics, and is willing to be challenged by an

OR model in the decision-making process (Harvey, 1970). Even if these requirements are met, practitioners need access to scientific databases and have to find, comprehend, and apply articles published by academics in scholarly journals – and this is a challenging, time-consuming task for practitioners to do (Altay and Green, 2006; Shapiro et al., 2007). Therefore, one paramount goal of the online OR toolkit for humanitarian logistics is to instruct practitioners on how to make use of available OR models that were published in academic journals. More exactly, the online toolkit should help practitioners to:

1. find, adapt, and combine available OR models for their specific problem(s), thereby reducing the practitioners' own modeling effort;
2. convert an OR model into a computerized model, thereby reducing the practitioners' own implementation effort; and
3. build a database for faster experimentations of the computerized models in the online toolkit.

As highlighted in Figure 3.2, the three main sub-processes of the general model development process should be supported by the OR toolkit. Such an OR toolkit should be made available online in order to virtually bring together academics and practitioners so as to increase the utilization of research findings in practice (Galindo and Batta, 2013b; Shapiro et al., 2007). More precisely, the online toolkit should help:

4. practitioners catch up with academics as the OR model developers, whereby academics help practitioners adapt and apply their models while practitioners provide feedback on the OR models' assumptions (conceptual model validation) and usefulness for their use cases (operational validation) while the feedback can again be used by the academics to update their OR models; and
5. academics to analyze available OR models whereby identifying open research questions and reducing the risk of redundant or useless OR model building.

Surely, initiating contacts and doing so with the right contact partner are the first steps of every collaboration process between an academic institution (i.e. a university, private research institute, or think tank) and a humanitarian organization. In the end, the relationships established through an online OR toolkit could grow into something more institutional such as consultancies or partnership agreements (ELRHA, n.d., p. 17).

An online OR toolkit for humanitarian logistics should be implemented as a website. Six major stages form the overall process of developing a website: site definition and planning, planning of the site's information architecture, site design, site construction, site marketing as well as the site's tracking, evaluation, and maintenance. During the site definition and planning stage, the website production team is composed and the budget is defined. During the information architecture stage, the website's content is structured (Lynch and Horton, n.d.b). Again, there are several steps in building a website's information architecture (Lynch and Horton, n.d.a):

a) building a content inventory;
b) establishing a hierarchical outline of the content;
c) presenting the content in a consistent modular structure;
d) developing diagrams that show the site structure; and
e) testing the site's proposed system with real users.

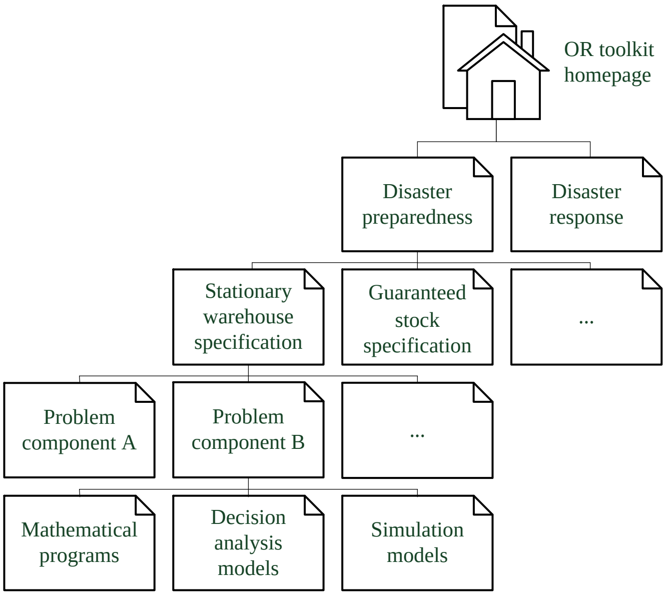


Figure 3.3. Excerpt of the hierarchical outline of the toolkit's structure

Table 3.5 (p. 27 f) can be interpreted as the online OR toolkit's content inventory: a collection of available mathematical programs for humanitarian logistics. Moreover, Table 3.5 can partly be viewed as a hierarchical outline of the content with disaster preparedness and disaster response as the most general concepts, each representing a submenu in the online toolkit. To each of these submenus, the corresponding logistical tasks are assigned. Each task is introduced by giving examples of implemented real-world solutions to a problem. To each task, the available mathematical programming models, decision analysis models, and simulation models are assigned. In a MMS, such a hierarchical outline of the content would be called its "model selection component" (Muhanna and Pick, 1994). An excerpt of the hierarchy of the online OR toolkit for humanitarian logistics is shown in Figure 3.3. There are also other ways to organize content apart from a categorization: for example, it may be organized by timeline, by geographic location, by alphabetical order, or by some sort of metric such as price, score, size, or weight. Generally, organizing by category is particularly useful when the elements being organized are of equal or unpredictable importance (Lynch and Horton, n.d.a).

In accordance with step c) of the content organizing process, each OR model should be characterized consistently. In the online toolkit, each OR model should be characterized by its mathematical formulation, the structure of the underlying problem, and one or more possible translations into program code (Gösling and Geldermann, 2014c). It is important that the overall structure should be filled with so-called “chunks” of information instead of long passages of text. Chunking information can help to organize content in a modular layout that is the same throughout the online toolkit. A consistent layout can help toolkit-users apply past experience with an OR model to future explorations of other OR models. Moreover, chunks of information are better suited to the computer screen which provides a limited view of long documents; long web pages tend to disorient readers (Lynch and Horton, n.d.a).

Firstly, the mathematical formulation of an OR model is reproduced using a consistent notation for the sets, parameters, and variables. By inserting the mathematical formulation, the OR toolkit allows the model developers to express themselves in their preferred modeling language, i.e. using their preferred OR methodology. Secondly, a translation of the mathematical formulation into language and ideas is given. This translation allows practitioners to better understand the underlying problem as managers think and work for most of their lives with language and ideas rather than numbers and mathematical symbols (Eden, 1988; Daft and Wiginton, 1979). Thirdly, a translation of the mathematical formulation into program code is presented, as not releasing such code raises needless roadblocks to reproducibility (Ince et al., 2012). Code should be expressed in the model developer’s preferred programming language. To allow only for a single programming language is not possible given the variety of available programming languages to formulate OR models, especially to transform mathematical programs into program code: AIMMS, AMPL, CAMPS, GAMS, LINGO, LPL, MPL, OPL, and UIMP (Valente and Mitra, 2007). A similar structure – consisting of problem statement, mathematical formulation, and program code – is used on the NEOS website to present selected case studies which have been targeted by the NEOS server.[5] However, the problem statements are inconsistent because they are not based on a pre-defined structure.

In this work, the problem structuring scheme outlined in Table 3.1 (p. 21) is used for a consitent, language-based characterization of OR models for humanitarian logistics. The problem structuring scheme is adapted to narrow its focus on decision problems in the field of humanitarian logistics. Clearly, the environment wherein these problems take place can be further specified as a disaster environment. Different elements can be found in such an environment: humanitarian organizations, locations for stationary and temporary facilities, arcs that link different locations, settlements, beneficiaries, companies, donors, the society, and the

---

[5] The NEOS server is a free web-based service for solving mathematical programs (NEOS (n.d.)).

eco-system. The organization that intends to set up and run a humanitarian logistics network within this environment, and that faces a decision problem may has several logistical resources at hand: facilities, transportation vehicles, technical equipment, and workers. These logistics resources realize the flow of relief items from suppliers to beneficiaries. If possible, the logistical facilities defined in an OR model are further broken down based on the structure of a humanitarian logistics network shown in Figure 2.3 (p. 11). If no direct counterpart exists in Figure 2.3 for a facility as defined in a model, the following procedure is used for its classification: a facility in a model that can not be identified as anything other than the source of a humanitarian logistics network is a “supply facility”, a facility that can only be identified as the sink of a humanitarian logistics network is a “demand facility”, and a facility that can only be identified as a facility between a source and a sink is a “transshipment facility”. Vehicles, equipment, and (aid) workers defined in a model are differentiated into those for warehousing, transportation, handling, distribution, and coordination. Critical dimensions and metrics of a humanitarian organization as well as the corresponding objectives, targets, and requirements are specified based on the framework outlined in Table 2.3 (p. 16).

Table 3.7. Problem structuring scheme for humanitarian logistics

Category	Sub-category	Representation
Disaster environment	Disasters, humanitarian organizations, locations for facilities, arcs, beneficiaries, companies, donors, society, eco-system	Mathematical expressions in OR model
Humanitarian organization	Available logistics facilities, vehicles, equipment, workers, and relief items	Mathematical expressions in OR model
	Use and interaction of logistics resources, relief items, and environment	Mathematical expressions in OR model
	Critical dimensions, metrics, objectives, targets, requirements	Mathematical expressions in OR model

Table 3.7 shows the adapted problem structuring scheme that will be used in the following to completely characterize the underlying problems of available OR models for humanitarian logistics. It ensures a consistent OR model characterization across models based on different OR methodologies and across models with different functional focuses. Moreover, the scheme includes a column to indicate which mathematical representation in an OR model captures a certain component of a problem. Clearly, differences in models belonging to the same class (e.g. to those for the planning of stationary warehouses) can be identified based on the filled out schemes. The identified differences allow for additional categorizations of OR models belonging to the same functional class within the hierarchical out-

line of the toolkit’s content – i.e. for categorizations based on certain problem components (see Figure 3.3, p. 34).

In contrast to the structuring scheme in Table 3.7, the classification schemes presented in the articles of Bodin and Golden (1981), Klose and Drexl (2005), and Silver (1981) as well as in the reviews of Anaya-Arenas et al. (2014), Caunhye et al. (2012), LaTorre et al. (2012), and Özdamar and Alp Ertem (2015) only allow for the characterization of a specific type of mathematical program (Table 3.6, p. 30). Furthermore, none of these classification schemes differentiate between the assumptions regarding the external environment, the organizational resources, the allowed interactions between available resources of the organization and the external environment, and the organization’s crucial dimensions, metrics, objectives, targets, and requirements – even though these components can be identified as the central components of any organizational problem (see section 3.1). However, the categories used in the mentioned classification schemes have intersections with those used in the problem structuring scheme presented in Table 3.7. Exemplarily, the intersections between the classification schemes in Anaya-Arenas et al. (2014) and the scheme used in the present work are shown in Table 3.8.

Table 3.8. Intersections of the problem structuring scheme for humanitarian logistics with the classification schemes used in Anaya-Arenas et al. (2014)

Category in the present work	Categories in Anaya-Arenas et al. (2014) for location models	Categories in Anaya-Arenas et al. (2014) for transportation models
Elements in disaster environment	Type of parameters, number of sources	Type of parameters
Available logistics resources and relief items of the humanitarian organization	Type of parameters, number of sources, number of different items, capacity limits	Type of parameters, number of vehicle depots, number of transportation modes, fleet composition, capacity limits
Use and interaction of logistics resources, relief items, and environment	Resource allocation	
Critical dimensions, metrics, objectives, targets, and requirements	Number of objectives, types of objectives (costs objective/ covering objective/ time objective, fairness objective/ other objective)	Number of objectives, types of objectives (costs objective/ covering objective/ time objective, fairness objective/ other objective)

The goal of this work is *not* to present a complete online OR toolkit for humanitarian logistics by inserting any OR model identified in section 3.3 and listed in Table 3.5. Instead, it should be demonstrated in section 4 that the proposed toolkit structure (i.e. the proposed information architecture of the corresponding website) can indeed serve the toolkit functions 1 to 5 as identified at the beginning of this section. This is done by inserting nine mathematical programs into the structure. Three models are included for the specification of stationary warehouses, three models are included for the specification of LDCs, and three models are included for the specification of transportation activities. By inserting these types of OR models into the structure, it is ensured that – while presenting a complete toolkit lies beyond the scope of this study – the shortened paper version presented in chapter 4 can still be used to specify the cornerstones of every humanitarian logistics network (Anaya-Arenas et al., 2014): stationary warehouses as the network's sources, LDCs as its sinks, and transportation vehicles to perform the interactions between sources and sinks.

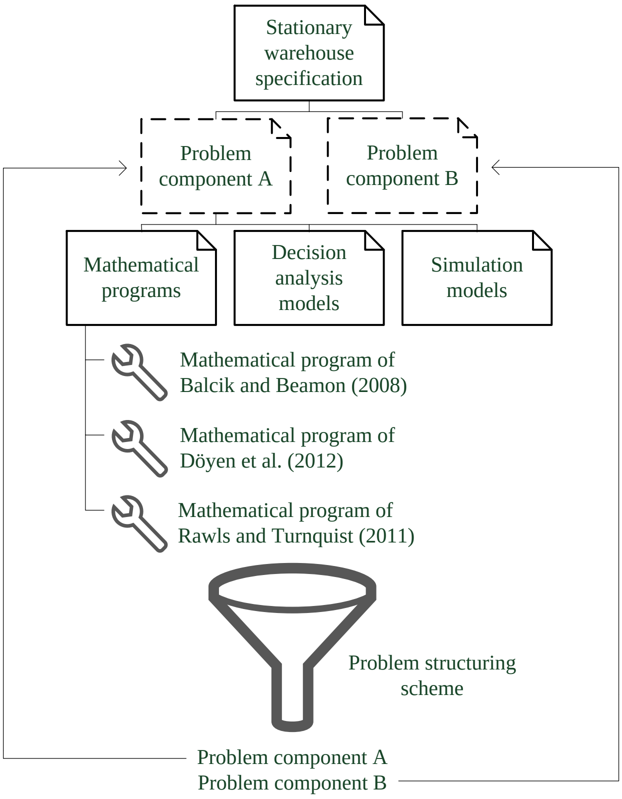


Figure 3.4. Procedure to determine additional levels in the hierarchical outline of the toolkit based on filled out problem structuring schemes

Those parts of the toolkit that are filled with tools (i.e. OR models) are marked in Table 3.9 and will be described in chapter 4. Each of the three sub-toolkits will be introduced via examples of real-world solutions and by guidelines for the selection of OR models assigned to a sub-toolkit. Exemplarily, guidance will be based on two problem components: (1) resource attributes to be specified in an OR model and (2) critical dimensions, objectives, targets, and requirements used to specify the resources' attributes in an OR model. Before guidance can be given based on problem components, the OR models' underlying problems need to be characterized using the proposed problem structuring scheme. Figure 3.4 shows the procedure to determine the problem components that can be used for guiding toolkit-users within the stationary warehouse specification toolkit.

Within each sub-toolkit, the included OR models will be ordered alphabetically by authors. If there are more than three models available for a problem class, the need for a selection arises. Firstly, only models published before 2014 were selected. Secondly, publications that have a primary focus on solution algorithms for OR models were excluded. This is because the proposed OR toolkit for practitioners only includes descriptions of problems that are captured in OR models and *not* descriptions of solution algorithms to solve these problems. Accordingly, publications such as "A Voronoi-based heuristic algorithm for locating distribution centers in disasters" by Yushimito et al. (2012), "Solution approaches for facility location of medical supplies for large-scale emergencies" by Jia et al. (2007b), and "A hierarchical clustering and routing procedure for large scale disaster relief logistics planning" by Özdamar and Demir (2012) were excluded. Thirdly, an OR model was chosen based on the citation level using Google Scholar. The model of Balcik and Beamon (2008) was therefore chosen as one model for the stationary warehouse specification toolkit[6], the model of Lee et al. (2009a) was chosen as one model for the LDC specification toolkit[7], and the model of Özdamar et al. (2004) was chosen as one model for the transport specification toolkit[8]. Based on this selection, the second and the third model were picked so that differences with respect to the chosen model could be expected in the results of the problem structuring process.

---

[6] According to Google Scholar as of January/Februrary 2015, Balcik and Beamon (2008) is cited **284 times**, Bozorgi-Amiri et al. (2013) 32 times, Campbell and Jones (2011) 51 times, Chang et al. (2007) 241 times, Davis et al. (2013) 8 times, Döyen et al. (2012) 22 times, Görmez et al. (2010) 29 times, Jia et al. (2007a) 196 times, Li et al. (2011) 15 times, Mete and Zabinsky (2010) 179 times, Rawls and Turnquist (2011) 31 times, Rawls and Turnquist (2012) 29 times, and Salmerón and Apte (2010) 101 times, and 17 times.

[7] According to Google Scholar as of January/Februrary 2015, Horner and Downs (2010) is cited 39 times, Lee et al. (2009a) **50 times**, Lee et al. (2009b) 23 times, and Murali et al. (2012) 38 times.

[8] According to Google Scholar as of January/Februrary 2015, Adıvar and Mert (2010) is cited 8 times, Afshar and Haghani (2012) 41 times, Angelis et al. (2007) 60 times, Balcik et al. (2008) 175 times, Barbarosoğlu et al. (2002) 253 times, Barbarosoğlu and Arda (2004) 397 times, Berkoune et al. (2012) 32 times, Campbell et al. (2008) 138 times, Gu (2011) 8 times, Haghani and Oh (1996) 338 times, Hu (2011) 38 times, Huang et al. (2012) 39 times, Lin et al. (2011) 64 times, Lin et al. (2012) 11 times, Najafi et al. (2013) 22 times, Naji-Azimi et al. (2012) 10 times, Nolz et al. (2011) 27 times, Özdamar et al. (2004) **600 times**, Özdamar (2011) 22 times, Shen et al. (2009) 34 times, Suzuki (2012) 3 times, Vitoriano et al. (2009) 22 times, Vitoriano et al. (2011) 55 times, Wohlgemuth et al. (2012) 10 times, and Yi and Özdamar (2007) 411 times.

Table 3.9. Parts of the toolkit for which content is specified in chapter 4

Problem	Model developer	Model profile
Specification of stationary warehouses	Mathematical program of Balcik and Beamon (2008)	Mathematical formulation Problem structure Program code
	Mathematical program of Döyen et al. (2012)	Mathematical formulation Problem structure Program code
	Mathematical program of Rawls and Turnquist (2011)	Mathematical formulation Problem structure Program code
Specification of guaranteed stocks at suppliers	-	-
Specification of vehicle depots	-	-
Specification of facilities that can be used during disaster response	-	-
Specification of community level assessment activities	-	-
Specification of temporary warehouses and handling points	-	-
Specification of LDCs	Mathematical program of Horner and Downs (2010)	Mathematical formulation Problem structure Program code
	Mathematical program of Lee et al. (2009a)	Mathematical formulation Problem structure Program code
	Mathematical program of Murali et al. (2012)	Mathematical formulation Problem structure Program code
Specification of staging areas for non-priority donations	-	-
Specification of replenishment orders for relief items	-	-
Specification of transportation activities	Mathematical program of Balcik et al. (2008)	Mathematical formulation Problem structure Program code
	Mathematical program of Özdamar et al. (2004)	Mathematical formulation Problem structure Program code
	Mathematical program of Vitoriano et al. (2011)	Mathematical formulation Problem structure Program code

4 Content of the online OR toolkit for humanitarian logistics

In this chapter, three parts of the proposed online toolkit are described in detail: the stationary warehouse specification toolkit, the local distribution center (LDC) specification toolkit, and the transport specification toolkit. As such, the two cornerstones of every humanitarian logistics network – stationary warehouses and LDCs – can be specified together with the interactions in-between. In accordance with the proposed structure in section 3.4, each of the three sub-toolkits is briefly introduced and guidance is given on how to make use of the three assigned models. Due to the nature of the present work, the content of the online OR toolkit is largely presented in text passages instead of information chunks as would be necessary for a website. Moreover, the problem descriptions have a common internal structure and are made of similar text modules in order to help toolkit-users apply past experience with a problem description to future explorations of other problem descriptions. Figure 4.1 shows the interrelations between this chapter's sections (4.1, 4.2, and 4.3) and the proposed hierarchical outline of the online OR toolkit for humanitarian logistics.

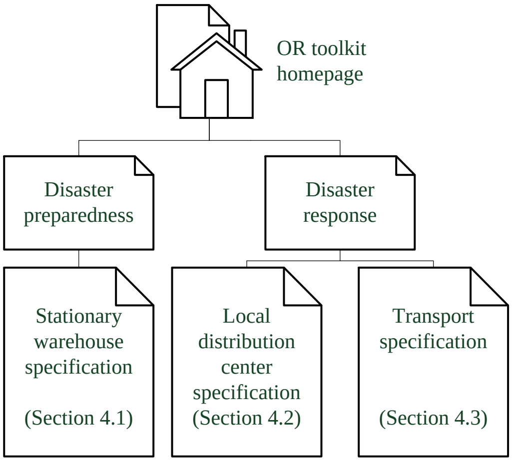


Figure 4.1. Parts of the online OR toolkit for which content is specified in section 4.1, 4.2, and 4.3

Before describing the content of the toolkit, some additional remarks are made concerning the process of choosing OR models out of the multitude of available models to include them to the present, static version of the toolkit; more exactly, to assign them to the present versions of the stationary warehouse specification toolkit, the LDC specification toolkit, and the transport specification toolkit.

The OR models available for the planning of stationary warehouses are almost solely based on mathematical programming (see section 3.3). As noted before in section 3.4, OR models published in 2014 onwards were excluded – this is true for the OR models of Barzinpour and Esmaeili (2014), Roh et al. (2015) which is a decision analysis model, and Yang et al. (2014). Of those published before 2014, the models of Balcik and Beamon (2008), Döyen et al. (2012), and Rawls and Turnquist (2011) were included. Balcik and Beamon (2008) was included as it has the highest number of citations according to Google Scholar. The other two models were selected to show whether and how OR models with different features can be captured by the problem structuring scheme. In fact, the OR model of Döyen et al. (2012) was included to show that facility location models with more than one echelon can be captured by the problem structuring scheme and the OR model of Rawls and Turnquist (2011) was included to show that facility location models with bidirectional arcs can be captured by the problem structuring scheme.

OR models available for the planning of LDCs are only based on mathematical programming (see section 3.3), namely the mathematical programs of Horner and Downs (2010), Jia et al. (2007b), Lee et al. (2009a), Lee et al. (2009b), and Murali et al. (2012). Even though the OR model of Jia et al. (2007b) has the highest number of citations based on Google Scholar, it was not included in this toolkit version because its main focus is on solution approaches. However, the OR model of Lee et al. (2009a) was included as it has the second-highest number of citations based on Google Scholar while Lee et al. (2009b) was excluded because it describes an identical OR model as the one of Lee et al. (2009a). Hence, the OR models of Horner and Downs (2010), Lee et al. (2009a), and Murali et al. (2012) were selected for illustrative purpose.

OR models available for the planning of transportation activities are only based on mathematical programming (see section 3.3). Özdamar et al. (2004) was included as it has the highest number of citations based on Google Scholar. The other two models were selected to show whether and how OR models with features different to that of Özdamar et al. (2004) can be captured by the problem structuring scheme. Balcik et al. (2008) was included to show that models belonging to the class of route enumeration models can be captured by the problem structuring scheme. Vitoriano et al. (2011) was included in order to prove whether programs based on the Goal Programming approach can be captured by the problem structuring scheme.

4.1 Stationary warehouse specification toolkit

Humanitarian organizations preposition relief items during the disaster preparedness phase in stationary warehouses. During the disaster response phase, the temporary facilities within the disaster area procure relief items from private companies, donors, or the stationary warehouses (see Figure 4.2). Each stationary warehouse is characterized by a location, a storage space, equipment and workers to put relief items in storage and to remove them from storage, suppliers of relief items, and relief item stocks.

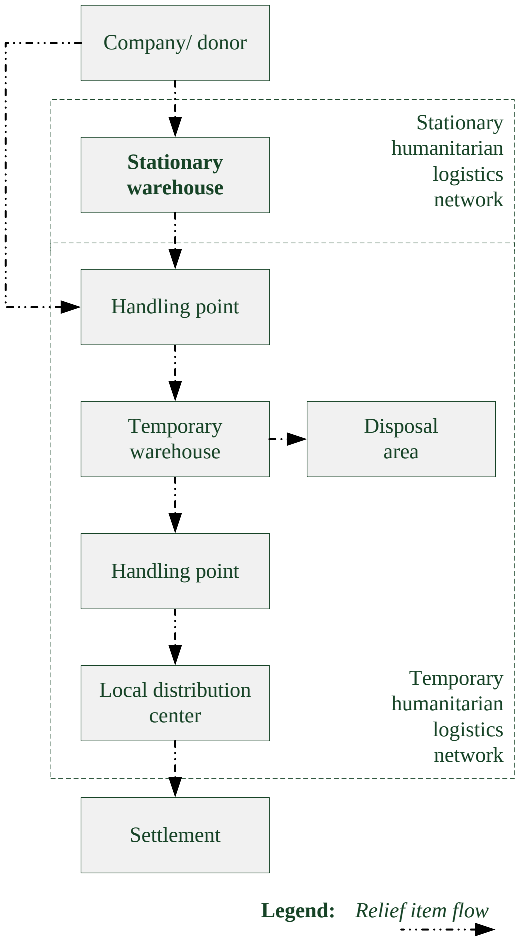


Figure 4.2. Stationary warehouse as a crucial part of a humanitarian logistics network

The United Nations Humanitarian Response Depot (UNHRD), for example, is a system that consists of several stationary warehouses for relief items. In five warehouses, located in Panama City (Panama), Brindisi (Italy), Accra (Ghana), Dubai (UAE), and Subang (Malaysia), different types of non-food relief items are stored. The stationary warehouse in Panama City consists of a covered area of 1,600 m². In Brindisi, two stationary warehouses are located within the borders of a military airport, partly using a former aircraft hangar. Together they provide a covered area of 10,250 m² and an open area of 5,900 m². The stationary warehouse in Accra is located within the city's international airport and has a covered storage area of 5,000 m². In Dubai, the stationary warehouse is located in the vicinity of the city's seaport and airport and has a covered storage area of 10,000 m².

Finally, the stationary warehouse in Subang has a covered area of 5,000 m² and an open area of 10,000 m² (UNHRD, n.d.). A second example of a system of stationary warehouses is the Strategic National Stockpile system in the USA. The stationary warehouses stock health care items (e.g. antibiotics and vaccines) which can be made available to respond to public-health threats such as pandemics or terrorist attacks using dirty bombs, anthrax, or smallpox (Jia et al., 2007a).

Table 4.1. Guide for the stationary warehouse specification toolkit

	Attributes of stationary warehouses			Key dimensions, objectives, and requirements			
OR model	Locations	Sizes	Stocks	Inputs	Delivered relief item quantity	Delivered relief item quality	Delivery time
Balcik and Beamon (2008)	■		■	R, R, R	O	O	O
Döyen et al. (2012)	■		■	O, R, R, R	O	O	R
Rawls and Turnquist (2011)	■	■	■	O	O, R	O, R	R

■: to be specified, O: objective, R: requirement

Table 4.1 gives guidance for choosing a suitable OR model: either based on the attributes of stationary warehouses the user wants to specify (left part of Table 4.1) or based on the used key dimensions, objectives, and requirements to identify the most advantageous configuration of warehouses (right part). For example, the model of Balcik and Beamon (2008) supports decisions to be made regarding locations and relief item stocks so that the delivered relief item quantity and quality are maximized while the delivery times are minimized and the inputs for setting up and running a humanitarian logistics network are limited. Inputs are limited by a budget for the disaster preparedness phase, by a budget for the possible disaster responses, and by fixing the maximum amount of relief items that can be distributed during the possible disaster responses.

4.1.1 Mathematical program of Balcik and Beamon (2008) for supporting decisions about the locations and stocks of stationary warehouses

In their paper "Facility location in humanitarian relief", Balcik and Beamon (2008) present a mathematical program supporting the planning of stationary warehouses. On a functional base, the program can be characterized as a facility location model. The program can also be defined as a MILP because of the use of real-valued flow variables together with binary location variables. Moreover, it can be defined as a two-stage stochastic program. Two-stage stochastic programs are characterized by the use of two types of variables: design and control variables (Mulvey et al., 1995). In the case of the program of Balcik and Beamon (2008), design variables are used to describe the locations and relief item stocks of stationary warehouses. These decisions are made in the first stage, i.e. in the disaster preparedness phase. Depending on the values assigned to the design variables, the program calculates – in the second stage – the values of the control variables for each possible disaster. In the model of Balcik and Beamon (2008), control variables are used to describe the values of the relief item flows between stationary warehouses and the demand location for each disaster scenario.

This section begins with a description of the mathematical formulation of the program. Names of sets, parameters, and variables in the present notation differ from the original notation in order to achieve a consistent notation within the toolkit. Afterwards, the underlying problem is analyzed.[9] Finally, a possible translation of the mathematical formulation into a program code is given. Balcik and Beamon (2008) present no unique solution algorithm; instead they refer to available commercial solvers for the solution of their program.

Mathematical formulation

The program's objective function (4.1) maximizes the coverage of possible demands for relief items. More exactly, the objective function maximizes the percentage of fulfilled demands for relief items over all disaster scenarios. A disaster scenario is described by a demand for certain types of relief items at one location and the probability of occurrence of a disaster at this location. Each delivered relief item contributes to the value of the objective function depending on the probability of the scenarios in which it is used to satisfy a demand, a factor representing the relief item's general importance for the beneficiaries, and a factor representing the importance of the coverage level. Several coverage levels can be defined for each relief item type. Each coverage level for a relief item type is defined by an upper and lower time limit. Constraint set (4.2) limits the number of relief items which can be distributed from a stationary warehouse during a possible disaster response to the number of relief items prepositioned in this stationary warehouse during the preparedness phase. Constraint set (4.3) ensures that only opened warehouses can stock relief items; and that opened warehouses can only stock relief items up to a location-dependent maximum storage space. Constraint (4.4) limits the budget in the preparedness phase which covers relief item procurement costs, relief item holding costs and warehouse setup costs while constraint set (4.5) limits the budgets for the disaster responses, i.e. the budgets to cover the costs for the transportation activities between opened stationary ware-

---

[9] A similar but less holistic/ detailed characterization of Balcik and Beamon (2008) can be found in Gösling and Geldermann (2014a).

houses and the demand location during the possible disasters. Constraint set (4.6) prohibits over-fulfillment of relief item demands in each possible scenario. Finally, constraint sets (4.7) and (4.8) ensure the non-negativity of the continuous variables and the binary of the location variables, respectively.

Sets:

I	Set of locations where stationary warehouses can be erected
R	Set of relief item types
S	Set of scenarios
A_r	Set of coverage levels for relief item type r
$I_{a_r s}$	Set of locations providing coverage of level a_r for the demand location in scenario s

Parameters:

bgt^{P}	Budget in the disaster preparedness (P) phase
bgt^{R}	Budget in the disaster response (R) phase
c_{ir}^{ah}	Costs for the acquisition and holding (ah) of a unit of relief item type r at location i
c_{irs}^{t}	Costs for the transportation (t) of a unit of relief item type r from location i to the demand location in scenario s
C_i^{s}	Costs for setting up (s) a stationary warehouse at location i
dmd_{rs}	Units of relief item type r demanded in scenario s
prb_s	Probability of occurrence of scenario s
$SpcW_i$	Storage space available to store relief items at location i where a stationary warehouse can be erected

$spcW_r$	Storage space used by a unit of relief item type *r*
t_{irs}^{sf}	Time for satisfying (sf) demand for relief item type *r* at demand location in scenario *s* from location *i*
tMn_{a_r}	Lower time limit defining coverage level a_r
tMx_{a_r}	Upper time limit defining coverage level a_r
ω_r	Importance factor of relief item type *r*
ω_{a_r}	Importance factor of coverage level a_r

Variables:

x_{ir}^{p}	Relief items of type *r* prepositioned (p) in stationary warehouse at location *i*
y_i	1 if a stationary warehouse is located at location *i*, 0 otherwise
α_{irs}	Percentage of demand for relief item type *r* satisfied from the stationary warehouse at location *i* in scenario *s*

MILP:

(4.1) Maximize

$$\sum_{s\in S}\sum_{r\in R}\sum_{a_r\in A_r}\sum_{i\in I_{a_r s}} prb_s dmd_{rs}\omega_r\omega_{a_r}\alpha_{irs}$$

s.t. (4.2) $\alpha_{irs} dmd_{rs} \le x_{ir}^{\mathrm{p}}$ $\qquad \forall i\in I, r\in R, s\in S$

(4.3) $\sum_{r\in R} spcW_r x_{ir}^{\mathrm{p}} \le SpcW_i y_i$ $\qquad \forall i\in I$

(4.4) $\sum_{i\in I}(C_i^{\mathrm{s}} y_i + \sum_{r\in R} c_{ir}^{\mathrm{ah}} x_{ir}^{\mathrm{p}}) \le bgt^{\mathrm{P}}$

$$\text{(4.5)} \quad \sum_{i\in I}\sum_{r\in R} dmd_{rs} c^{\mathrm{t}}_{irs} \alpha_{irs} \le bgt^{\mathrm{R}} \qquad \forall s \in S$$

$$\text{(4.6)} \quad \sum_{i\in I} \alpha_{irs} \le 1 \qquad \forall r \in R, s \in S$$

$$\text{(4.7)} \quad \alpha_{irs}, x^{\mathrm{p}}_{ir} \ge 0 \qquad \forall i \in I, r \in R, s \in S$$

$$\text{(4.8)} \quad y_i \in \{0,1\} \qquad \forall i \in I$$

Problem structure

In this sub-section, the problem that is captured in the OR model of Balcik and Beamon (2008) is described based on the problem structuring scheme outlined in section 3.4. In the first step, the environment is characterized; and in the second step, the assumed organization that operates the whole humanitarian logistics network in this environment is specified. The results of the structuring process are outlined in Table 4.2 (pp. 53ff).

Firstly, the environment is described in which the humanitarian logistics network has to be interlaced. This environment is single-organizational and is characterized by the locations to which stationary warehouses and demand facilities can be assigned and by the unidirectional arcs between. Locations for stationary warehouses are characterized by coordinates and potential storage spaces. Locations for demand facilities are characterized by coordinates and demands for certain types of relief items. Each arc is characterized by the two locations it connects, a distance, a direction, and speed limitations. The environment is probably affected by disasters which may happen in the future and it is assumed that demands for certain types of relief items occur at a dedicated location only in the event of a disaster. The humanitarian organization has information about the occurrence of several possible disasters that might take place in the environment. It is assumed that the humanitarian organization has enough information available to quantify the uncertainty of a possible disaster in terms of probabilities. A scenario's probability of occurrence is represented by a parameter in the mathematical program. Available information about one possible disaster outcome also comprises the expected demands for relief items triggered at a specific location. Furthermore, the humanitarian organization has information about the coordinates of the locations for stationary warehouses, about the potential storage spaces at these locations, about the coordinates of the locations where demands might occur, about the distances and directions of the arcs between locations, and about speed limitations on arcs. Attributes of environmental elements are explicitly or implicitly represented by parameters in the mathematical program. Implicitly represented attributes are coordinates of locations as well as distances and speed limitations between locations. They are represented by the parameters which describe the times necessary to satisfy relief item demands at specific locations. The program's parameters which describe certain attributes of environmental elements are outlined in Table 4.2.

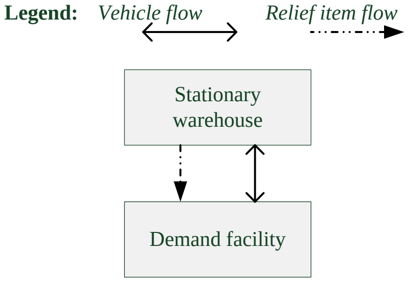


Figure 4.3. Simple example of the humanitarian logistics network in the OR model of Balcik and Beamon (2008)

Secondly, the assumed inputs of the humanitarian organization are characterized: stationary warehouses, demand facilities, transportation vehicles, and relief items. In Figure 4.3, a simple example of the humanitarian logistics network is presented, consisting of one stationary warehouse and one demand facility. Demand facilities can have different counterparts in a real-world humanitarian logistics network; in fact, a demand facility could represent a handling point, a temporary warehouse, or a LDC within the disaster-affected area. In any case, a demand facility is located downstream from a stationary warehouse. Possible counterparts for a demand facility are highlighted in Figure 4.4 using the reference structure for humanitarian logistics networks, which was described in section 2.1. A stationary warehouse, as defined in the OR model of Balcik and Beamon (2008), has an exact counterpart in this reference structure.

Each relief item type is characterized by a volume and weight. Each transportation vehicle type is characterized by the maximum speed of travel, the maximum transport volume and weight per vehicle, the number of available vehicles on arcs, and the transferred loads of relief items on specific arcs in case of a disaster. Each stationary warehouse is characterized by the location it is assigned to and its stocks of relief items. Each demand facility is characterized by the location it is assigned to and the amounts of certain types of relief items distributed at the facility in case of a disaster. The volume and weight of a certain type of relief item as well as the travel speed, transport volume and weight, and number of available vehicles of a certain transportation vehicle type on certain arcs are assumed to be already known by the humanitarian organization. The location of each demand facility is also assumed to be already known by the humanitarian organization: a demand facility is located at each location where demand for relief items can occur in order to cope with these demands in case of a disaster. The values of the already known attributes are – explicitly or implicitly – represented by parameters in the mathematical program. Locations of demand facilities, weights of relief items, travel speeds of transportation vehicles, maximum transport volumes and weights of vehicles, and the numbers of available transportation vehicles on arcs are implicitly represented by the parameters which describe the necessary times to satisfy relief item demands at demand facilities in case of disasters (obviously, these values have to be known in order to calculate the necessary times to satisfy demands at demand facilities).

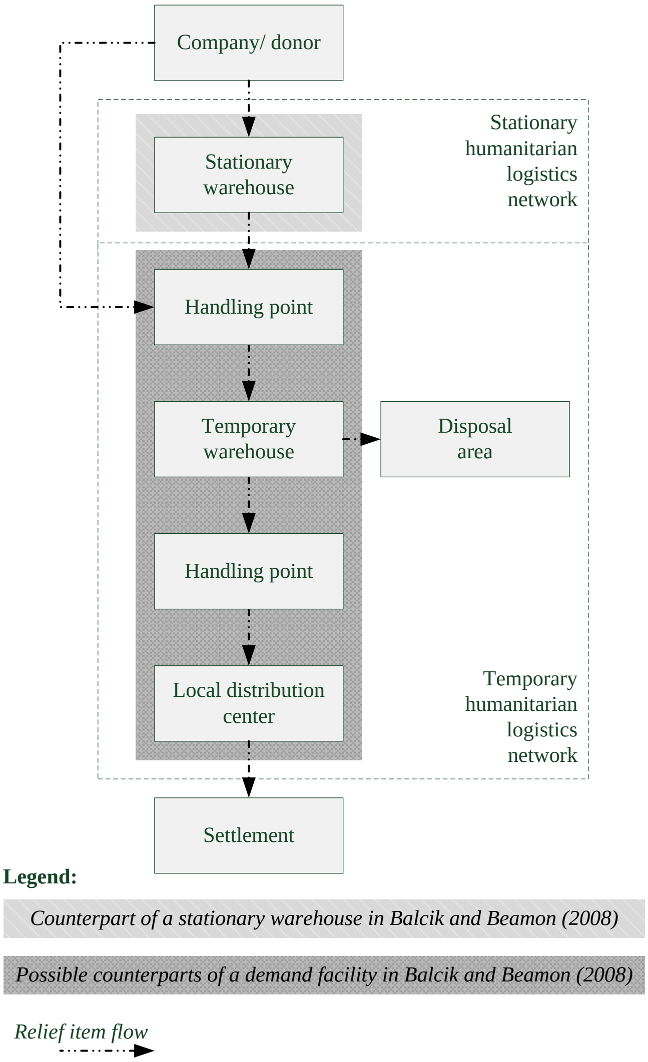


Figure 4.4. Counterparts of the facilities defined in Balcik and Beamon (2008) in the reference structure for humanitarian logistics networks

Furthermore, locations and relief item stocks of stationary warehouses as well as the relief item flows (i.e. the relief item loads of the transportation vehicles) on arcs for each possible disaster, and the amounts of relief items distributed at demand facilities for each possible disaster are the values to be determined by the humanitarian organization. These values are implicitly or explicitly represented by decision variables in the mathematical program. Relief item loads of transportation vehicles and the numbers of relief items distributed at demand facilities are implicitly represented; they can be deduced from the variables describing the percentages of relief item demands satisfied by certain stationary warehouses in case of a disaster. Balcik and Beamon (2008) assume that the locations of stationary warehouses can be chosen out of a discrete set of alternative locations whereas the values of stocked, transferred, and distributed relief items are positive real numbers. Because the values of warehouse stocks and relief item flows are positive real numbers, the number of solutions to the problem captured in the OR model of Balcik and Beamon (2008) is continuous. The parameters and decision variables which describe the attributes of logistics resources and relief items are outlined in Table 4.2.

The assumed humanitarian organization has to adhere to certain rules when using the logistics resources and relief items as well as when interacting with the environment. The following two rules are known to the humanitarian organization:

- The maximum number of relief items stocked in a stationary warehouse depends on the storage space given by a specific location and the necessary volume to stock a unit of a certain relief item type.
- During a possible disaster response, the stocked relief items at the stationary warehouses limit the number of relief items that can be sent to the one demand facility that is opened in the case of a disaster.

In the mathematical program, the allowed use and interaction between resources, relief items, and elements in the environment are represented by constraints. The constraints which represent certain relationships are outlined in Table 4.2.

When setting up a humanitarian logistics network, the assumed humanitarian organization takes into account several critical dimensions in order to identify the most advantageous network configuration. On the one hand, the configuration's inputs – the relief items and the resources for warehousing and transportation – represent critical dimensions. Warehouse setup costs, transportation costs, procurement costs, and holding costs are utilization metrics used to quantify the inputs. On the other hand, the configuration's outputs – the delivered relief item quantity, the delivered relief item quality, and the corresponding delivery times – are critical dimensions. The percentage of fulfilled demand for a specific type of relief item at a demand facility is an effectiveness metric that is used to capture the dimension *relief item quantity*. The importance weight of the delivered relief items for beneficiaries is an effectiveness metric that is used to capture the dimension *relief item quality*. The dimension *delivery time* is captured by the values of the achieved coverage levels for demand facilities. These values can be assigned to the class of effectiveness metrics. The mathematical program's expressions for these metrics are outlined in Table 4.2. The following factors and bounds have to be known in order to determine the values of these metrics: transportation costs between two locations per relief item type unit, procurement and holding costs per relief item type unit, warehouse setup costs per location, upper and lower time limits of a coverage level, weights that describe the importances of coverage levels for beneficiaries, weights that describe the importances of relief item types for beneficiaries, the budget for the disaster preparedness phase, and the budget for the disaster response phase. The program's parameters that describe the values of factors and bounds are outlined in Table 4.2.

The humanitarian organization intends to maximize the percentages of fulfilled demands, to maximize the amounts of important relief items among the delivered relief items, and to maximize the coverage levels of the demand facilities while to limit the amounts of inputs used during the preparedness phase as well as to limit the amounts of inputs used during the possible disaster responses. In other words, the humanitarian organization is about to maximize the system's overall outputs and to limit its overall inputs. The program's parts which represent these objectives and requirements are outlined in Table 4.2. Generally speaking, generating a maximum efficiency of a humanitarian logistics network is the overarching objective of the problem captured in the OR model of Balcik and Beamon (2008).

Table 4.2. Problem structuring scheme for Balcik and Beamon (2008)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disasters	Probability of occurrence	Parameter prb_s
		Locations for stationary warehouses	Coordinates	Parameter t_{irs}^{sf}
			Storage space	Parameter $SpcW_i$
		Locations for demand facilities	Coordinates	Parameter t_{irs}^{sf}
			Relief item demand in disasters	Parameter dmd_{rs}
		Arcs	Start location	Parameter t_{irs}^{sf}
			End location	Parameter t_{irs}^{sf}
			Distance	Parameter t_{irs}^{sf}
			Speed limitations	Parameter t_{irs}^{sf}
Humanitarian organization	*Logistics resources and relief items*	Stationary warehouses	Stationary warehouse location (DV)	Variable y_i
			Relief items stocked (CV)	Variable x_{ir}^{p}
		Demand facilities	Demand facility location	Parameter t_{irs}^{sf}
			Relief items distributed in disasters (CV)	Variable α_{irs}
		Transportation vehicle types	Speed of travel	Parameter t_{irs}^{sf}
			Transport volume	Parameter t_{irs}^{sf}
			Transport weight	Parameter t_{irs}^{sf}
			Vehicles on arcs	Parameter t_{irs}^{sf}
			Relief items transferred on arcs in disasters (CV)	Variable α_{irs}

	Relief item types	Volume	Parameter $spcW_r$
		Weight	Parameter t_{irs}^{sf}
Use and interaction of logistics resources, relief items, and elements in environment	Location-dependent available storage space and the necessary storage space per unit of a relief item type limit the number of relief items that can be stocked at a stationary warehouse		Constraint set 4.3
	Relief items stocked during the disaster preparedness phase limit the number of relief items that can be distributed during a possible disaster response		Constraint set 4.2
Key dimensions, metrics, objectives, and requirements	Inputs	Warehousing resources: warehouse setup costs and relief item holding costs	Expressions $\sum_{i \in I} C_i^{\mathrm{s}} y_i$, $\sum_{i \in I} \sum_{r \in R} x_{ir}^{\mathrm{p}} c_{ir}^{\mathrm{ah}}$
		Transportation resources: transportation costs in disasters	Expression $\sum_{r \in R} \sum_{i \in I} dmd_{rs} c_{irs}^{\mathrm{t}} \alpha_{irs}$
		Relief items: procurement costs	Expression $\sum_{i \in I} \sum_{r \in R} x_{ir}^{\mathrm{p}} c_{ir}^{\mathrm{ah}}$
	Outputs	Delivered relief item quantity: percentage of fulfilled demand at demand facility in disasters	Expression $\sum_{r \in R} \sum_{i \in I} dmd_{rs} \alpha_{irs}$
		Delivered relief item quality: weighted percentage of fulfilled demand at demand facility in disasters	Expression $\sum_{r \in R} \sum_{i \in I} dmd_{rs} \omega_r \alpha_{irs}$
		Delivery time: demand facility coverage level in disasters	Expression $\sum_{r \in R} \sum_{a_r \in A_r} \sum_{i \in I_{a_r s}} dmd_{rs} \omega_{a_r} \alpha_{irs}$
	Objectives and requirements	Limiting inputs	Constraint 4.4, constraint sets 4.5, 4.6
		Maximizing delivered relief item quantity	Objective function 4.1
		Maximizing delivered relief item quality	Objective function 4.1
		Minimizing delivery times	Objective function 4.1

Factors and bounds	Setup costs per location for stationary warehouses	Parameter C_i^{s}
	Transportation costs between two locations per relief item type unit	Parameter c_{irs}^{t}
	Procurement and holding costs per relief item type unit and location for stationary warehouses	Parameter c_{ir}^{ah}
	Upper time limit per coverage level	Parameter tMx_{a_r}
	Lower time limit per coverage level	Parameter tMn_{a_r}
	Importance factor per coverage level	Parameter ω_{a_r}
	Importance factor per relief item type	Parameter ω_r
	Budget in the disaster preparedness phase	Parameter bgt^{P}
	Budget in the disaster response phase	Parameter bgt^{R}

Program code

Below is a possible translation of the mathematical formulation into a program code, using the OPL language. This language is frequently used to code a MILP such as the one of Balcik and Beamon (2008). A MILP coded in this language can be automatically solved with the commercial CPLEX solver. Before the MILP is solved, for each location at which a demand facility can be erected, several sets must be created. Each set comprises all those locations for stationary warehouses which can supply a demand location with a certain type of relief item within the lower and upper time limits of a specific coverage level. Therefore the number of sets per demand location depends on the number of coverage levels. These sets are built by the execute function in the OPL formulation.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Balcik and Beamon (2008)
 * Creation Date: 15.01.2015 at 13:06:07
 *********************************************/
{string} LocationsForStationaryWarehouses = ...;
{string} ReliefItemTypes = ...;
{string} Scenarios = ...;
{string} CoverageLevels = ...;
{string} LocationsForStationaryWarehousesProvidingCoverageLevels
[CoverageLevels,ReliefItemTypes,Scenarios];
float BudgetPreparedness = ...;
float BudgetResponse = ...;
float CostForAquiringAndHolding
[LocationsForStationaryWarehouses,ReliefItemTypes] = ...;
float CostForTransferring
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios] = ...;
float Demand[ReliefItemTypes,Scenarios] = ...;
float CostSetupWarehouseAt[LocationsForStationaryWarehouses] = ...;
float Probability[Scenarios] = ...;
float SpaceAvailable[LocationsForStationaryWarehouses] = ...;
float SpaceNecessary[ReliefItemTypes] = ...;
float TimeSatisfyingDemand
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios] = ...;
float LowerTimeLimit[CoverageLevels,ReliefItemTypes] = ...;
float UpperTimeLimit[CoverageLevels,ReliefItemTypes] = ...;
float ImportanceFactorReliefItemType[ReliefItemTypes] = ...;
float ImportanceFactorCoverageLevelReliefItemType
[CoverageLevels,ReliefItemTypes] = ...;
```

```
execute {
for (var s in Scenarios) {
 for (var i in LocationsForStationaryWarehouses) {
  for (var a in CoverageLevels) {
   for (var r in ReliefItemTypes) {
    if (TimeSatisfyingDemand[i][r][s] >= LowerTimeLimit[a][r] &&
        TimeSatisfyingDemand[i][r][s] <= UpperTimeLimit[a][r]) {
         LocationsForStationaryWarehousesProvidingCoverageLevels
         [a][r][s].add(i);
     }
    }
   }
  }
 }
}

dvar float+ PercentageDemandSatisfied
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios];
dvar float+ Prepositoned
[LocationsForStationaryWarehouses,ReliefItemTypes];
dvar boolean Open[LocationsForStationaryWarehouses];

maximize

sum (s in Scenarios, r in ReliefItemTypes, a in CoverageLevels, i in Loca-
tionsForStationaryWarehousesProvidingCoverageLevels[a,r,s])
Probability[s] * Demand[r,s] * ImportanceFactorReliefItemType[r] * Im-
portanceFactorCoverageLevelReliefItemType[a,r] * PercentageDemandSat-
isfied[i,r,s];

subject to{
ct2:
forall(i in LocationsForStationaryWarehouses, r in ReliefItemTypes, s in
Scenarios)
PercentageDemandSatisfied[i,r,s] * Demand[r,s]
<= Prepositoned[i,r];

ct3:
forall(i in LocationsForStationaryWarehouses)
sum (r in ReliefItemTypes)
(SpaceNecessary[r] * Prepositoned[i,r])
<= SpaceAvailable[i] * Open[i];

ct4:
```

```
sum (i in LocationsForStationaryWarehouses)
(CostSetupWarehouseAt[i] * Open[i])
+ sum (i in LocationsForStationaryWarehouses, r in ReliefItemTypes)
(CostForAquiringAndHolding[i,r] * Prepositoned[i,r])
<= BudgetPreparedness;

ct5:
forall(s in Scenarios)
sum (i in LocationsForStationaryWarehouses, r in ReliefItemTypes)
(Demand[r,s] * CostForTransferring[i,r,s] * PercentageDemandSatisfied
[i,r,s])
<= BudgetResponse;

ct6:
forall(r in ReliefItemTypes, s in Scenarios)
sum (i in LocationsForStationaryWarehouses)
PercentageDemandSatisfied[i,r,s] <= 1;
}
```

4.1.2 Mathematical program of Döyen et al. (2012) for supporting decisions about the locations and stocks of stationary warehouses

In their paper entitled “A two-echelon stochastic facility location model for humanitarian relief logistics”, Döyen et al. (2012) present a mathematical program that supports the planning of stationary warehouses. On a functional level, the program can be characterized as a facility location model. It can also be defined as a MILP because of the use of real-valued flow variables together with binary location variables. Moreover, it can be defined as a two-stage stochastic program, which is characterized by the use of two types of variables: design and control variables (Mulvey et al., 1995). In the case of the model of Döyen et al. (2012), design variables are used to describe the locations and relief item stocks of stationary warehouses. These decisions are made in the first stage, i.e. in the disaster preparedness phase. Depending on the values assigned to the design variables, the program calculates – in the second stage – the values of the control variables for each possible disaster. Control variables are used to describe the locations of transshipment facilities and the values of relief item flows between stationary warehouses, transshipment facilities, and demand facilities for each disaster scenario.

In this section, the program of Döyen et al. (2012) is analyzed. The analysis starts with a description of the mathematical formulation. Names of sets, parameters, and variables in the present notation differ from the original notation in order to achieve a consistent notation in the toolkit. The analysis goes on with the description of the underlying problem’s structure. Finally, a possible translation of the mathematical formulation into a program code is presented. Döyen et al.

(2012) present a solution algorithm in their publication which can be applied if the size of the problem overwhelms commercial solvers. How this algorithm works is described in their paper.

Mathematical formulation

The program's objective function (4.9) minimizes the costs that are associated with the coverage and non-coverage of the relief item demands over all disaster scenarios. A disaster scenario is characterized by a probability of occurrence and by demands for certain types of relief items at a set of locations. According to the objective function, costs can be incurred with the setup of stationary warehouses and their stocking with relief items as well as with the setup of transshipment facilities, the transfer of relief items between stationary warehouses, transshipment facilities, and demand facilities, and the failure to completely fulfill demands. In the objective function, the scenario-dependent costs (transshipment facility setup costs, transportation costs, and relief item shortage costs) are weighted by the scenario's probability of occurrence. Constraint set (4.10) ensures that transshipment facilities can only be assigned to opened stationary warehouses and constraint set (4.11) makes sure that a transshipment facility is supplied by no more than one stationary warehouse. Constraint set (4.12) limits the maximum allowed transportation time between stationary warehouses and transshipment facilities. Constraint set (4.13) ensures – firstly – that flows between a stationary warehouse and a transshipment facility can only occur when the transshipment facility is assigned to this stationary warehouse and – secondly – that the flow of relief items between them cannot exceed the capacity of the transshipment facility. Constraint set (4.14) limits the maximum amount of relief items to be distributed from a stationary warehouse to the amount of relief items prepositioned in this warehouse during the preparedness phase. Constraint set (4.15) comprises the flow conservation constraints; in this particular case they determine, that the amount of relief items going into a transshipment facility has to be equal to the amount of relief items going out of it. Constraint set (4.16) ensures that demand facilities can only be assigned to opened transshipment facilities and constraint set (4.17) determines that a facility's demand for a certain relief item can only be satisfied by no more than one transshipment facility. Constraint set (4.18) makes sure that relief item flows occur only between a transshipment facility and a demand facility if the demand facility is assigned to this transshipment facility; and that the flow cannot exceed the location-dependent demand at this demand facility. Constraint set (4.19) calculates the relief item shortages at demand facilities. Finally, constraint set (4.20) defines the non-negativity of the real-valued flow variables and constraint set (4.21) defines the binary location variables.

Sets:

I	Set of locations where stationary warehouses can be erected

P	Set of locations where transshipment facilities can be erected
Q	Set of locations where demand facilities are erected
R	Set of relief item types
S	Set of scenarios

Parameters:

c^{h}_{ir}	Costs for the holding (h) of a unit of relief item type *r* at location *i*
c^{t}_{iprs}	Costs for the transportation (t) of a unit of relief item type *r* from location *i* to location *p* in scenario *s*
c^{t}_{pqrs}	Costs for the transportation (t) of a unit of relief item type *r* from location *p* to location *q* in scenario *s*
c^{u}_{r}	Costs for a unit of unsatisfied (u) demand for relief item type *r*
C^{s}_{i}	Costs for setting up (s) a stationary warehouse at location *i*
C^{s}_{ps}	Costs for setting up (s) a transshipment facility at location *p* in scenario *s*
$CapH_{ps}$	Capacity available to handle relief items at location *p* where a transshipment facility can be erected in scenario *s*
$capH_{r}$	Capacity necessary to handle a unit of relief item type *r*
dmd_{qrs}	Units of relief item type *r* demanded at location *q* in scenario *s*
prb_{s}	Probability of occurrence of scenario *s*
t^{t}_{ips}	Time for transferring (t) relief items from location *i* to location *p* in scenario *s*

tMx	Upper time limit

Variables:

x_{ir}^{p}	Relief items of type *r* prepositioned (p) in stationary warehouse at location *i*
x_{iprs}^{t}	Relief items of type *r* transferred (t) from stationary warehouse at location *i* to transshipment facility at location *p* in scenario *s*
x_{pqrs}^{t}	Relief items of type *r* transferred (t) from transshipment facility at location *p* to demand facility at location *q* in scenario *s*
x_{qrs}^{u}	Relief item demand of type *r* unsatisfied (u) at demand facility at location *q* in scenario *s*
y_i	1 if a stationary warehouse is located at location *i*, 0 otherwise
y_{ips}	1 if a transshipment facility is located at location *p* and assigned to stationary warehouse at location *i* in scenario s, 0 otherwise
y_{pqrs}	1 if the demand for relief item type *r* at location *q* is satisfied by transshipment facility at location *p* in scenario *s*, 0 otherwise

MILP:

(4.9) Minimize

$$\sum_{i\in I} C_i^{\mathrm{s}} y_i + \sum_{i\in I}\sum_{r\in R} c_{ir}^{\mathrm{h}} x_{ir}^{\mathrm{p}}$$

$$+\sum_{s\in S} prb_s \left[\sum_{i\in I}\sum_{p\in P} C_{ps}^{\mathrm{s}} y_{ips} + \sum_{i\in I}\sum_{p\in P}\sum_{r\in R} c_{iprs}^{\mathrm{t}} x_{iprs}^{\mathrm{t}} + \sum_{p\in P}\sum_{q\in Q}\sum_{r\in R} c_{pqrs}^{\mathrm{t}} x_{pqrs}^{\mathrm{t}} + \sum_{q\in Q}\sum_{r\in R} c_r^{\mathrm{u}} x_{qrs}^{\mathrm{u}} \right]$$

s.t. (4.10) $y_{ips} \le y_i \qquad \forall i \in I, p \in P, s \in S$

(4.11) $\sum_{i \in I} y_{ips} \leq 1 \qquad \forall p \in P, s \in S$

(4.12) $t^{\mathrm{t}}_{ips} y_{ips} \leq tMx \qquad \forall i \in I, p \in P, s \in S$

(4.13) $\sum_{r \in R} capH_r x^{\mathrm{t}}_{iprs} \leq CapH_{ps} y_{ips} \qquad \forall i \in I, p \in P, s \in S$

(4.14) $\sum_{p \in P} x^{\mathrm{t}}_{iprs} \leq x^{\mathrm{p}}_{ir} \qquad \forall i \in I, r \in R, s \in S$

(4.15) $\sum_{i \in I} x^{\mathrm{t}}_{iprs} = \sum_{q \in Q} x^{\mathrm{t}}_{pqrs} \qquad \forall p \in P, r \in R, s \in S$

(4.16) $y_{pqrs} \leq \sum_{i \in I} y_{ips} \qquad \forall p \in P, q \in Q, r \in R, s \in S$

(4.17) $\sum_{p \in P} y_{pqrs} \leq 1 \qquad \forall q \in Q, r \in R, s \in S$

(4.18) $x^{\mathrm{t}}_{pqrs} \leq dmd_{qrs} y_{pqrs} \qquad \forall p \in P, q \in Q, r \in R, s \in S$

(4.19) $\sum_{p \in P} x^{\mathrm{t}}_{pqrs} + x^{\mathrm{u}}_{qrs} = dmd_{qrs} \qquad \forall q \in Q, r \in R, s \in S$

(4.20) $x^{\mathrm{t}}_{iprs}, x^{\mathrm{t}}_{pqrs}, x^{\mathrm{u}}_{qrs}, x^{\mathrm{p}}_{ir} \geq 0 \qquad \forall i \in I, p \in P, q \in Q, r \in R, s \in S$

(4.21) $y_i, y_{ips}, y_{pqrs} \in \{0,1\} \qquad \forall i \in I, p \in P, q \in Q, r \in R, s \in S$

Problem structure

In this sub-section, the problem captured in the OR model of Döyen et al. (2012) is analyzed based on the problem structuring scheme outlined in section 3.4. In the first step, the disaster environment is characterized; and in the second step, the humanitarian organization that is responsible for the humanitarian logistics network is specified. The results of the problem structuring process are outlined in Table 4.3 (pp. 68ff).

Firstly, the environment is analyzed. The disaster environment is single-organizational and contains three types of locations: locations for stationary warehouses, for transshipment facilities, and for demand facilities. Unidirectional arcs connect locations for stationary warehouses with locations for transshipment facilities as well as locations for transshipment facilities with locations for demand facilities. Locations for stationary warehouses and transshipment facilities are characterized by coordinates. Locations for demand facilities are defined by coordinates and demands for certain types of relief items. Each arc between two locations is defined by the two locations it connects, a direction, a distance, and speed limitations. The environment is said to be probably affected by disasters in the future. The humanitarian organization has information about the occurrence of several possible disasters within the task environment. It is assumed that the humanitarian organization can quantify a disaster's uncertainty in terms of probabilities. A possible disaster's probability of occurrence is explicitly represented by a parameter in the mathematical program. The available information about one possible disaster outcome also comprises relief item demands triggered at locations for demand facilities and speed limitations on arcs. Furthermore, the humanitarian organization has information about those attributes of the elements in the task environment which do not depend on the outcome of possible disasters; that is, information about the coordinates of locations for stationary warehouses, transshipment facilities, and demand facilities as well as about the distances and directions of arcs. Attributes are implicitly or explicitly represented by parameters in the mathematical program. Coordinates of locations as well as distances and speed limitations of arcs are implicitly represented by parameters describing the transportation times and transportation costs (because in order to define transportation times and costs, the coordinates of locations, the distances of arcs, and the speed limitations on arcs need to be known). Parameters that describe certain attributes of the elements in the environment are outlined in Table 4.3.

In the second part of the problem structuring process, the available inputs of the humanitarian organization are described: stationary warehouses, transshipment facilities, demand facilities, transportation vehicles, handling equipment, and relief items. In Figure 4.5, a simple example of the assumed humanitarian logistics network is presented. Transshipment and demand facilities can have different counterparts in a real-world humanitarian logistics network. A possible counterpart for a transshipment facility is a handling point or a temporary warehouse while a possible counterpart for a demand facility is a handling point, a temporary warehouse, or a LDC. Possible counterparts for transshipment and demand facilities are highlighted in Figure 4.6 (p. 65) using the reference structure for humanitarian logistics networks as described in section 2.1. A stationary warehouse in the OR model of Döyen et al. (2012) has an exact counterpart in this reference structure.

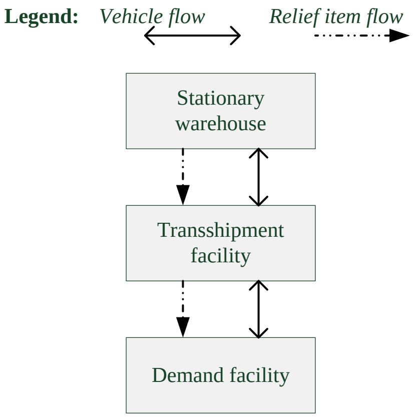


Figure 4.5. Simple example of the humanitarian logistics network in the OR model of Döyen et al. (2012)

Each relief item type is characterized by a volume and weight. Each type of handling equipment is defined by a speed of handling, the available handling volume and weight per vehicle, and the amount of handling equipment at locations for transshipment facilities. Each type of transportation vehicle is defined by a maximum travel speed, the transport volume and weight per vehicle, the number of available vehicles on specific arcs, and the relief item loads on specific arcs. Stationary warehouses are defined by their locations and prepositioned relief item stocks. Transshipment facilities are defined by their locations and the amounts of relief items that flow in and out of it, i.e. the handled relief items for each possible disaster. Demand facilities are defined by their locations and the amounts of relief items that flow in, i.e. the distributed relief items for each possible disaster. The location of each demand facility is already known by the humanitarian organization: a demand facility is located at each potential location in order to cope with relief item demands in the case of a disaster. The volume and weight per unit of a relief item type as well as – for each type of transportation vehicle – the travel speed, transport volume, and transport weight of a vehicle and the numbers of vehicles on specific arcs and – for each type of handling equipment – the handling speed, handling volume, and handling weight of a vehicle and the amounts of equipment at specific locations are already known by the humanitarian organization. These attributes are implicitly or explicitly represented by parameters in the mathematical program. The travel speed, transport volume, and transport weight of a vehicle and the numbers of transportation vehicles on specific arcs are implicitly represented by the parameters that describe the transportation times between locations (because to calculate transportation times these values have to be known). Handling speed, handling volume, and handling weight of a vehicle as well as the amounts of handling equipment at certain locations for transshipment facilities are implicitly represented by the parameters describing the handling capacities of locations (because to calculate handling capacities these values have to be known). Finally, the volume and weight per unit of a relief item type are implicitly represented by the parameter describing the necessary handling capacity per unit of this relief item type.

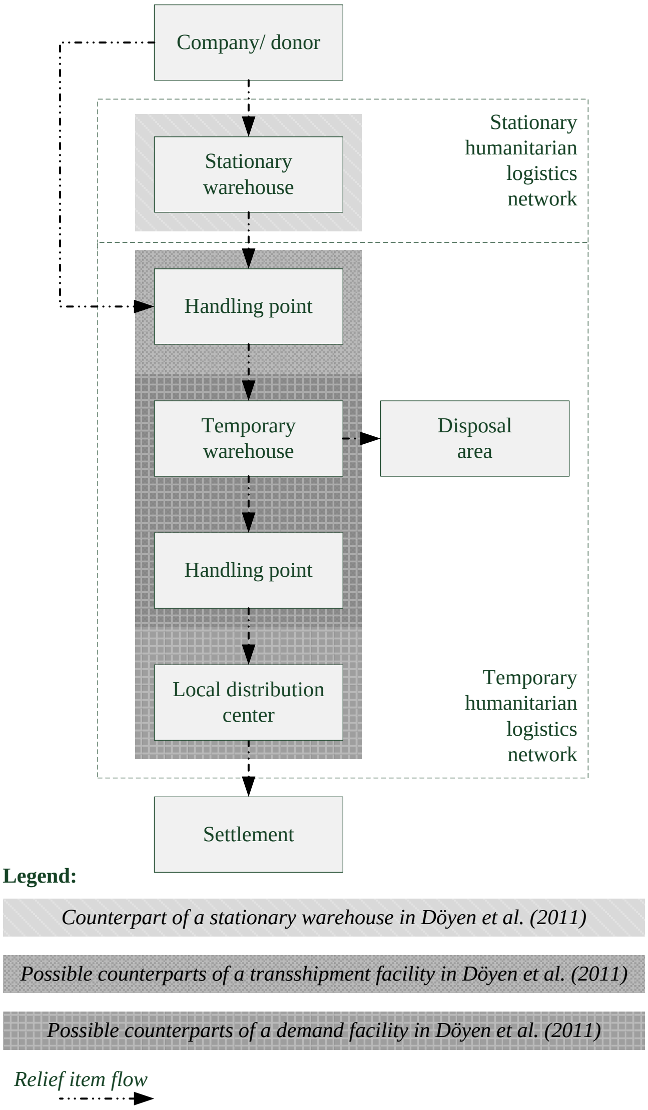


Figure 4.6. Counterparts of the facilities defined in Döyen et al. (2012) in the reference structure for humanitarian logistics networks

Furthermore, the locations and stocks of stationary warehouses, the locations of transshipment facilities for each possible disaster outcome, the relief item flows (i.e. the inflows and outflows of relief items for each facility) for each possible disaster outcome, and the relief item loads of transportation vehicles on specific arcs for each possible disaster outcome are the values to be determined in the decision problem. These attributes are explicitly represented by decision variables in the mathematical program – apart from the quantities of transferred, handled, and distributed relief items which are implicitly represented by variables describing the relief item flows on arcs. The locations of stationary warehouses and transshipment facilities can be chosen out of discrete sets of alternative locations whereas the values of stocked, transferred, handled, and distributed relief items are positive real numbers. Given that the relief item quantities are positive real numbers, the number of alternative solutions to the decision problem is continuous. The parameters and variables which describe logistics resources and relief items of the humanitarian organization are outlined in Table 4.3.

The humanitarian organization has to adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements of the environment. The following relationships are known to the organization:

- Relief item stocks at a stationary warehouse limit the number of relief items that can be distributed during a disaster response.
- The amount and characteristics of the available handling equipment at a transshipment facility as well as the volume and weight per relief item unit limit the number of handled relief items at a transshipment facility during a disaster response.
- Transshipment facilities can only be served by an opened stationary warehouse.
- The amounts of inflowing relief items at a transshipment facility have to be equal to the amounts of outflowing relief items.
- Demand for relief items at demand facilities can only be served from opened transshipment facilities.

In the mathematical program, the allowed use and interaction between logistics resources, relief items, and elements in the environment are represented by constraints. These constraints are outlined in Table 4.3.

When setting up a humanitarian logistics network, several key dimensions are taken into account to identify the most advantageous network configuration. On the one hand, the configuration's input is captured, i.e. the amount of resources for warehousing, handling, transportation, and coordination. The input of coordination resources is measured by the numbers of assigned transshipment facilities to stationary warehouses as well as by the numbers of assigned demand facilities to transshipment facilities. The input of resources for warehousing, handling, and transportation is measured by warehouse setup costs, relief item holding costs, transshipment facility setup costs, and transportation costs. On the other hand, the configuration's output is captured, i.e. the delivered relief item quantity, the delivered relief item quality, and the corresponding delivery times. The value of the relief item shortage costs that accumulates during a disaster response is an effectiveness metric that is used to capture the dimensions *relief item quantity* and *relief* *item quality*. The dimension *delivery time* is captured by the actual transportation times between stationary warehouses and transshipment facilities. These values also belong to the class of effectiveness metrics. The mathematical program's expressions for these metrics are outlined in Table 4.3. The following factors and bounds have to be known to determine the values of metrics: transportation costs between two locations per unit of a certain relief item type, holding costs per unit of a certain relief item type, stationary warehouse and transshipment facility setup costs per location, shortage costs per unit of a certain relief item type, an upper time limit for the transportation times between supply facilities and transshipment facilities, and the planned durations of the possible disaster responses. The program's parameters that represent factors and bounds are outlined in Table 4.3. The planned durations of the disaster responses are implicitly represented by the parameters describing the available handling capacities during possible disasters at locations.

The organization intends to minimize the setup, handling, transportation, and shortage costs, to cap the coordination effort by selecting not more than one stationary warehouse as a supplier for an opened transshipment facility, to cap the coordination effort by selecting not more than one transshipment facility as a supplier of a certain relief item type for an opened demand facility, to prevent the overfulfillment of relief item demands, and to limit the transportation times between stationary warehouses and transshipment facilities. The mathematical program's parts which represent these objectives and requirements are outlined in Table 4.3. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the problem captured in the OR model of Döyen et al. (2012).

Table 4.3. Problem structuring scheme for Döyen et al. (2012)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disasters	Probability of occurrence	Parameter prb_s
		Locations for stationary warehouses	Coordinates	Parameter t^{t}_{ips}
		Locations for transshipment facilities	Coordinates	Parameter t^{t}_{ips}
		Locations for demand facilities	Coordinates	Parameter c^{t}_{pqrs}
			Relief item type demand in disasters	Parameter dmd_{qrs}
		Arcs	Start location	Parameters t^{t}_{ips}
			End location	Parameters t^{t}_{ips}, c^{t}_{pqrs}
			Distance	Parameter t^{t}_{ips}
			Speed limitations in disasters	Parameter t^{t}_{ips}
Humanitarian organization	*Logistics resources and relief items*	Stationary warehouses	Stationary warehouse location (DV)	Variable y_i
			Relief items stocked (CV)	Variable x^{p}_{ir}
		Transshipment facilities	Transshipment facility location in disasters (DV)	Variable y_{ips}
			Relief items handled in disasters (CV)	Variable x^{t}_{iprs}
		Demand facilities	Demand facility location	Parameter c^{t}_{pqrs}
			Relief items distributed in disasters (CV)	Variable x^{t}_{pqrs}
		Transportation vehicle types	Speed of travel	Parameter t^{t}_{ips}
			Transport volume	Parameter t^{t}_{ips}

		Transport weight	Parameter t^{t}_{ips}
		Vehicles on arcs	Parameter t^{t}_{ips}
		Relief items transferred on arcs (CV)	Variables x^{t}_{iprs} , x^{t}_{pqrs}
	Handling equipment types	Speed of handling	Parameter $CapH_{ps}$
		Handling volume	Parameter $CapH_{ps}$
		Handling weight	Parameter $CapH_{ps}$
		Equipment at locations for transshipment facilities	Parameter $CapH_{ps}$
	Relief item types	Volume	Parameter $capH_{r}$
		Weight	Parameter $capH_{r}$
Use and interaction of logistics resources, relief items, and elements in environment	Relief item stocks at a stationary warehouse limit the number of relief items that can be distributed during a disaster response		Constraint set 4.14
	Amount and characteristics of available handling equipment at a transshipment facility as well as the volume and weight of relief items limit the number of handled relief items at a transshipment facility during a disaster response		Constraint set 4.13
	Transshipment facilities can only be served by an opened stationary warehouse		Constraint set 4.10
	Amounts of inflowing relief items at a transshipment facility equal the amounts of outflowing relief items		Constraint set 4.15
	Demand for relief items at demand facilities can only be served from opened transshipment facilities		Constraint set 4.16
Key dimensions, metrics, objectives, and requirements	Inputs	Warehousing resources: stationary warehouse setup costs, relief item holding costs	Expressions $\sum_{i\in I} C^{\mathrm{s}}_{i} y_{i}$, $\sum_{i\in I}\sum_{r\in R} c^{\mathrm{h}}_{ir} x^{\mathrm{p}}_{ir}$
		Handling resources: transshipment facility setup costs in disasters	Expression $\sum_{i\in I}\sum_{p\in P} C^{\mathrm{s}}_{ps} y_{ips}$

	Transportation resources: transportation costs in disasters	Expressions $\sum_{i\in I}\sum_{p\in P}\sum_{r\in R} c^{\mathrm{t}}_{iprs} x^{\mathrm{t}}_{iprs}$, $\sum_{p\in P}\sum_{q\in Q}\sum_{r\in R} c^{\mathrm{t}}_{pqrs} x^{\mathrm{t}}_{pqrs}$
	Coordination resources: numbers of assigned transshipment facilities to stationary warehouses in disasters, numbers of assigned demand facilities to transshipment facilities per relief item type in disasters	Expressions $\sum_{i\in I} y_{ips}$, $\sum_{p\in P} y_{pqrs}$
Outputs	Delivered relief item quantity: shortage costs in disasters	Expression $\sum_{q\in Q}\sum_{r\in R} c^{\mathrm{u}}_{r} x^{\mathrm{u}}_{qrs}$
	Delivered relief item quality: shortage costs in disasters	Expression $\sum_{q\in Q}\sum_{r\in R} c^{\mathrm{u}}_{r} x^{\mathrm{u}}_{qrs}$
	Delivery time: transportation times between stationary warehouses and transshipment facilities in disasters	Expressions $t^{\mathrm{t}}_{ips} y_{ips}$
Objectives and requirements	Minimizing inputs	Objective function 4.9
	Limiting inputs	Constraint sets 4.11, 4.17, 4.18
	Maximizing delivered relief item quantity	Objective function 4.9
	Maximizing delivered relief item quality	Objective function 4.9
	Limiting delivery times	Constraint set 4.12
Factors and bounds	Stationary warehouse setup costs per location	Parameter C^{s}_{i}
	Transshipment facility setup costs per location in disasters	Parameter C^{s}_{ps}
	Transportation costs between two locations per unit of a relief item type in disasters	Parameter c^{t}_{iprs} , c^{t}_{pqrs}

	Holding costs per unit of a relief item type and location for stationary warehouses	Parameter c_{ir}^{h}
	Shortage costs per unit of a relief item type	Parameter c_{r}^{u}
	Upper time limit between stationary warehouses and transshipment facilities	Parameter tMx
	Planned duration per possible disaster response	Parameter $CapH_{ps}$

Program code

Below is a possible translation into program code of Döyen et al. (2012), using the OPL language. This language is frequently used to code a MILP such as that of Döyen et al. (2012). MILPs coded in this language can be automatically solved with the commercial CPLEX solver.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Döyen et al. (2012)
 * Creation Date: 14.11.2013 at 14:03:27
 *********************************************/
{string} LocationsForStationaryWarehouses = ...;
{string} LocationsForTransshipmentFacilities = ...;
{string} LocationsForDemandFacilities = ...;
{string} ReliefItemTypes = ...;
{string} Scenarios = ...;
float CostForHolding
[LocationsForStationaryWarehouses,ReliefItemTypes] = ...;
float CostForTransferringWarehouseToTransshipment
[LocationsForStationaryWarehouses,LocationsForTransshipmentFacilities,
ReliefItemTypes,Scenarios] = ...;
float CostForTransferringTransshipmentToDistribution
[LocationsForTransshipmentFacilities,LocationsForDemandFacilities,
ReliefItemTypes,Scenarios] = ...;
float CostForShortage[ReliefItemTypes] = ...;
float CostStationaryWarehouseSetup
[LocationsForStationaryWarehouses] = ...;
float CostTransshipmentFacilitySetup
[LocationsForTransshipmentFacilities,Scenarios] = ...;
float HandlingCapacityAvailable
[LocationsForTransshipmentFacilities,Scenarios] = ...;
float HandlingCapacityNecessary[ReliefItemTypes] = ...;
float Demand
[LocationsForDemandFacilities,ReliefItemTypes,Scenarios] = ...;
float Probability[Scenarios] = ...;
float TransportationTime
[LocationsForStationaryWare-
houses,LocationsForTransshipmentFacilities,Scenarios] = ...;
float UpperTimeLimit = ...;
dvar float+ Prepositoned
[LocationsForStationaryWarehouses,ReliefItemTypes];
```

```
dvar float+ TransferredWarehouseToTransshipment
[LocationsForStationaryWarehouses,LocationsForTransshipmentFacilities,
ReliefItemTypes,Scenarios];
dvar float+ TransferredTransshipmentToDistribution
[LocationsForTransshipmentFacilities,LocationsForDemandFacilities,
ReliefItemTypes,Scenarios];
dvar float+ Shortage
[LocationsForDemandFacilities,ReliefItemTypes,Scenarios];
dvar boolean OpenWarehouse[LocationsForStationaryWarehouses];
dvar boolean OpenTransshipmentFacilityAssignedToWarehouse
[LocationsForStationaryWarehouses,LocationsForTransshipmentFacilities,
Scenarios];
dvar boolean DemandFacilityAssignedToTransshipmentFacility
[LocationsForTransshipmentFacilities,LocationsForDemandFacilities,
ReliefItemTypes,Scenarios];

minimize

sum (i in LocationsForStationaryWarehouses)
CostStationaryWarehouseSetup[i] * OpenWarehouse[i] +
sum (i in LocationsForStationaryWarehouses, r in ReliefItemTypes)
CostForHolding[i,r] * Prepositoned[i,r] +
sum (s in Scenarios)
Probability[s] * (
sum (i in LocationsForStationaryWarehouses, p in LocationsForTransshipmentFacilities)
CostTransshipmentFacilitySetup[p,s] *
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s] +
sum (i in LocationsForStationaryWarehouses, p in LocationsForTransshipmentFacilities, r in ReliefItemTypes)
CostForTransferringWarehouseToTransshipment[i,p,r,s] *
TransferredWarehouseToTransshipment[i,p,r,s] +
sum (p in LocationsForTransshipmentFacilities, q in LocationsForDemandFacilities, r in ReliefItemTypes)
CostForTransferringTransshipmentToDistribution[p,q,r,s] *
TransferredTransshipmentToDistribution[p,q,r,s] +
sum (q in LocationsForDemandFacilities, r in ReliefItemTypes)
(CostForShortage[r] * Shortage[q,r,s]));

subject to{
ct10:
forall (i in LocationsForStationaryWarehouses, p in LocationsForTransshipmentFacilities,s in Scenarios)
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s]
```

```
<= OpenWarehouse[i];

ct11:
forall (p in LocationsForTransshipmentFacilities, s in Scenarios)
sum (i in LocationsForStationaryWarehouses)
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s]
<= 1;

ct12:
forall (i in LocationsForStationaryWarehouses, p in LocationsForTrans-
shipmentFacilities, s in Scenarios)
TransportationTime[i,p,s] *
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s]
<= UpperTimeLimit;

ct13:
forall (i in LocationsForStationaryWarehouses, p in LocationsForTrans-
shipmentFacilities, s in Scenarios)
sum (r in ReliefItemTypes)
HandlingCapacityNecessary[r] *
TransferredWarehouseToTransshipment[i,p,r,s]
<= HandlingCapacityAvailable[p,s] *
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s];

ct14:
forall (i in LocationsForStationaryWarehouses, r in ReliefItemTypes, s in
Scenarios)
sum (p in LocationsForTransshipmentFacilities)
TransferredWarehouseToTransshipment[i,p,r,s]
<= Prepositoned[i,r];

ct15:
forall (p in LocationsForTransshipmentFacilities, r in ReliefItemTypes, s in
Scenarios)
sum (i in LocationsForStationaryWarehouses)
TransferredWarehouseToTransshipment[i,p,r,s]
== sum (q in LocationsForDemandFacilities)
TransferredTransshipmentToDistribution[p,q,r,s];

ct16:
forall (p in LocationsForTransshipmentFacilities, q in LocationsForDe-
mandFacilities, r in ReliefItemTypes, s in Scenarios)
DemandFacilityAssignedToTransshipmentFacility[p,q,r,s]
<= sum (i in LocationsForStationaryWarehouses)
```

```
OpenTransshipmentFacilityAssignedToWarehouse[i,p,s];

ct17:
forall (q in LocationsForDemandFacilities, r in ReliefItemTypes, s in Sce-
narios)
sum (p in LocationsForTransshipmentFacilities)
DemandFacilityAssignedToTransshipmentFacility[p,q,r,s]
<= 1;

ct18:
forall (p in LocationsForTransshipmentFacilities, q in LocationsForDe-
mandFacilities, r in ReliefItemTypes, s in Scenarios)
TransferredTransshipmentToDistribution[p,q,r,s]
<= Demand[q,r,s] *
DemandFacilityAssignedToTransshipmentFacility[p,q,r,s];

ct19:
forall (q in LocationsForDemandFacilities, r in ReliefItemTypes, s in Sce-
narios)
sum (p in LocationsForTransshipmentFacilities)
TransferredTransshipmentToDistribution[p,q,r,s] + Shortage[q,r,s]
== Demand[q,r,s];
}
```

4.1.3 Mathematical program of Rawls and Turnquist (2011) for supporting decisions about the locations, sizes, and stocks of stationary warehouses

In the present section, the paper “Pre-positioning planning for emergency response with service quality constraints” by Rawls and Turnquist (2011) is analyzed. The article contains a mathematical program which supports the planning of stationary warehouses. On a functional level, the program qualifies as a facility location model. The program can also be marked as a MILP given the use of real-valued flow variables together with binary location variables. Moreover, it can be defined as a two-stage stochastic program given its use of design and control variables (Mulvey et al., 1995). In the program, design variables are used to describe the locations, sizes, and relief item stocks of stationary warehouses. These decisions are made in the first stage, i.e. in the disaster preparedness phase. Depending on the values assigned to the design variables, the program calculates – in the second stage – the values of the control variables: the values of the relief item flows between locations for each possible disaster response.

Firstly, a description of the mathematical formulation is presented. Names of sets, parameters, and variables in the present notation differ from the original notation in order to achieve a consistent notation within the toolkit. Following this, a description of the underlying problem is given.[10] Finally, a possible translation of the mathematical formulation into program code is shown. Rawls and Turnquist (2011) present no unique solution algorithm; instead they refer to available commercial solvers for the solution of their program.

Mathematical formulation

The program's objective function (4.22) minimizes the costs associated with the coverage and non-coverage of the relief item demands over all disaster scenarios. Each disaster scenario is described by one or more locations with demands for specific types of relief items, percentages of destroyed relief item stocks at locations for stationary warehouses, reductions of the transportation capacities of specific arcs, and a probability of occurrence. Costs can incur with the setup of stationary warehouses (stationary warehouse setup costs) and the acquisition with relief items (procurement costs) during the disaster preparedness phase as well as with the transfer of relief items between stationary warehouses and demand locations (transportation costs), with the non-usage of prepositioned relief items (holding costs), and with the failure to fulfill demands completely (shortage costs) during a disaster response. In the objective function, disaster-dependent costs are weighed by the scenario's probability of occurrence. Constraint set (4.23) ensures flow conservation, i.e. that the undamaged amount of relief items that was prepositioned in a stationary warehouse during the disaster preparedness phase together with those arriving in a disaster's aftermath from other stationary warehouses can either be used to cover a location's own demand, be left untouched, be sent to another location with a demand for relief items, or be not enough to cover the particular location's relief item demand (resulting in relief item shortages). Constraint set (4.24) ensures that the storage space of an opened stationary warehouse is not exceeded. Constraint set (4.25) limits the maximum number of stationary warehouses per location to one warehouse. Constraint set (4.26) ensures that the arcs' capacities are not exceeded. Constraint (4.27) defines the reliability set; that is, a subset of the disaster scenarios in which relief item demands have to be fulfilled completely. Complete satisfaction of these demands is ensured by constraint set (4.28). Constraint set (4.29) limits the average distance of transports if they are executed in response to a possible disaster included in the reliability set. Finally, constraint set (4.30) determines the non-negativity of the real-valued flow variables and constraint set (4.31) defines the binary location variables.

Sets:

I	Set of locations where stationary warehouses can be erected

---

[10] A similar but less holistic/ detailed characterization of Rawls and Turnquist (2011) can be found in Gösling and Geldermann (2014c).

R	Set of relief item types
S	Set of scenarios
U	Set of facility sizes

Parameters:

big	Big number
c_r^{a}	Costs for the acquisition (a) of a unit of relief item type *r*
c_r^{h}	Costs for the holding (h) of an unused unit of relief item type *r*
c_{ijrs}^{t}	Costs for the transportation (t) of a unit of relief item type *r* from location *i* to location *j* in scenario *s*
c_r^{u}	Costs for a unit of unsatisfied (u) demand for relief item type *r*
C_{iu}^{s}	Costs for setting up (s) a stationary warehouse of size *u* at location *i*
$CapT_{ijs}$	Capacity available to transfer relief items on arc between location *i* and location *j* in scenario *s*
$capT_r$	Capacity necessary to transfer a unit of relief item type *r*
d_{ij}	Distance between location *i* and location *j*
dmd_{irs}	Units of relief item type *r* demanded at location *i* in scenario *s*
dMx_r	Upper distance limit to transfer relief item type *r*
dsd_{irs}	Percentage of relief item type *r* usable at location *i* in scenario *s*
prb_s	Probability of occurrence of scenario *s*

$SpcW_u$	Storage space available to store relief items in a stationary warehouse with size *u*
$spcW_r$	Storage space used by a unit of relief item type *r*
γ	Collective probability of occurrence of scenarios in the reliability set

Variables:

x_{ir}^{p}	Relief items of type *r* prepositioned (p) in stationary warehouse at location *i*
x_{ijrs}^{t}	Relief items of type *r* transferred (t) from location *i* to location *j* in scenario *s*
x_{irs}^{h}	Relief items of type *r* held (h) in the stationary warehouse at location *i* in scenario *s*
x_{irs}^{u}	Relief item demand of type *r* unsatisfied (u) at location *i* in scenario *s*
y_{iu}	1 if a stationary warehouse is located at location *i* and has a size *u*, 0 otherwise
γ_s	1 if scenario *s* is included in reliability set, 0 otherwise

MILP:

(4.22) Minimize

$$\sum_{i\in I}\sum_{u\in U} C_{iu}^{\mathrm{s}} y_{iu} + \sum_{i\in I}\sum_{r\in R} c_r^{\mathrm{a}} x_{ir}^{\mathrm{p}}$$

$$+\sum_{s\in S} prb_s \left[\sum_{i\in I}\sum_{j\in I}\sum_{r\in R} c_{ijrs}^{\mathrm{t}} x_{ijrs}^{\mathrm{t}} + \sum_{i\in I}\sum_{r\in R} \left(c_r^{\mathrm{u}} x_{irs}^{\mathrm{u}} + c_r^{\mathrm{h}} x_{irs}^{\mathrm{h}} \right) \right]$$

s.t. (4.23) $$\sum_{j \in I: j \neq i} x^{\mathrm{t}}_{jirs} + dsd_{irs} x^{\mathrm{p}}_{ir} - x^{\mathrm{h}}_{irs} = \sum_{j \in I: i \neq j} x^{\mathrm{t}}_{ijrs} + dmd_{irs} - x^{\mathrm{u}}_{irs} \qquad \forall i \in I, r \in R, s \in S$$

(4.24) $$\sum_{r \in R} spcW_r x^{\mathrm{p}}_{ir} \leq \sum_{u \in U} SpcW_u y_{iu} \qquad \forall i \in I$$

(4.25) $$\sum_{u \in U} y_{iu} \leq 1 \qquad \forall i \in I$$

(4.26) $$\sum_{r \in R} capT_r x^{\mathrm{t}}_{ijrs} \leq CapT_{ijs} \qquad \forall i, j \in I, s \in S$$

(4.27) $$\sum_{s \in S} prb_s \gamma_s \geq \gamma$$

(4.28) $$x^{\mathrm{u}}_{irs} \leq dmd_{irs} \left(1 - \gamma_s\right) \qquad \forall i \in I, r \in R, s \in S$$

(4.29) $$\sum_{i \in I} \sum_{j \in I} d_{ij} x^{\mathrm{t}}_{ijrs} \leq dMx_r \sum_{i \in I} dmd_{irs} + big\left(1 - \gamma_s\right) \qquad \forall r \in R, s \in S$$

(4.30) $$x^{\mathrm{t}}_{ijrs}, x^{\mathrm{u}}_{irs}, x^{\mathrm{h}}_{irs}, x^{\mathrm{p}}_{ir} \geq 0 \qquad \forall i, j \in I, r \in R, s \in S$$

(4.31) $$y_{iu}, \gamma_s \in \left\{0,1\right\} \qquad \forall i \in I, u \in U$$

Problem structure

In this sub-section, the problem captured in the OR model of Rawls and Turnquist (2011) will be structured based on the problem structuring scheme outlined in section 3.4 – starting with an analysis of the disaster environment. Then, the humanitarian organization responsible for the whole humanitarian logistics network within the environment is characterized. The results of the problem structuring process are outlined in Table 4.4 (pp. 84ff).

In the first part of the problem structuring process, the features of the environment are outlined. The disaster environment is single-organizational and contains only one type of location. Each location is characterized by coordinates, a demand for certain types of relief items, and a loss of certain types of relief items. Bidirectional arcs connect locations with each other. Each arc is defined by the two locations it connects, a distance, and speed limitations. The environment will probably be affected by disasters in the future and these disasters will have an impact on relief item demands triggered at specific locations, on the loss of relief item stocks at certain locations, and on speed limitations on arcs. The humanitarian organization has information about the occurrence of several possible disasters within the environment. It is assumed that the organization can quantify the uncertainty of a possible disaster in terms of probabilities. A possible disaster's probability of occurrence is explicitly represented by a parameter in the mathematical program. The humanitarian organization also has information about those attributes of the environmental elements which are independent of the outcome of a disaster: coordinates of locations as well as distances of arcs. Attributes are implicitly or explicitly represented by parameters in the mathematical program. Coordinates of locations are implicitly represented by the parameters which describe the distances between locations (because coordinates have to be known to calculate distances between locations). Speed limitations of arcs are implicitly represented by the parameters describing the capacities of arcs (because to calculate arc capacities these speed limitations have to be known). The parameters which describe certain elements in the environment are outlined in Table 4.4.

In the second part of the problem structuring process, the humanitarian organization is characterized. The organization has certain inputs available to set up and run a humanitarian logistics network within the disaster environment: facilities that are used as stationary warehouses, transshipment facilities, and/ or demand facilities, transportation vehicles, and relief items. In Figure 4.7, a simple example of the humanitarian logistics network is presented.

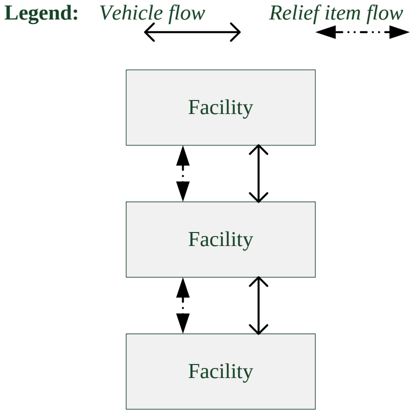


Figure 4.7. Simple example of the humanitarian logistics network in the OR model of Rawls and Turnquist (2011)

Each facility that can be used as a combination of a stationary warehouse, transshipment facility, and demand facility could have several counterparts in a real-world humanitarian logistics network. Possible counterparts are: a stationary warehouse, a handling point, a temporary warehouse, and/ or a LDC. Possible counterparts of a facility as defined in the OR model of Rawls and Turnquist (2011) are highlighted in Figure 4.8 using the reference structure for humanitarian logistics networks as described in section 2.1.

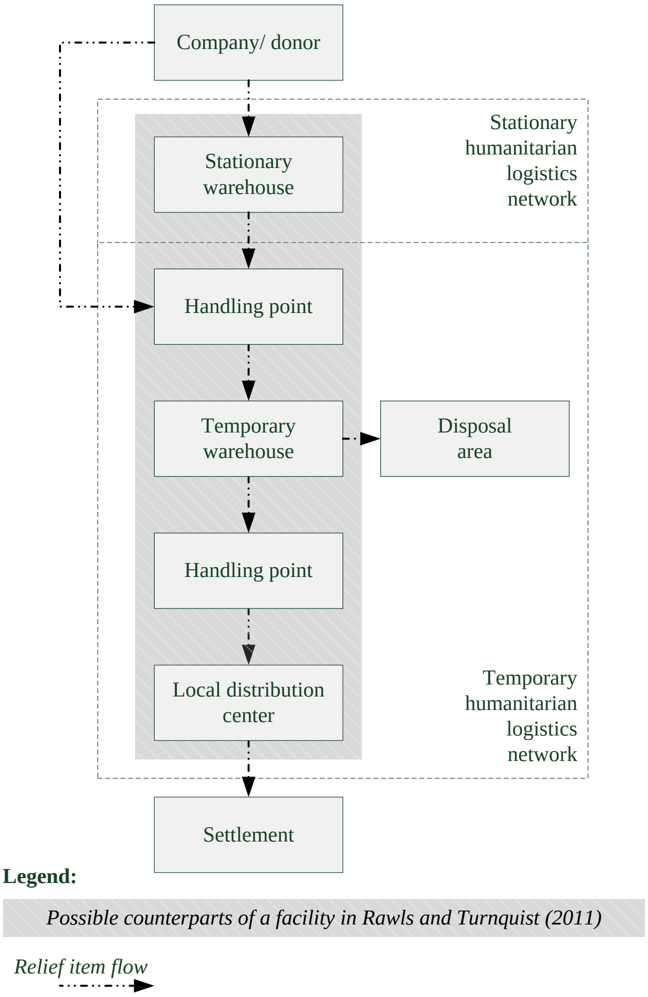


Figure 4.8. Counterparts of a facility defined in Rawls and Turnquist (2011) in the reference structure for humanitarian logistics networks

Each relief item type is characterized by a volume and weight per unit. Each type of transportation vehicle is defined by a speed of travel, a transport volume and weight per vehicle, a number of available vehicles on specific arcs, and relief item loads on specific arcs in specific disasters. Each facility used as a combination of stationary warehouse, transshipment facility, and demand facility is defined by the location it is assigned to, a size to stock relief items, and amounts of prepositioned, handled, and distributed relief items. Each facility that is used as a combination of a transshipment and demand facility (and *not* as a stationary warehouse) is defined by a location as well as the amounts of handled and distributed relief items. Locations for facilities which can be used as combinations of transshipment and demand facilities, the transport volume, transport weight, and travel speed per transportation vehicle type, the number of available vehicles on specific arcs as well as the volume and weight per relief item unit are already determined by the humanitarian organization. The volume per unit of a relief item type is explicitly represented by a parameter in the mathematical program. However, the locations for facilities which can be used as combinations of transshipment and demand facilities, the weight per unit of a relief item type, the speed of travel per transportation vehicle type, the transport volume and weight per vehicle, and the number of available vehicles on specific arcs are implicitly given in the mathematical program by the parameters which describe the distances and capacities of arcs.

The locations, sizes, and relief item stocks of facilities used as stationary warehouses and the relief item flows between all facilities for each possible disaster are the values to be determined. These values are represented by decision variables in the mathematical program. Locations and sizes of those facilities used as stationary warehouses can be chosen out of discrete sets of alternatives whereas the values of stocked, transferred, handled, and distributed relief items are positive real numbers. Since relief item quantities are positive real numbers, the number of alternative solutions to the problem is continuous. Parameters and variables which describe the characteristics of the logistics resources and relief items are outlined in Table 4.4.

The humanitarian organization has to adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements of the environment. The following relationships are known:

- Facilities can be expanded to serve as stationary warehouses with certain sizes.
- Stationary warehouses can be stocked during the preparedness phase with relief items depending on their sizes and on the volumes of the relief items.
- During a possible disaster response, the amount of relief items that arrives at a facility together with the amount of prepositioned and undamaged relief items at a facility (if it is used as a stationary warehouse) and the amount of unsatisfied relief item demand (relief item shortage) must be equal to the amount of outflowing relief items, the amount of relief items distributed at the facility to cover the location’s demand, and the amount of prepositioned but unused relief items.

- The maximum number of transferred relief items over a specific arc depends on the arc's speed limitations, the number of available transportation vehicles on that arc, their maximum speed of travel, and their transport volume and weight as well as on the necessary volume and weight per relief item.

In the mathematical program, the allowed uses of/ interactions between logistics resources, relief items, and elements in the environment are represented by constraints. The constraints which represent these relationships are outlined in Table 4.4.

When setting up a humanitarian logistics network, several critical dimensions are taken into account to identify the most advantageous network configuration. On the one hand, certain inputs of a configuration – the necessary relief items and necessary resources for warehousing and transportation – represent critical dimensions. Warehouse setup costs, relief item procurement costs, holding costs for unused relief items, and transportation costs are utilization metrics to quantify the amounts of inputs. On the other hand, the configuration's outputs – the quantity and quality of delivered relief items and the corresponding delivery times – qualify as critical dimensions. The relief item shortage costs which accumulate during a disaster response are used to capture the dimensions *relief item quantity* and *relief item quality*. The dimension *delivery time* is captured by the transport performance on arcs. These metrics belong to the class of effectiveness metrics. The mathematical program's expressions for these metrics are outlined in Table 4.4. The following factors and bounds are necessary in order to determine the values of metrics: transportation costs between two locations per unit of a certain relief item type, procurement costs per unit of a certain relief item type, stationary warehouse setup costs per location and facility size, shortage costs per unit of a certain relief item type, holding costs per unit of a certain relief item type, an upper distance limit per relief item type, and the planned durations of the disaster responses. The parameters which represent these factors and bounds are outlined in Table 4.4. The durations of the disaster responses are implicitly represented by the parameters that describe the capacities of arcs.

The humanitarian organization is set to minimize the setup, procurement, holding, transportation, and shortage costs while limiting the transportation distances. In other words, the organization intends to minimize the sum of inputs as well as to maximize the relief item quantity and quality while limiting the delivery times to a certain figure. However, the limits for the delivery times only hold for a specific set of disasters, the so-called "reliability set", which composition is to be determined in the mathematical program while the reliability set's maximum size is represented by a parameter. Furthermore, relief item demands have to be fulfilled completely if they occur in possible disasters which are included in this reliability set. The mathematical program's parts which represent these objectives and requirements are outlined in Table 4.4. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the problem captured in the OR model of Rawls and Turnquist (2011).

Table 4.4. Problem structuring scheme for Rawls and Turnquist (2011)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disasters	Probability of occurrence	Parameter prb_s
		Locations	Coordinates	Parameter d_{ij}
			Relief item type loss in disasters	Parameter dsd_{irs}
			Relief item type demand in disasters	Parameter dmd_{irs}
		Arcs	Start location	Parameter d_{ij}
			End location	Parameter d_{ij}
			Distance	Parameter d_{ij}
			Speed limitations in disasters	Parameter $CapT_{ijs}$
Humanitarian organization	*Logistics resources and relief items*	Stationary warehouses/ transshipment/ demand facilities	Location (DV)	Variable y_{iu}
			Size (DV)	Variable y_{iu}
			Relief items stocked (CV)	Variable x_{ir}^{p}
			Relief items handled in disasters (CV)	Variable x_{ijrs}^{t}
			Relief items distributed in disasters (CV)	Variable x_{ijrs}^{t}
		Transshipment/ demand facilities	Location	Parameter d_{ij}
			Relief items handled in disasters (CV)	Variable x_{ijrs}^{t}
			Relief items distributed in disasters (CV)	Variable x_{ijrs}^{t}
		Transportation vehicle types	Speed of travel	Parameter $CapT_{ijs}$
			Transport volume	Parameter $CapT_{ijs}$
			Transport weight	Parameter $CapT_{ijs}$

		Vehicles on arcs	Parameter $CapT_{ijs}$
		Relief items transferred on arcs in disasters (CV)	Variable x^{t}_{ijrs}
	Relief item types	Volume	Parameter $spcW_r$
		Weight	Parameter $capT_r$
Use and interaction of logistics resources, relief items, and elements in environment	Facilities can be expanded to serve as stationary warehouses with certain sizes.		Constraint set 4.25
	Stationary warehouses can be stocked during the preparedness phase with relief items depending on their sizes and on the volumes of the relief items.		Constraint set 4.24
	During a possible disaster response, the amount of relief items that arrives at a facility together with the amount of prepositioned and undamaged relief items at a facility (if it is used as a stationary warehouse) and the amount of unsatisfied relief item demand must be equal to the sum of the amount of outflowing relief items, the amount of relief items that is distributed at the facility to cover the location's demand, and the amount of prepositioned but unused relief items		Constraint set 4.23
	The maximum number of transferred relief items over a specific arc depends on the arc's speed limitations, the number of transportation vehicles on that arc, their speed of travel, and the transport volume and weight per vehicle as well as on the characteristics of a relief item unit		Constraint set 4.26
Key dimensions, metrics, objectives, and requirements	Inputs	Relief items: procurement cost	Expression $\sum_{i\in I}\sum_{r\in R} c^{\mathrm{a}}_{r} x^{\mathrm{p}}_{ir}$
		Warehousing resources: stationary warehouse setup costs, holding costs in disasters	Expressions $\sum_{i\in I}\sum_{u\in U} C^{\mathrm{s}}_{iu} y_{iu}$, $\sum_{i\in I}\sum_{r\in R} c^{\mathrm{h}}_{r} x^{\mathrm{h}}_{irs}$

	Transportation resources: transportation costs in disasters	Expression $\sum_{i\in I}\sum_{j\in I}\sum_{r\in R} c^{\mathrm{t}}_{ijrs} x^{\mathrm{t}}_{ijrs}$
Outputs	Delivered relief item quantity: shortage costs in disasters	Expression $\sum_{i\in I}\sum_{r\in R} c^{\mathrm{u}}_{r} x^{\mathrm{u}}_{irs}$
	Delivered relief item quality: shortage costs in disasters	Expression $\sum_{i\in I}\sum_{r\in R} c^{\mathrm{u}}_{r} x^{\mathrm{u}}_{irs}$
	Delivery time: transportation performance in disasters	Expression $\sum_{i\in I}\sum_{j\in I} d_{ij} x^{\mathrm{t}}_{ijrs}$
Objectives and requirements	Minimizing inputs	Objective function 4.22
	Maximizing, ensuring delivered relief item quantity	Objective function 4.22, constraint 4.27, constraint set 4.28
	Maximizing, ensuring delivered relief item quality	Objective function 4.22, constraint 4.27, constraint set 4.28
	Limiting delivery times	Constraint 4.27, constraint set 4.29
Factors and bounds	Stationary warehouse setup costs per location and size	Parameter C^{s}_{iu}
	Transportation costs between two locations per unit of a relief item type in disasters	Parameter c^{t}_{ijrs}
	Procurement costs per unit of a relief item type	Parameter c^{a}_{r}
	Holding costs per unit of a relief item type	Parameter c^{h}_{r}
	Shortage costs per unit of a relief item type	Parameter c^{u}_{r}
	Upper distance limit per relief item type	Parameter dMx_{r}
	Planned duration per possible disaster response	Parameter $CapT_{ijs}$
	Size limit for the reliability set	Parameter γ

Program code

Below is the program code of Rawls and Turnquist (2011), using the OPL language. This language is frequently used to code a MILP such as that found in Rawls and Turnquist (2011). MILPs coded in this language can be automatically solved with the CPLEX solver.

```
/************************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Rawls and Turnquist (2011)
 * Creation Date: 27.01.2015 at 11:06:17
 ************************************************/
{string} LocationsForStationaryWarehouses = ...;
{string} ReliefItemTypes = ...;
{string} Scenarios = ...;
{string} StationaryWarehouseSizes = ...;
float BigNumber = ...;
float CostForAquiring[ReliefItemTypes] = ...;
float CostForTransferring
[LocationsForStationaryWare-
houses,LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios]
= ...;
float CostForShortage[ReliefItemTypes] = ...;
float CostForHolding[ReliefItemTypes] = ...;
float CostStationaryWarehouseSetup
[LocationsForStationaryWarehouses,StationaryWarehouseSizes] = ...;
float CapacityAvailable
[LocationsForStationaryWare-
houses,LocationsForStationaryWarehouses,Scenarios] = ...;
float CapacityNecessary[ReliefItemTypes] = ...;
float Distance
[LocationsForStationaryWarehouses,LocationsForStationaryWarehouses]  =
...;
float Demand
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios] = ...;
float UpperDistanceLimit[ReliefItemTypes] = ...;
float ProportionUsable
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios] = ...;
float Probability[Scenarios] = ...;
float SpaceAvailable[StationaryWarehouseSizes] = ...;
float SpaceNecessary[ReliefItemTypes] = ...;
float ConfideneLevel = ...;
```

```
dvar float+ Transferred
[LocationsForStationaryWarehouses,LocationsForStationaryWarehouses,
ReliefItemTypes,Scenarios];
dvar float+ Shortage
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios];
dvar float+ Held
[LocationsForStationaryWarehouses,ReliefItemTypes,Scenarios];
dvar float+ Prepositioned
[LocationsForStationaryWarehouses,ReliefItemTypes];
dvar boolean Open
[LocationsForStationaryWarehouses,StationaryWarehouseSizes];
dvar boolean inReliabilitySet[Scenarios];

minimize

sum (i in LocationsForStationaryWarehouses, u in StationaryWarehouseSizes)
CostStationaryWarehouseSetup[i,u] * Open[i,u] +
sum (i in LocationsForStationaryWarehouses, r in ReliefItemTypes)
CostForAquiring[r] * Prepositioned[i,r] +
sum (s in Scenarios)
Probability[s] * (
sum (i in LocationsForStationaryWarehouses, j in LocationsForStationaryWarehouses, r in ReliefItemTypes)
CostForTransferring[i,j,r,s] * Transferred[i,j,r,s] +
sum (i in LocationsForStationaryWarehouses, r in ReliefItemTypes)
(CostForHolding[r] * Held[i,r,s] +
CostForShortage[r] * Shortage[i,r,s]));

subject to{
ct23:
forall(i in LocationsForStationaryWarehouses, r in ReliefItemTypes, s in
Scenarios)
sum (j in LocationsForStationaryWarehouses:j!=i)
(Transferred[j,i,r,s]) +
ProportionUsable[i,r,s] * Prepositioned[i,r] -
Held[i,r,s]
== sum (j in LocationsForStationaryWarehouses:j!=i)
(Transferred[i,j,r,s]) +
Demand[i,r,s] -
Shortage[i,r,s];
ct24:
forall(i in LocationsForStationaryWarehouses)
sum (r in ReliefItemTypes)
```

```
(SpaceNecessary[r] * Prepositioned[i,r])
<= sum (u in StationaryWarehouseSizes)
(SpaceAvailable[u] * Open[i,u]);

ct25:
forall(i in LocationsForStationaryWarehouses)
sum (u in StationaryWarehouseSizes)
Open[i,u]
<= 1;

ct26:
forall(i  in  LocationsForStationaryWarehouses,  j  in  LocationsForStation-
aryWarehouses, s in Scenarios)
sum (r in ReliefItemTypes)
(CapacityNecessary[r] * Transferred[i,j,r,s])
<= CapacityAvailable[i,j,s];

ct27:
sum (s in Scenarios)
(Probability[s] * inReliabilitySet[s])
>= ConfideneLevel;

ct28:
forall(i  in  LocationsForStationaryWarehouses,  r  in  ReliefItemTypes,  s  in
Scenarios)
Shortage[i,r,s]
<= Demand[i,r,s] *
(1 - inReliabilitySet[s]);

ct29:
forall(r in ReliefItemTypes, s in Scenarios)
sum  (i  in  LocationsForStationaryWarehouses,  j  in  LocationsForStation-
aryWarehouses)
(Distance[i,j] * Transferred[i,j,r,s])
<= UpperDistanceLimit[r] *
sum (i in LocationsForStationaryWarehouses)
Demand[i,r,s] +
BigNumber * (1 - inReliabilitySet[s]);
}
```

4.2 Local distribution center specification toolkit

Local distribution centers (LDCs) are crucial facilities within a humanitarian logistics network because during disaster responses beneficiaries pick up relief items at these temporary facilities within the affected area. Each LDC is characterized by a location, a storage space, equipment and workers to distribute relief items to beneficiaries, suppliers of relief items, and an amount of stocked and distributed relief items. LDCs are supplied by upstream facilities in the humanitarian logistics network such as stationary warehouses, handling points, or temporary warehouses (see Figure 4.9).

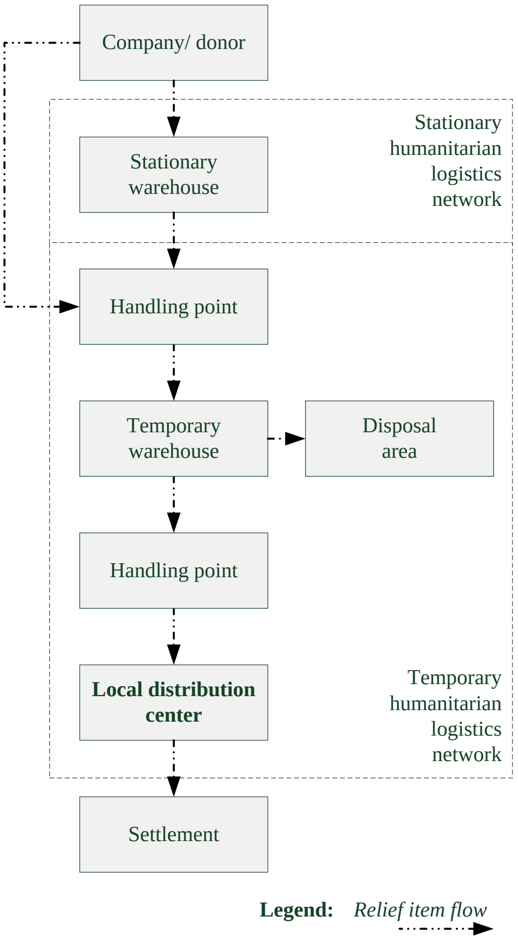


Figure 4.9. Local distribution center as a crucial part of a humanitarian logistics network

An example for the distribution of relief items using LDCs is the operation in the Sare-e-Pul province of Afghanistan after floodings in 2014. The distribution of relief items was conducted by four workers of an NGO named Islamic Relief Afghanistan and was separated into three phases: 160 households were supported from three different LDCs in the first phase, 500 households were supported from one LDC in the second phase, and 604 households were supported from one LDC in the third phase (Raufi, 2014). Another example of a rather small-scale distribution is the operation of the IFRC that occurred in the aftermath of floodings in the Mumbwa District (Zambia) caused by heavy rains in January 2013. The flood affected over 300 households in the district. All 300 households were assisted by one-off relief item distributions of food and non-food items that took place at two LDCs in the settlements of Nangoma and Kabulwebulwe (IFRC, 2013).

Table 4.5. Guide for the local distribution center specification toolkit

	Attributes of LDC			Key dimensions, objectives, and requirements			
OR model	Locations	Aid workers/ equipment	Suppliers	Transportation resources	Distribution resources	Delivered relief item quantity	Distance to LDC
Horner and Downs (2010)	■	■	■	O	R	R	O
Lee et al. (2009a)	■				O, R	R	R
Murali et al. (2012)	■				R, R	O	R

■: to be specified, O: objective, R: requirement

Table 4.5 may assist the user of the OR toolkit to select the most appropriate of the three currently included OR models. The left section of the table may help to identify the most appropriate model based on the attributes of LDCs the user wants to specify while the right section may help to identify the most appropriate model based on critical dimensions, objectives, and requirements. The model of Horner and Downs (2010), for example, supports decisions about locations, the aid workers/distribution equipment, and suppliers of LDCs. Decisions are made so that the distances between beneficiaries and LDCs are minimized, the input of transportation resources is minimized, a certain quantity of delivered relief items is ensured, and the number of opened LDCs is limited.

4.2.1 Mathematical program of Horner and Downs (2010) for supporting decisions about the locations, equipment, and suppliers of local distribution centers

Horner and Downs (2010) presented a mathematical program in their publication with the title “Optimizing hurricane disaster relief goods distribution: model development and application with respect to planning strategies”. The program supports the specification of LDCs. On a functional level, the program can be characterized as a facility location model. The program can also be defined as a MILP because of the use of real-valued flow variables together with binary location variables.

The following model profile includes a description of the mathematical formulation, a description of the underlying problem’s structure, and a possible translation of the mathematical formulation into program code. Names of sets, parameters, and variables in the present notation differ from the original notation in order to achieve a consistent notation within the OR toolkit.

Mathematical formulation

The program’s objective function (4.32) minimizes the total costs for distributing relief items from supply facilities via LDCs to the beneficiaries located at settlements. Total costs include the costs for the relief item transport between supply facilities and LDCs and the costs of the beneficiaries to overcome the distances between settlements and LDCs in order to pick up the needed relief items. Constraint set (4.33) is a set of flow constraints and ensures that the amount of relief items flowing into a LDC is equal to the amount of relief items distributed among the settlements assigned to this LDC. The same constraint set ensures complete relief item demand satisfactions of all settlements. Constraint set (4.34) requires that not more than one LDC can serve a settlement. Constraint set (4.35) makes sure that settlements can only be assigned to erected LDCs. Constraint set (4.36) limits the capacity of the LDCs and constraint set (4.37) specifies the maximum numbers of LDCs with certain sizes. Finally, constraint set (4.38) ensures non-negativity of the real-valued variables (amount of relief items sent from supply facilities to LDCs) and constraint set (4.39) defines the binary variables (locations and sizes of LDCs as well as the assignments of settlements to LDCs).

Sets:

B	Set of settlements
M	Set of locations where LDCs can be erected
O	Set of locations where supply facilities are erected

U	Set of facility sizes

Parameters:

c^{c}_{bmu}	Costs for the collection (c) of a relief item unit coming from location *b* at location *m* where a LDC of size *u* is erected
c^{t}_{omu}	Costs for the transportation (t) of a relief item unit from location *o* to location *m* where a LDC of size *u* is erected
$CapD_{mu}$	Capacity available to distribute relief items at location *m* if a LDC is erected with size *u*
dmd_b	Units of relief items demanded at location *b*
$NfMx_u$	Maximum number of facilities with size *u* to be erected

Variables:

x^{t}_{omu}	Relief items transferred (t) from supply facility at location *o* to LDC at location *m* with size *u*
y_{mu}	1 if a LDC is located at location *m* with size *u*, 0 otherwise
y_{bmu}	1 if the demand for relief items at location *b* is satisfied by LDC at location *m* with size *u*

MILP:

(4.32) Minimize

$$\sum_{o\in O}\sum_{m\in M}\sum_{u\in U} c^{\mathrm{t}}_{omu}x^{\mathrm{t}}_{omu} + \sum_{b\in B}\sum_{m\in M}\sum_{u\in U} dmd_b c^{\mathrm{c}}_{bmu} y_{bmu}$$

s.t. (4.33) $\sum_{o\in O} x^{\mathrm{t}}_{omu} = \sum_{b\in B} dmd_b y_{bmu} \qquad \forall m \in M, u \in U$

$$(4.34)\ \sum_{m \in M} \sum_{u \in U} y_{bmu} = 1 \qquad \forall b \in B$$

$$(4.35)\ y_{mu} \geq y_{bmu} \qquad \forall b \in B, m \in M, u \in U$$

$$(4.36)\ \sum_{b \in B} dmd_b y_{bmu} \leq CapD_{mu} \qquad \forall m \in M, u \in U$$

$$(4.37)\ \sum_{m \in M} y_{mu} \leq NfMx_u \qquad \forall u \in U$$

$$(4.38)\ x^{\mathrm{t}}_{omu} \geq 0 \qquad \forall m \in M, o \in O, u \in U$$

$$(4.39)\ y_{bmu}, y_{mu} \in \{0,1\} \qquad \forall b \in B, m \in M, u \in U$$

Problem structure

In this sub-section, the problem as captured in the OR model of Horner and Downs (2010) will be structured based on the scheme outlined in section 3.4. In the first step, the disaster environment is characterized; and in the second step, the humanitarian organization operating the humanitarian logistics network in this environment is specified. The results of the problem structuring process are outlined in Table 4.6 (pp. 99ff).

The environment is single-organizational and contains locations and unidirectional arcs. Three types of locations exist: locations for supply facilities, locations for LDCs, and settlements. All types of locations are characterized by coordinates. Additionally, settlements are specified by demands for relief items due to a disaster. An arc is specified by the two locations it connects, a distance, and speed limitations. Attributes of the elements in the environment are defined as static and deterministic. They are implicitly or explicitly represented by parameters in the mathematical program. Those implicitly represented attributes are the coordinates of locations as well as the distances and speed limitations between locations (represented by the parameters that describe the transportation costs to travel over arcs because distances and speed limitations between locations are necessary to determine transportation costs). Beneficiaries live in the settlements and are characterized by the flows of relief items they realize on specific arcs between settlements and locations for LDCs. The humanitarian organization intends to know the magnitudes of the relief item flows realized by beneficiaries. Hence, these flows are values to be determined in the problem. These flows are implicitly represented in the mathematical program by binary variables which describe the assignments of populations to LDCs. Parameters and variables which describe certain attributes of the elements in the environment are outlined in Table 4.6.

The organization has certain inputs available to set up and run a humanitarian logistics network within the borders of the environment: supply facilities, LDCs, transportation vehicles, aid workers/ distribution equipment, and relief items. In Figure 4.10, a simple example of the assumed humanitarian logistics network is presented.

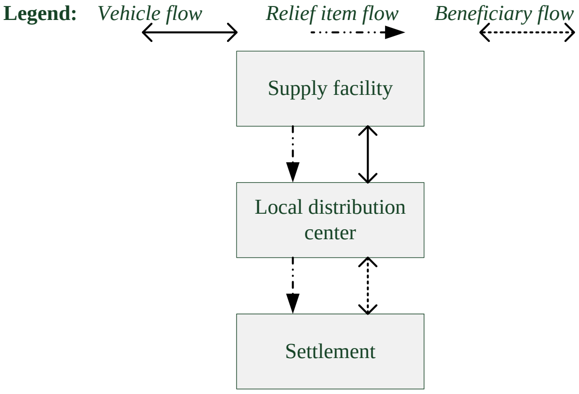


Figure 4.10. Simple example of the humanitarian logistics network in the OR model of Horner and Downs (2010)

A supply facility could have different counterparts in a real-world humanitarian logistics network; in fact, a supply facility could be a handling point, a temporary warehouse, or a stationary warehouse. In any case, it is a facility upstream from a LDC. Possible counterparts for a supply facility are highlighted in Figure 4.11 using the reference structure for humanitarian logistics networks, which was described in section 2.1. A settlement and LDC as defined in the OR model of Horner and Downs (2010) have both a direct counterpart in this reference structure.

Supply facilities are defined by their locations. LDCs are defined by their locations, one or more suppliers, and amounts of distribution equipment/ numbers of aid workers. A relief item is defined by its volume, weight, and distribution time. Moreover, the different types of transportation vehicles are specified by their speed of travel, an available transport weight and volume per vehicle, the number of available vehicles on arcs between supply facilities and LDCs, and the vehicles' loads of relief items. Finally, the different types of aid workers/ distribution equipment are characterized by working times and numbers of available aid workers/ amounts of available distribution equipment at locations for LDCs.

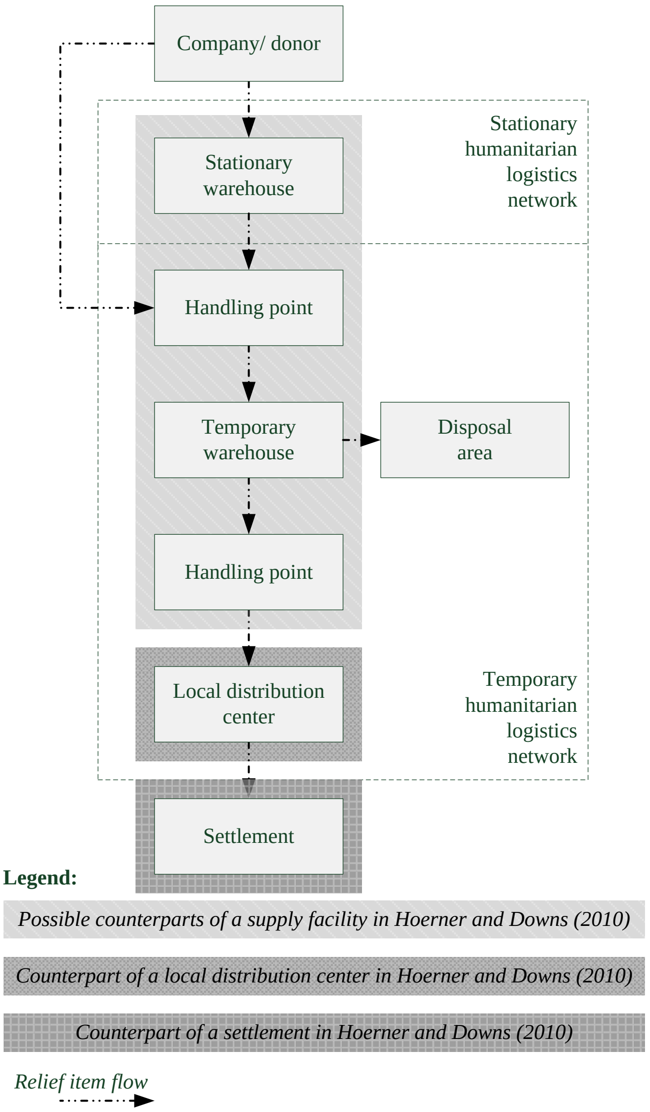


Figure 4.11. Counterparts of the facilities/ locations defined in Horner and Downs (2010) in the reference structure for humanitarian logistics networks

Locations of supply facilities are assumed to be already determined by the humanitarian organization. Volume, weight, and distribution time per relief item unit are also already fixed by the humanitarian organization. Speed of travel, available transport weight and volume per transportation vehicle, numbers of transportation vehicles on arcs between supply facilities and LDCs, numbers of aid workers/ amounts of distribution equipment at locations for LDCs as well as the working times of aid workers/ the distribution equipment are also already defined. Weight and volume per relief item unit, speed of travel, available transport weight and volume per transportation vehicle, and numbers of transportation vehicles on arcs between supply facilities and LDCs are implicitly represented in the mathematical program by the parameters describing the transportation costs between supply facilities and LDCs. The numbers of available aid workers/ the amounts of distribution equipment, working times of the aid workers/ distribution equipment, and the distribution time per relief item unit are implicitly represented by the parameters which describe the potential capacities of LDCs at specific locations.

Locations, aid workers/ equipment, and suppliers of LDCs as well as the amounts of transferred and distributed relief items are the values to be determined by the decision problem. The numbers of aid workers/ amounts of equipment at LDCs are implicitly represented by the binary variables which describe the sizes of LDCs opened at certain locations. Suppliers of opened LDCs and the amounts of transferred and distributed relief items are implicitly represented in the program by the variables which describe the relief item flows between supply facilities and LDCs. Because the relief item flows are positive real-valued numbers, the number of solutions to the decision problem is continuous. Parameters and variables which represent attributes of logistics resources and relief items are outlined in Table 4.6.

The humanitarian organization has to adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements in the environment. Four relationships are known by the organization (each represented by a constraint in the program):

- The amount of relief items flowing into a LDC is equal to the amount of relief items to be distributed among the settlements assigned to this center.
- The number of available aid workers/ amount of available distribution equipment at a location, the working times of workers and equipment, and the distribution time per relief item unit restrict the number of relief items that can be distributed to beneficiaries by a LDC opened at a specific location.
- The population of a settlement can only travel to open LDCs.
- The total population of a settlement travels to only one LDC; this has to be realized by notifying a settlement's population of its LDC.

The humanitarian organization takes into account several critical dimensions in order to identify the most advantageous configuration of the humanitarian logistics network. On the one hand, the inputs – the resources for distribution and transportation – represent key dimensions. The number of opened LDCs with a specific amount of equipment/ number of aid workers is an utilization metric, used to measure the dimension *distribution resources*. The value of the transportation costs is also an utilization metric, used to measure the dimension *transportation resources*. On the other hand, the configuration's outputs – the delivered relief item quantity and the beneficiaries' distances to LDCs – represent critical dimensions. The dimension *distance to LDCs* is measured by the beneficiaries' transportation costs for receiving relief items. This metric belongs to the class of effectiveness metrics. The dimension *delivered relief item quantity* is measured by the amount of distributed relief items during the disaster response. This metric also belongs to the class of effectiveness metrics. The mathematical program's expressions for these metrics are outlined in Table 4.6. The humanitarian organization has to define factors and bounds to determine values for these metrics: duration of the disaster response, transportation costs between two locations per relief item unit, and the maximum number of LDCs with a certain amount of equipment/ number of aid worker that can be erected. The program's parameters which represent particular factors and bounds are outlined in Table 4.6. The duration of the disaster response is implicitly represented by the parameter that describes an available distribution capacity at a location.

The organization intends to minimize the amount of transportation resources, to minimize the distances between settlements and the locations of opened LDCs, to limit the number of LDCs as well as to ensure an amount of delivered relief items. The parts of the mathematical program which represent these objectives and requirements are outlined in Table 4.6. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the problem captured in the OR model of Horner and Downs (2010).

Table 4.6. Problem structuring scheme for Horner and Downs (2010)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Locations for supply facilities	Coordinates	Parameter c^{t}_{omu}
		Locations for LDCs	Coordinates	Parameter c^{t}_{omu} , c^{c}_{bmu}
		Settlements	Coordinates	Parameter c^{t}_{bmu}
			Relief item demand	Parameter dmd_{b}
		Arcs	Start location	Parameter c^{t}_{omu} , c^{c}_{bmu}
			End location	Parameter c^{t}_{omu} , c^{c}_{bmu}
			Distance	Parameter c^{t}_{omu} , c^{c}_{bmu}
			Speed limitations	Parameter c^{t}_{omu}
		Beneficiaries	Relief items transferred on arcs (CV)	Variable y_{bmu}
Humanitarian organization	*Logistics resources and relief items*	Supply facilities	Supply facility location	Parameter c^{t}_{omu}
		LDCs	LDC location (DV)	Variable y_{mu}
			Aid workers/ equipment types (DV)	Variable y_{mu}
			Suppliers (DV)	Variable x^{t}_{omu}
			Relief items distributed (CV)	Variable x^{t}_{omu}
		Transportation vehicle types	Speed of travel	Parameter c^{t}_{omu}
			Transport volume	Parameter c^{t}_{omu}
			Transport weight	Parameter c^{t}_{omu}

		Vehicles on arcs	Parameter c^{t}_{omu}
		Relief items transferred on arcs (CV)	Variable x^{t}_{omu}
	Aid workers/ equipment types	Working time	Parameter $CapD_{mu}$
		Number/ amount at locations for LDCs	Parameter $CapD_{mu}$
	Relief item	Volume	Parameter c^{t}_{omu}
		Weight	Parameter c^{t}_{omu}
		Time for distribution	Parameter $CapD_{mu}$
Use and interaction of logistics resources, relief items, and elements in environment	The amount of relief items flowing into a LDC is equal to the amount of relief items to be distributed among the settlements assigned to this center		Constraint set 4.33
	The number of available aid workers/ the amount of available distribution equipment at a specific location, the working times of workers and equipment, and the time for the distribution per relief item unit restrict the number of relief items that can be distributed to beneficiaries by a LDC opened at a specific location		Constraint set 4.36
	The population of a settlement can only travel to open LDCs		Constraint set 4.35
	The total population of a settlement can only travel to one LDC; this has to be realized by notifying a settlement's population of its LDC		Constraint set 4.34
Key dimensions, metrics, objectives, and requirements	Inputs	Distribution resources: number of LDCs	Expression $\sum_{m\in M}\sum_{u\in U} y_{mu}$
		Transportation resources: transportation costs	Expression $\sum_{o\in O}\sum_{m\in M}\sum_{u\in U} c^{\mathrm{t}}_{omu} x^{\mathrm{t}}_{omu}$

Outputs	Delivered relief item quantity: amount of distributed relief items	Expression $\sum_{o\in O}\sum_{m\in M}\sum_{u\in U} x^{\mathrm{t}}_{omu}$
	Distance to LDCs: neighborhood costs for collecting relief items at LDCs	Expression $\sum_{b\in B}\sum_{m\in M}\sum_{u\in U} dmd_{b}c^{\mathrm{c}}_{bmu}y_{bmu}$
Objectives and requirements	Minimizing transportation resources	Objective function 5.32
	Minimizing distance to LDCs	Objective function 5.32
	Limiting number of distribution resources	Constraint set 5.37
	Ensuring delivered relief item quantity	Constraint set 5.34
Factors and bounds	Planned duration of disaster response	Parameter $CapD_{mu}$
	Transportation costs between two locations per unit of a relief item type	Parameter c^{t}_{omu}, c^{c}_{bmu}
	Maximum number of LDCs with a certain number of aid workers/ amount of equipment	Parameter $NfMx_{u}$

Program code

Below is a possible translation into program code of the OR model of Horner and Downs (2010), using the OPL language. This language is frequently used to code a MILP such as the one of Horner and Downs (2010). MILPs coded in this language can be automatically solved with the CPLEX solver.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Horner and Downs (2010)
 * Creation Date: 28.01.2015 at 13:14:04
 *********************************************/
{string} Settlements = ...;
{string} LocationsForLDCs = ...;
{string} LocationsForSupplyFacilities = ...;
{string} LDCSizes = ...;
float BeneficiariesCostForTransferring
[Settlements,LocationsForLDCs,LDCSizes] = ...;
float CostForTransferring
[LocationsForSupplyFacilities,LocationsForLDCs,LDCSizes] = ...;
float Capacity[LocationsForLDCs,LDCSizes] = ...;
float Demand[Settlements] = ...;
float MaximumNumberLDCs[LDCSizes] = ...;
dvar float+ Transferred
[LocationsForSupplyFacilities,LocationsForLDCs,LDCSizes];
dvar boolean Open[LocationsForLDCs,LDCSizes];
dvar boolean SettlementAssignedToLDC
[Settlements,LocationsForLDCs,LDCSizes];
minimize
sum (o in LocationsForSupplyFacilities, m in LocationsForLDCs, u in
LDCSizes)
CostForTransferring[o,m,u] * Transferred[o,m,u]
+ sum (b in Settlements, m in LocationsForLDCs, u in LDCSizes)
Demand[b] * BeneficiariesCostForTransferring[b,m,u] *
SettlementAssignedToLDC[b,m,u];

subject to{
ct33:
forall(m in LocationsForLDCs, u in LDCSizes)
sum (o in LocationsForSupplyFacilities)
Transferred[o,m,u]
== sum (b in Settlements)
Demand[b] * SettlementAssignedToLDC[b,m,u];
```

```
ct34:
forall(b in Settlements)
sum (m in LocationsForLDCs, u in LDCSizes)
SettlementAssignedToLDC[b,m,u]
== 1;

ct35:
forall(b in Settlements, m in LocationsForLDCs, u in LDCSizes)
Open[m,u]
>= SettlementAssignedToLDC[b,m,u];

ct36:
forall(m in LocationsForLDCs, u in LDCSizes)
sum (b in Settlements)
Demand[b] * SettlementAssignedToLDC[b,m,u]
<= Capacity[m,u];

ct37:
forall(u in LDCSizes)
sum (m in LocationsForLDCs)
Open[m,u]
<= MaximumNumberLDCs[u];
}
```

4.2.2 Mathematical program of Lee et al. (2009a) for supporting decisions about the locations of local distribution centers

Lee et al. (2009a) published a scientific paper entitled: “Modeling and Optimizing the Public-Health Infrastructure for Emergency Response”. In it, they describe two mathematical programs. One of them supports the planning of LDCs in response to a disaster. On a functional level, the mathematical program can be characterized as a facility location model. Furthermore, the program can be defined as an IP because only binary variables are included.

This section comprises a description of the model’s mathematical formulation, of the underlying problem, and of a possible translation of the mathematical formulation into program code. Names of sets, parameters, and variables in the notation of the mathematical formulation differ from the original notation in Lee et al. (2009a) to achieve a consistent notation within the toolkit.

Mathematical formulation

The program's objective function (4.40) minimizes the number of opened LDCs. In their publication, Lee et al. (2009a) mention an alternative formulation for the objective function in which the average distance travelled by beneficiaries is minimized. Constraint (4.41) ensures that at least two LDCs are opened. Constraint set (4.42) limits the maximum distance between a location where a LDC is opened and a location whose population is assigned to this LDC. Constraint set (4.43) makes sure that every location's population is assigned to only one LDC and constraint set (4.44) determines that a location's population can only be assigned to an open LDC and that a LDC's capacity cannot be exceeded. Finally, constraint set (4.45) defines the binary location and assignment variables.

Sets:

M	Set of locations where LDCs can be erected

Parameters:

$CapB_m$	Capacity available to service beneficiaries at location *m* where a LDC can be erected
d_{mn}	Distance between location *m* and location *n*
dMx	Upper distance limit
Ppl_m	Population at location *m*

Variables:

y_m	1 if a LDC is located at location *m*, 0 otherwise
y_{mn}	1 if the population of location *n* is served by a LDC at location *m*, 0 otherwise

MILP:

(4.40) Minimize

$$\sum_{m \in M} y_m$$

s.t. (4.41) $\sum_{m \in M} y_m \geq 2$

(4.42) $d_{mn} y_{mn} \leq y_m dMx \qquad \forall m, n \in M$

(4.43) $\sum_{m \in M} y_{mn} = 1 \qquad \forall n \in M$

(4.44) $\sum_{n \in M} y_{mn} Ppl_n \leq CapB_m \qquad \forall m \in M$

(4.45) $y_m, y_{mn} \in \{0,1\} \qquad \forall m, n \in M$

Problem structure

In this sub-section, the mathematical program of Lee et al. (2009a) is structured based on the problem structuring scheme outlined in section 3.4. According to this scheme, the characteristics of the disaster environment are described first – followed by a description of the humanitarian organization operating the humanitarian logistics network in this disaster environment. The results of the problem structuring process are outlined in Table 4.7 (pp. 109f).

The environment is single-organizational and contains one type of location. A LDC can be located at each location in order to distribute relief items among beneficiaries in response to a disaster. Each location is also a settlement, characterized by coordinates and a demand for relief items. Each bidirectional arc between two locations is characterized by a start, an end, and a distance. The attributes of the elements in the environment qualify as static and deterministic. They are explicitly or implicitly represented by parameters in the mathematical program. Attributes that are implicitly represented are coordinates of locations and demands for relief items – namely, by the parameters that describe the distances between locations and the numbers of beneficiaries at settlements, respectively. Beneficiaries are characterized by the relief item flows they realize on specific arcs. It is assumed that the magnitudes of the relief item flows realized by beneficiaries depend on the configuration of the logistics network. Hence, the values of these flows are to be determined in the decision problem; they are implicitly represented by the binary variables that describe assignments of settlements to LDCs.

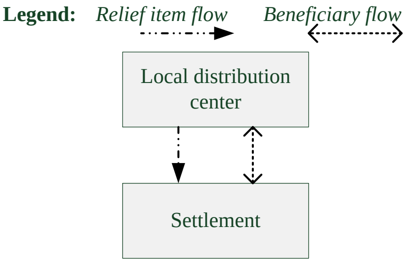


Figure 4.12. Simple example of the humanitarian logistics network in the OR model of Lee et al. (2009a)

The humanitarian organization has three types of inputs available to set up and run a humanitarian logistics network within the borders of the disaster environment: LDCs that can be located at settlements, aid workers/distribution equipment, and relief items. In Figure 4.12, a simple example of the assumed humanitarian logistics network is presented. A LDC and a settlement as defined in Lee et al. (2009a) have both an exact counterpart in the reference structure for humanitarian logistics networks as described in section 2.1. Their counterparts in the reference structure are marked in Figure 4.13.

A relief item is characterized by the distribution time per unit. The different types of distribution equipment/ aid workers are characterized by working times and the amounts of available distribution equipment/ numbers of available aid workers at specific settlements. All these attributes are implicitly represented in the mathematical program by the parameters which describe the abilities of settlements to host LDCs with certain capacities. Each LDC is defined by its location and the number of distributed relief items – and it is assumed that the humanitarian organization decides about the locations of opened LDCs and about the quantities of distributed relief items. Consequently, the locations of opened LDCs and the quantities of distributed relief items at these LDCs are values to be determined in the decision problem. These values are explicitly or implicitly represented by decision variables in the mathematical program. The quantities of distributed relief items are implicitly represented by the variables that describe the assignments of populations to LDCs. Locations of LDCs and assignments of populations can both be chosen out of discrete sets of alternatives. Therefore, the number of alternative solutions to the decision problem is discrete. Variables and parameters which represent attributes of logistics resources and relief items are outlined in Table 4.7.

The humanitarian organization must adhere to two rules when setting up a system of LDCs. Firstly, the number of beneficiaries serviced by a LDC cannot exceed the center's capacity which in turn is determined by the availability of distribution equipment/ aid workers, the working time of the equipment/ workers, and the distribution time per relief item. Secondly, a settlement's relief item demand is assigned as a whole to one LDC; this must be realized by notifying a settlement's population of its LDC. These two rules are represented by constraints in the mathematical program. The constraints which represent these relationships are outlined in Table 4.7.

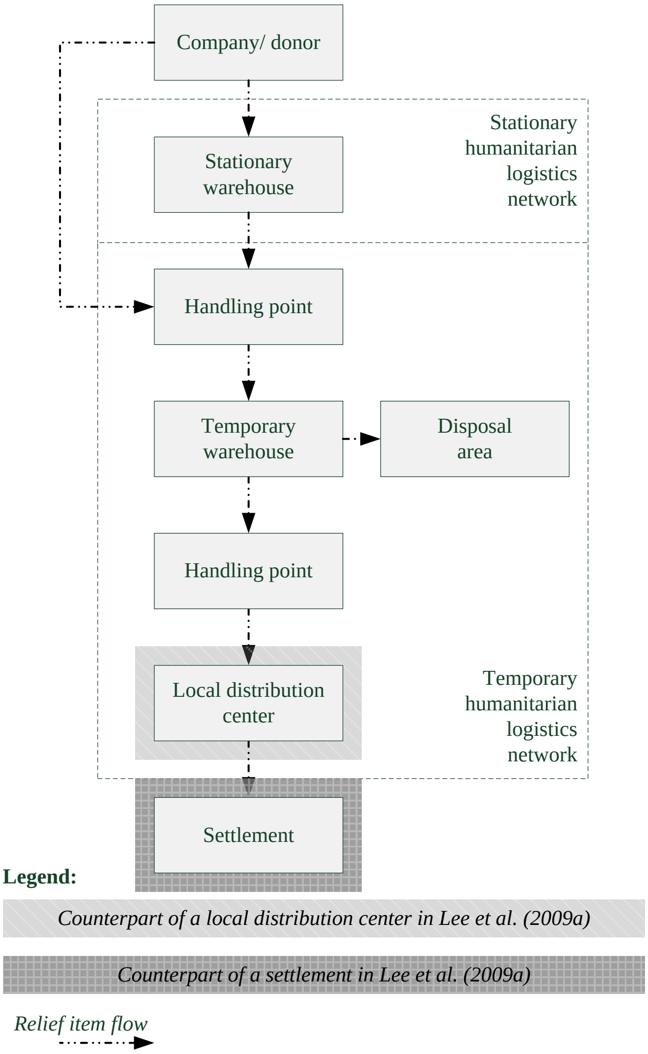


Figure 4.13. Counterparts of the facilities/ locations defined in Lee et al. (2009a) in the reference structure for humanitarian logistics networks

When setting up the system of LDCs, the humanitarian organization takes into account three crucial dimensions in order to identify the most advantageous configuration. On the one hand, the configuration's input – the amount of distribution resources – represents one crucial dimension. The number of opened LDCs is the corresponding utilization metric. On the other hand, the configuration's outputs – the delivered relief item quantity and the beneficiaries' distance to LDCs – are crucial dimensions. The dimension *distance to LDCs* is captured by the distances of the arcs used by beneficiaries, which is an effectiveness metric. The dimension *delivered relief item quantity* is captured by the assignments of populations to LDCs during the disaster response, which is also an effectiveness metric. The mathematical program's expressions for these metrics are outlined in Table 4.7. To determine the values of the metric for the dimension *distance to LDCs*, a distance has to be defined that beneficiaries are able to overcome at the maximum. Moreover, the duration of the disaster response has to be defined. The program's parameters for these bounds are outlined in Table 4.7. The planned duration of the disaster response is implicitly represented by the parameter describing the available distribution capacity at a location.

The humanitarian organization intends to minimize the number of LDCs, to limit the distances between beneficiaries and LDCs, and to ensure a certain quantity of delivered relief items. Moreover, the organization intends to ensure a minimum number of LDCs – at least two – in event that one LDC cannot be used. The parts of the mathematical program which represent these objectives and requirements are outlined in Table 4.7. Generally speaking, maximizing the efficiency of a system of LDCs is the overarching objective of the problem captured in the OR model of Lee et al. (2009a).

Table 4.7. Problem structuring scheme for Lee et al. (2009a)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Settlements	Coordinates	Parameter d_{mn}
			Relief item demand	Parameter Ppl_m
		Arcs	Start location	Parameter d_{mn}
			End location	Parameter d_{mn}
			Distance	Parameter d_{mn}
		Beneficiaries	Relief items transferred on arcs (DV)	Variable y_{mn}
Humanitarian organization	*Logistics resources and relief items*	LDCs	Located at settlement (DV)	Variable y_m
			Relief items distributed (DV)	Variable y_{mn}
		Aid workers/ equipment types	Working time	Parameter $CapB_m$
			Numbers/ amounts at settlements	Parameter $CapB_m$
		Relief item	Time for distribution	Parameter $CapB_m$
	Use and interaction of logistics resources, relief items, and elements in environment	Availability of distribution equipment and aid workers, the working time of workers and equipment, and the distribution time per relief item restrict the number of relief items to be distributed at a LDC		Constraint set 4.44
		Relief item demand of a location can only be assigned as a whole to one LDC; this has to be realized by notifying a settlement's population of its LDC		Constraint set 4.43

Key dimensions, metrics, objectives, and requirements	Input	Distribution resources: number of LDCs	Expression $\sum_{m \in M} y_m$
	Outputs	Delivered relief item quantity: assignments of beneficiaries to LDCs	Expressions $y_{mn} Ppl_n$
		Distance to LDCs: distances of arcs used by beneficiaries to reach LDCs	Expressions $d_{mn} y_{mn}$
	Objectives and requirements	Minimizing number of distribution resources	Objective function 4.40
		Ensuring number of LDCs	Constraint 4.41
		Limiting distance to LDCs	Constraint set 4.42
		Ensuring delivered relief item quantity	Constraint set 4.43
	Bounds	Upper distance limit	Parameter dMx
		Planned duration of disaster response	Parameter $CapB_m$

Program code

Below is a possible translation into program code of one of the two OR models (the one specifying the locations of LDCs) presented in Lee et al. (2009a), using the OPL language. This language is frequently used to code a MILP such as the one of Lee et al. (2009a). MILPs coded in this language can be automatically solved with the CPLEX solver.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Lee et al. (2009a)
 * Creation Date: 28.01.2015 at 17:24:55
 *********************************************/
{string} Settlements = ...;
float Population[Settlements] = ...;
float Capacity[Settlements] = ...;
float Distance[Settlements,Settlements] = ...;
float UpperDistanceLimit = ...;
dvar boolean Open[Settlements];
dvar boolean
SettlementAssignedToSettlementWithLDC[Settlements,Settlements];

minimize
sum (m in Settlements)
Open[m];

subject to{
ct41:
sum (m in Settlements)
Open[m]
>= 2;

ct42:
forall(m in Settlements, n in Settlements)
SettlementAssignedToSettlementWithLDC[m,n] * Distance[m,n]
<= Open[m] * UpperDistanceLimit;

ct43:
forall(n in Settlements)
sum (m in Settlements)
SettlementAssignedToSettlementWithLDC[m,n]
== 1;
```

```
ct44:
forall(m in Settlements)
sum (n in Settlements)
SettlementAssignedToSettlementWithLDC[m,n] * Population[n]
<= Open[m] * Capacity[m];
}
```

4.2.3 Mathematical program of Murali et al. (2012) for supporting decisions about the locations of local distribution centers

This section comprises the profile of a mathematical program developed by Murali et al. (2012) and presented in their publication with the title “Facility location under demand uncertainty: Response to a large-scale bio-terror attack”. The mathematical program supports the specification of LDCs in response to a disaster. On a functional level, the program can be characterized as a facility location model. The program can also be defined as a MILP because of the use of real-valued flow variables together with binary location variables.

In the following, the profile of this OR model is described. The profile includes the mathematical formulation, a description of the underlying problem, and a possible translation of the mathematical formulation into program code. Names of sets, parameters, and variables in the present notation of the mathematical formulation differ from the original notation in order to achieve a consistent notation within the toolkit. Murali et al. (2012) present a unique solution algorithm for their program. How this algorithm works is described in their publication.

Mathematical formulation

Murali et al. (2012) present two versions of their program: a deterministic and a stochastic formulation. In the following, the deterministic variant is presented. The program’s objective function (4.46) maximizes the number of relief items distributed among the beneficiaries, which are located in settlements. Constraint (4.47) ensures that a certain number of LDCs is opened. Constraint set (4.48) limits the amount of relief items to be distributed at a LDC to the amount of relief items allocated to this LDC and constraint set (4.49) ensures that a center cannot distribute more relief items than the location-specific capacity allows. Constraint (4.50) limits the overall amount of relief items that can be distributed to the total available amount of relief items. Constraint set (4.51) stipulates that at most a certain share of a settlement’s demand for relief items can be satisfied from LDCs located within a certain distance range from the settlement. Constraint set (4.52) ensures that if a LDC’s location is too far away from a settlement’s location, it cannot be used to satisfy the settlement’s demand. Constraint set (4.53) ensures that not more relief items can be distributed to a settlement than its actual demand for relief items. Finally, constraint set (4.54) defines the binary location variables and constraint set (4.55) ensures non-negativity of the real-valued flow variables.

Sets:

A	Coverage levels
B	Set of settlements
M	Set of locations where LDCs can be erected

Parameters:

$CapD_m$	Capacity available to distribute relief items at location m where a LDC can be erected
d_{bm}	Distance between location b and location m
dmd_b	Units of relief items demanded at location b
dMx_a	Upper distance limit of coverage level a
Nf	Number of facilities to be erected
shr_a	Maximum percentage of relief item demand at a settlement to be satisfied from LDCs providing coverage level a
spl	Units of relief items available

Variables:

x^{c}_{bm}	Relief items collected (c) from a LDC at location m by beneficiaries from settlement b
x^{t}_{m}	Relief items transferred (t) to LDC at location m
y_m	1 if a LDC is located at location m, 0 otherwise

MILP:

(4.46) Maximize

$$\sum_{b \in B} \sum_{m \in M} x^{\mathrm{c}}_{bm}$$

s.t. (4.47) $\sum_{m \in M} y_m = Nf$

(4.48) $\sum_{b \in B} x^{\mathrm{c}}_{bm} \le x^{\mathrm{t}}_m \qquad \forall m \in M$

(4.49) $x^{\mathrm{t}}_m \le CapD_m y_m \qquad \forall m \in M$

(4.50) $\sum_{m \in M} x^{\mathrm{t}}_m \le Spl$

(4.51) $\sum_{m | dMx_{a-1} < d_{bm} \le dMx_a} x^{\mathrm{c}}_{bm} \le shr_a dmd_b \qquad \forall a \in A, b \in B$

(4.52) $\sum_{m | d_{bm} > dMx_A} x^{\mathrm{c}}_{bm} = 0 \qquad \forall b \in B$

(4.53) $\sum_{m \in M} x^{\mathrm{c}}_{bm} \le dmd_b \qquad \forall b \in B$

(4.54) $y_m \in \{0,1\} \qquad \forall m \in M$

(4.55) $x^{\mathrm{t}}_m, x^{\mathrm{c}}_{bm} \ge 0 \qquad \forall b \in B, m \in M$

Problem structure

In this sub-section, the problem as captured in the OR model of Murali et al. (2012) is characterized based on the structuring scheme outlined in section 3.4. Accordingly, the disaster environment and the humanitarian organization, which is responsible for the humanitarian logistics network in this environment, are analyzed in detail. The results of the problem structuring process are outlined in Table 4.8 (pp. 119f).

The disaster environment is single-organizational and consists of locations and unidirectional arcs. Locations can either host LDCs or settlements. Locations for LDCs are characterized by coordinates. Settlements are characterized by coordinates and demands for relief items. Unidirectional arcs connect the settlements with the locations for LDCs. Each arc is specified by a start, an end, and a distance. All these attributes of the elements in the environment are defined as being static and deterministic; and these attributes are explicitly or implicitly represented by parameters in the mathematical program. Coordinates of locations are implicitly represented by the parameters describing the distances between two locations (because to calculate distances these coordinates have to be known). Beneficiaries live in settlements and are characterized by the flows of relief items they may realize on specific arcs between settlements and LDCs. The magnitudes of these flows are to be determined in the decision problem. They are implicitly represented in the mathematical program by continuous variables that describe the assignments of relief items to settlements.

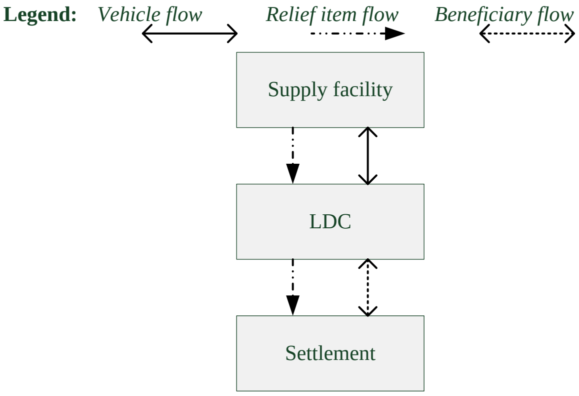


Figure 4.14. Simple example of the humanitarian logistics network in the OR model of Murali et al. (2012)

The humanitarian organization has certain inputs available to set up a humanitarian logistics network within the environment: a supply facility, LDCs, transportation vehicles, aid workers/ distribution equipment, and relief items. Transportation vehicles realize the relief item flows from the supply facility to the LDCs. In Figure 4.14, a simple example of the humanitarian logistics network is presented. The supply facility could have different counterparts in a real-world humanitarian logistics network; in fact, a supply facility could be a handling point, a temporary warehouse, or a stationary warehouse. In any case, it is a facility located upstream from LDCs. Possible counterparts for the supply facility as defined in the model of Murali et al. (2012) are highlighted in Figure 4.15 (p. 117) using the reference structure for humanitarian logistics networks as described in section 2.1. Settlements and LDCs as defined in Murali et al. (2012) have distinct counterparts in this reference structure.

The supply facility is solely characterized by an amount of available relief items. LDCs are characterized by their locations and the amounts of distributed relief items. Transportation vehicles are specified by the amounts of relief items transferred between the supply facility and opened LDCs. Each type of aid worker/ distribution equipment is specified by a working time and the numbers of aid workers/ the amounts of equipment at certain locations for LDCs. The relief item type is specified by a distribution time per unit. The supply facility's relief item stock, the characteristics of the aid workers/ distribution equipment, and the characteristics of the relief item type are assumed to be already known by the humanitarian organization. These values are explicitly or implicitly represented by parameters in the mathematical program. The distribution time per relief item and the characteristics of the available aid workers/ distribution equipment are implicitly represented by the parameters describing the potential distribution capacities of locations.

Furthermore, it is assumed that the humanitarian organization decides about the locations of LDCs, the magnitudes of relief items flows from the supply facility to LDCs, and the quantities of distributed relief items. These values are implicitly or explicitly represented by decision variables. The quantities of transferred and distributed relief items can be derived from variables describing the relief item flows to LDCs. Locations of LDCs can be chosen out of a discrete set whereas the values of transferred and distributed relief items are positive real numbers. Therefore, the number of solutions to the problem is continuous. The program's variables and parameters representing the attributes of logistics resources and relief items are outlined in Table 4.8.

The humanitarian organization has to adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements in the environment. The following relationships are known:

- The available relief items at the supply facility determine the amount of relief items that can be allocated to LDCs.
- The availability of aid workers/ distribution equipment at a location where a LDC can be opened, the working time of aid workers/ equipment together with the distribution time per relief item limit the amount of relief items that can be allocated to a LDC.
- The amount of received relief items at a LDC limits the amount of relief items that can be distributed at a LDC among beneficiaries.
- Beneficiaries do not collect more relief items from LDCs than they need.

In the mathematical program, the allowed use and interaction between logistics resources, relief items, and elements in the environment are represented by constraints. These constraints are outlined in Table 4.8.

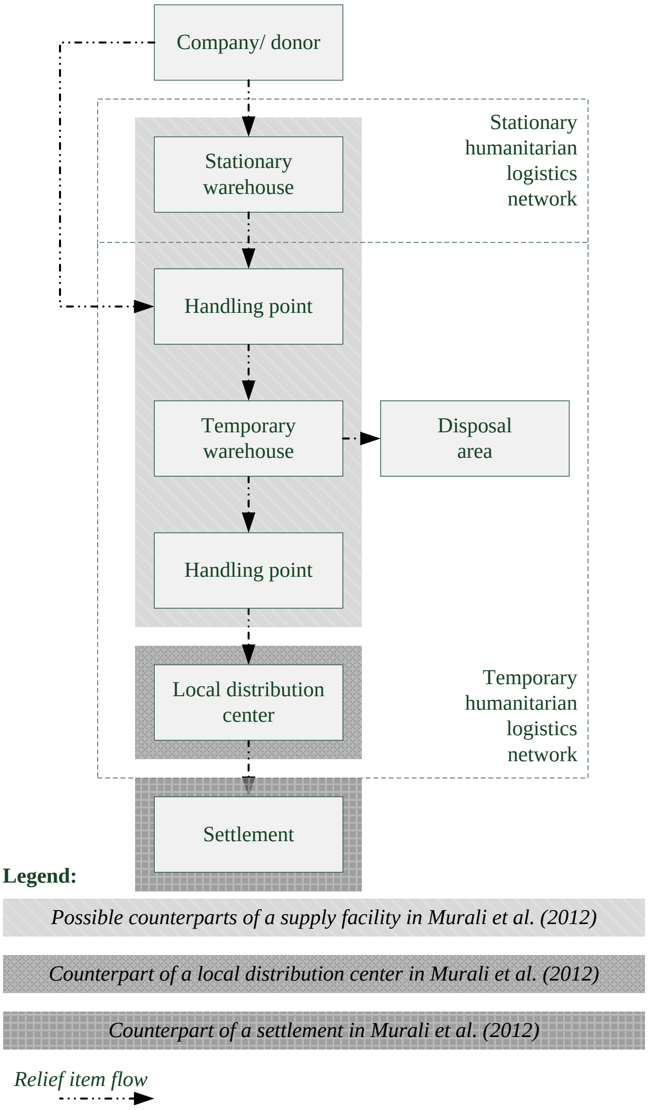


Figure 4.15. Counterparts of the facilities/ locations defined in Murali et al. (2012) in the reference structure for humanitarian logistics networks

When setting up a system of LDCs, the humanitarian organization takes into account several key dimensions in order to identify the most advantageous configuration. On the one hand, a configuration's input, the amount of distribution resources, represents a key dimension. It is measured by the number of opened LDCs. This value belongs to the class of utilization metrics. On the other hand, the outputs of the humanitarian logistics network – the delivered relief item quantity and the distances between beneficiaries and LDCs – represent key dimensions. The amount of distributed relief items during the disaster response is an effectiveness metric and captures the dimension *relief item quantity*. Distances between settlements and LDCs are converted into coverage levels. The amount of relief items that can be collected from LDCs providing a certain coverage level for a settlement is a metric that also belongs to the class of effectiveness metrics and captures the dimension *distances to LDCs*. The mathematical program's expressions for these metrics are outlined in Table 4.8. The following bounds and factors have to be defined to determine the values of metrics: the planned duration of the disaster response, the maximum number of LDCs to be erected, upper distance limit of a coverage level, and the maximum percentage of relief item demand at a settlement to be satisfied from LDCs that provide a certain coverage level. The parameters which represent bounds and factors are outlined in Table 4.8. The planned duration of the disaster response is implicitly represented by the parameter describing the capacity at a potential LDC location.

It is assumed that the organization limits the number of LDCs while ensuring a certain number of centers. Moreover, the organization maximizes the amount of distributed relief items and limits the distances between beneficiaries and LDCs. The parts of the mathematical program which represent these objectives and requirements are outlined in Table 4.8. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective in the decision problem that is captured in the OR model of Murali et al. (2012).

Table 4.8. Problem structuring scheme for Murali et al. (2012)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Locations for LDCs	Coordinates	Parameter d_{bm}
		Settlements	Coordinates	Parameter d_{bm}
			Relief item demand	Parameter dmd_b
		Arcs	Start location	Parameter d_{bm}
			End location	Parameter d_{bm}
			Distance	Parameter d_{bm}
		Beneficiaries	Relief items transferred on arcs (CV)	Variable x_{bm}^{c}
Humanitarian organization	*Logistics resources and relief items*	Supply facility	Relief items stocked	Parameter spl
		LDCs	Location (DV)	Variable y_m
			Relief items distributed (CV)	Variable x_m^{t}
		Transportation resource	Relief items transferred (CV)	Variable x_m^{t}
		Aid workers/ equipment types	Working time	Parameter $CapD_m$
			Number/ amount at locations for a LDC	Parameter $CapD_m$
		Relief item	Time for distribution	Parameter $CapD_m$
	Use and interaction of logistics resources, relief items, and elements in en-	Available relief items at the supply facility determine the amount of relief items that can be allocated to LDCs		Constraint 4.50
		Available aid workers/ equipment at a location, working time of aid workers/ equipment, and distribution time per relief item limit		Constraint set 4.49

vironment	the amount of relief items that can be allocated to a LDC		
	Amount of received relief items at a LDC limits the amount of relief items that can be distributed at a LDC among beneficiaries		Constraint set 4.48
	Beneficiaries do not collect more relief items from LDCs than they need.		Constraint set 4.53
Key dimensions, metrics, objectives, and requirements	Input	Distribution resources: number of LDCs	Expression $\sum_{m \in M} y_m$
	Outputs	Delivered relief item quantity: amount of allocated relief items	Expression $\sum_{b \in B} \sum_{m \in M} x^{\mathrm{c}}_{bm}$
		Distance to LDCs: amount of relief items allocated to LDCs that provide a certain coverage level for a settlement	Expression $\sum_{m \mid dMx_{a-1} < d_{bm} \leq dMx_a} x^{\mathrm{c}}_{bm}$
	Objectives and requirements	Limiting number of distribution resources	Constraint 4.47
		Ensuring number of distribution resources	Constraint 4.47
		Maximizing delivered relief item quantity	Objective function 4.46
		Limiting distance to LDCs	Constraint sets 4.51, 4.52
	Factors and bounds	Planned duration of disaster response	Parameter $CapD_m$
		Number of LDCs to be erected	Parameter Nf
		Upper distance limit per coverage level	Parameter dMx_a
		Maximum percentage of demand at a settlement that can be satisfied from LDCs that provide a certain coverage level	Parameter shr_a

Program code

Below is a possible translation of the mathematical formulation into a program code using the OPL language. This language is frequently used to code a MILP such as the one of Murali et al. (2012). A MILP coded in this language can be solved automatically with the CPLEX solver. In the mathematical formulation, a coverage level is only described by an upper distance limit whereas in the program code below a coverage level is described explicitly by an upper and lower distance limit. Before the MILP is executed, several sets are created for each settlement. Each set comprises all those locations for LDCs which can supply a specific settlement within the distance limits of a specific coverage level. Therefore the number of sets per settlement depends on the number of coverage levels. These sets are built by the execute function in the OPL formulation. Also in the execute function, one set of LDC locations is built for each settlement that contains all those LDC locations which provide no sufficient coverage for a settlement.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Murali et al. (2012)
 * Creation Date: 29.01.2015 at 15:05:08
 *********************************************/
{string} CoverageLevels = ...;
{string} Settlements = ...;
{string} LocationsForLDCs = ...;
{string} LocationsForLDCProvidingCoverageLevels
[Settlements,CoverageLevels];
{string} LocationsForLDCProvidingNoCoverageLevel[Settlements];
float Capacity[LocationsForLDCs] = ...;
float Distance[LocationsForLDCs,Settlements] = ...;
float Demand[Settlements] = ...;
float NumberLDCs = ...;
float LowerDistanceLimit[CoverageLevels] = ...;
float UpperDistanceLimit[CoverageLevels] = ...;
float DemandShare[CoverageLevels] = ...;
float Supply = ...;
dvar float+ Collected[LocationsForLDCs,Settlements];
dvar float+ Transferred[LocationsForLDCs];
dvar boolean Open[LocationsForLDCs];

execute {
 for (var b in Settlements) {
  for (var a in CoverageLevels) {
   for (var m in LocationsForLDCs) {
```

```
        if (LowerDistanceLimit[a] < Distance[m][b] &&
        UpperDistanceLimit[a] >= Distance[m][b]) {
        LocationsForLDCProvidingCoverageLevels[b][a].add(m)
    }
   }
  }
 }
 var MaximumDistance = 0
 for (var a in CoverageLevels) {
  if (UpperDistanceLimit[a] >= MaximumDistance) {
      MaximumDistance = UpperDistanceLimit[a]
  }
 }
 for (var b in Settlements) {
  for (var m in LocationsForLDCs) {
   if (Distance[m][b] > MaximumDistance) {
   LocationsForLDCProvidingNoCoverageLevel[b].add(m)
   }
  }
 }
}

maximize
sum (m in LocationsForLDCs, b in Settlements)
Collected[m,b];

subject to{
ct47:
sum (m in LocationsForLDCs)
Open[m]
== NumberLDCs;

ct48:
forall(m in LocationsForLDCs)
sum (b in Settlements)
Collected[m,b]
<= Transferred[m];

ct49:
forall(m in LocationsForLDCs)
Transferred[m]
<= Capacity[m] * Open[m];

ct50:
```

```
sum (m in LocationsForLDCs)
Transferred[m]
<= Supply;

ct51:
forall(b in Settlements, a in CoverageLevels)
sum (m in LocationsForLDCProvidingCoverageLevels[b,a])
Collected[m,b]
<= DemandShare[a] * Demand[b];

ct52:
forall(b in Settlements)
sum (m in LocationsForLDCProvidingNoCoverageLevel[b])
Collected[m,b]
== 0;

ct53:
forall(b in Settlements)
sum (m in LocationsForLDCs)
Collected[m,b]
<= Demand[b];
}
```

4.3 Transport specification toolkit

The distances between the different nodes of a humanitarian logistics network, i.e. stationary warehouses, temporary warehouses, handling points, and LDCs, are overcome by transportation vehicles. Generally speaking, transportation activities realize the flow of relief items (represented by the arcs in Figure 4.16) and are characterized by the used mode of transportation, the number of vehicles of a certain type and mode, and the vehicles' loads, routes, schedules, and drivers.

For example, the Logistics Cluster, lead by the WFP, has – in response to the Ebola outbreak that started in 2014 – facilitated the transportation of over 9,000 m³ of cargo in Guinea, over 21,000 m³ of cargo in Liberia, and over 10,000 m³ of cargo in Sierra Leone (WFP, 2015). This includes air as well as road transportation, e.g. the transportation of two truckloads of relief items from Conakry to Nzerekore on behalf of the Government of Guinea's Ebola response unit in September 2014 (Logistics Cluster, 2014). A second example, again for the transportation activities of the Logistics Cluster, is the transportation of seven truckloads from Maputo to Quelimane, Namacurra, Morrumbala, Nicoadala, and Mopeia in response to floods in Mozambique in February 2015. Moreover, a helicopter transported relief items to various locations in the affected regions of Mozambique

(Logistics Cluster, 2015). The WFP operates its own airline (the UN Humanitarian Air Service) with a fleet of 50 aircrafts including helicopters (WFP, 2015).

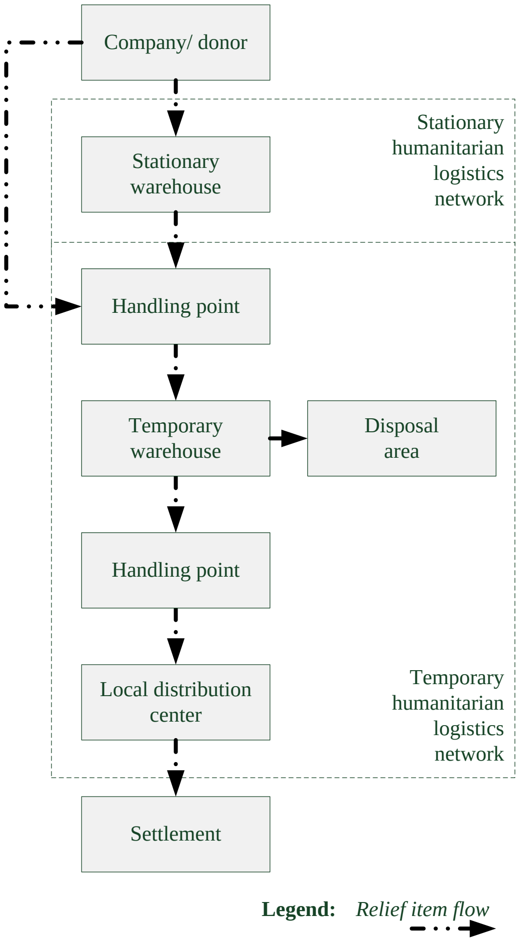


Figure 4.16. Transportation activities realizing relief item flows within a humanitarian logistics network

Published OR models which can support a humanitarian organization specifying modes, types, numbers, loads, routes/ used arcs, schedules, and drivers of transportation vehicles are only based on mathematical programming (see section 3.3). Table 4.9 may assist users of the toolkit to choose the most appropriate of the three currently included OR models (Balcik et al., 2008; Özdamar et al., 2004; Vitoriano et al., 2011). The section on the left in Table 4.9 may help to identify the most appropriate model based on the attributes of transportation activities the user wants to specify; and the section on the right may help users to identify the most appropriate model based on the used key dimensions, objectives, targets, and requirements. For example, the model of Özdamar et al. (2004) supports decisions about the modes and types of transportation vehicles in transportation activities and about the amounts of relief items transferred by specific types of transportation vehicles over certain arcs. These decisions are made so that the delivered relief item quantity is maximized while the input of transportation resources is limited.

Table 4.9. Guide for the transport specification toolkit

	Attributes of transportation activity				Key dimensions, objectives, and requirements			
OR model	Modes of transportation	Vehicle types	Loads	Routes/ used arcs	Transportation resources	Delivered relief item quantity	Delivery time	Workforce safety & security
Balcik et al. (2008)			■	■	O	O, R	O	
Özdamar et al. (2004)	■	■	■	■	R	O		
Vitoriano et al. (2011)		■	■	■	R, T	R, T, T	T	T, T, T, T

■: to be specified, O: objective, R: requirement, T: target

4.3.1 Mathematical program of Balcik et al. (2008) for supporting decisions about the routes and loads of transportation vehicles

Balcik et al. (2008), in their publication entitled “Last Mile Distribution in Humanitarian Relief”, present a mathematical program supporting the specification of transportation activities in response to a disaster. On a functional level, the program can be characterized as a model for transportation planning; more exactly, the program can be identified as a model using the route enumeration approach (Özdamar and Alp Ertem, 2015). The program can also be characterized as a MILP because of the use of binary together with real-valued variables.

This section comprises the profile of this mathematical program. The profile includes a description of the mathematical formulation, a description of the underlying problem’s structure, and a possible translation of the mathematical formulation into program code. Names of sets, parameters, and variables in the present notation of the mathematical formulation differ from the original notation in order to achieve a consistent notation within the toolkit.

Mathematical formulation

The program’s objective function (4.56) minimizes both the total costs that come with the assignments of transportation vehicles to routes and the sum of maximum shortage costs. Maximum shortage costs are calculated for each time period and relief item type in constraint set (4.57). Unfulfilled demands at LDCs are calculated in the constraint set (4.58) and (4.59). Balcik et al. (2008) distinguish between two types of relief items. Demands for the first type of relief item occur only at the beginning of the time horizon. They are immediately distributed after they arrive at a LDC. In contrast, demands for the second type of relief item occur at the beginning of each time period. Hence, they can either be distributed after they arrive at a LDC or stocked for coming time periods. The amounts of distributed and stocked relief items of the second type at the LDCs are calculated in constraint set (4.59). Constraint set (4.60) ensures that the entire demand for the first type of relief item is satisfied until the end of the planning horizon. Constraint set (4.61) prohibits the supply facility to distribute more relief items during a time period than there are relief items available at the beginning of the time period. Constraint set (4.62) determines that the maximum load of a transportation vehicle limits the amount of relief items that can be distributed on a route. Constraint set (4.63) limits the number of routes that can be executed by a transportation vehicle during one time period. Constraint set (4.64) defines the lower and upper bound for the variables describing the percentages of unfulfilled demands at LDCs for each relief item type and time period. Constraint set (4.65) ensures that the relief item stocks of LDCs are zero at the beginning of the time horizon. Finally, constraint sets (4.66), (4.67), and (4.68) define the binary assignment variables as well as the non-negativity of the real-valued variables.

Sets:

M	Set of locations where LDCs are erected
R	Set of relief item types; R = {1,2}
T	Set of time periods
Ψ	Set of transportation vehicles
Θ	Set of routes
M_{ϑ}	Set of locations visited on route ϑ

Parameters:

$c^{\mathrm{d}}_{\psi\vartheta}$	Costs for driving (d) the transportation vehicle ψ on route ϑ
c^{u}_{mrt}	Costs for a unit of unsatisfied (u) demand for relief item type *r* at location *m* in time period *t*
Ld_{ψ}	Maximum load of transportation vehicle ψ
dmd_{mr}	Units of relief item type *r* demanded at location *m*
dmd_{mrt}	Units of relief item type *r* demanded at location *m* in time period *t*
spl_{rt}	Units of relief item type *r* available at the beginning of time period *t*
$t^{\mathrm{t}}_{\psi\vartheta}$	Time for transferring (t) relief items on route ϑ using transportation vehicle ψ

Variables:

$MxSC_{rt}$	Maximum shortage costs due to unsatisfied demand for relief item type *r* in time period *t*
x^{p}_{mrt}	Relief items of type *r* prepositioned (p) in LDC at location *m* in time period *t*
$x^{\mathrm{t}}_{\psi\vartheta mrt}$	Relief items of type *r* transferred (t) by transportation vehicle ψ on route ϑ to LDC at location *m* in time period *t*
$y_{\psi\vartheta t}$	1 if transportation vehicle ψ uses route ϑ in time period *t*, 0 otherwise
β_{mrt}	Percentage of demand for relief item type *r* unsatisfied at location *m* in time period *t*

MILP:

(4.56) Minimize

$$\sum_{\psi\in\Psi}\sum_{\vartheta\in\Theta}\sum_{t\in T} c^{\mathrm{d}}_{\psi\vartheta} y_{\psi\vartheta t} + \sum_{r\in R}\sum_{t\in T} MxSC_{rt}$$

s.t. (4.57) $MxSC_{rt} \geq c^{\mathrm{u}}_{mrt}\beta_{mrt} \qquad \forall m\in M, r\in R, t\in T$

$$(4.58)\ \beta_{mrt} = \frac{(dmd_{mr} - \sum_{\vartheta|m\in M_{\vartheta}}\sum_{t'=1}^{t}\sum_{\psi\in\Psi} x^{\mathrm{t}}_{\psi\vartheta mrt'})}{dmd_{mr}} \qquad \forall m\in M, r=1, t\in T$$

$$(4.59)\ \beta_{mrt} = \frac{(dmd_{mrt} + x^{\mathrm{p}}_{mr,t+1} - \sum_{\vartheta|m\in M_{\vartheta}}\sum_{\psi\in\Psi} x^{\mathrm{t}}_{\psi\vartheta mrt} - x^{\mathrm{p}}_{mrt})}{dmd_{mrt}} \qquad \forall m\in M, r=2, t\in T$$

$$(4.60)\ \sum_{\vartheta|m\in M_{\vartheta}}\sum_{\psi\in\Psi}\sum_{t\in T} x^{\mathrm{t}}_{\psi\vartheta mrt} \geq dmd_{mr} \qquad \forall m\in M, r=1$$

$$(4.61)\ \sum_{\vartheta\in\Theta}\sum_{m\in M_{\vartheta}}\sum_{\psi\in\Psi}\sum_{t'=1}^{t} x^{\mathrm{t}}_{\psi\vartheta mrt'} \leq \sum_{t'=1}^{t} spl_{rt'} \qquad \forall r\in R, t\in T$$

$$(4.62)\ \sum_{m\in M_{\vartheta}}\sum_{r\in R} x^{\mathrm{t}}_{\psi\vartheta mrt} \leq Ld_{\psi}\, y_{\psi\vartheta t} \qquad \forall t\in T, \psi\in\Psi, \vartheta\in\Theta$$

$$(4.63)\ \sum_{\vartheta\in\Theta} t_{\psi\vartheta} y_{\psi\vartheta t} \leq 1 \qquad \forall t\in T, \psi\in\Psi$$

(4.64) $0 \leq \beta_{mrt} \leq 1 \qquad \forall m\in M, r\in R, t\in T$

(4.65) $x^{\mathrm{p}}_{mrt} = 0 \qquad \forall m\in M, r=1, t=1$

(4.66) $x^{\mathrm{p}}_{mrt} \geq 0 \qquad \forall m\in M, r=1, t\in T$

$$(4.67)\ x^{t}_{\psi\vartheta mrt} \geq 0 \qquad \forall m \in M, r \in R, t \in T, \psi \in \Psi, \vartheta \in \Theta$$

$$(4.68)\ y_{\psi\vartheta t} \in \{0,1\} \qquad \forall t \in T, \psi \in \Psi, \vartheta \in \Theta$$

Problem structure

In this sub-section, the problem as captured in the OR model of Balcik et al. (2008) will be described based on the problem structuring scheme outlined in section 3.4. Firstly, the disaster environment is described. Secondly, the humanitarian organization, which is responsible for the logistics network in the disaster environment, is characterized. The results of the problem structuring process are outlined in Table 4.10 (pp.133ff).

The environment is single-organizational and contains two types of locations: locations for supply facilities and locations for LDCs. All locations are characterized by coordinates. Moreover, locations for LDCs are characterized by demands for certain types of relief items. Each route is characterized by a start location, a final location, the locations in between, a distance, and speed limitations. The attributes of the environmental elements are defined as static and deterministic. They are explicitly or implicitly represented by parameters in the mathematical program. Coordinates of locations, distances of routes, and speed limitations on routes are implicitly represented by the parameters describing the transportation times of certain routes. The parameters which describe attributes of the environmental elements are outlined in Table 4.10.

The available inputs of the humanitarian organization are: one supply facility, LDCs, two types of relief items, and transportation vehicles. In Figure 4.17, a simple example of the humanitarian logistics network is presented.

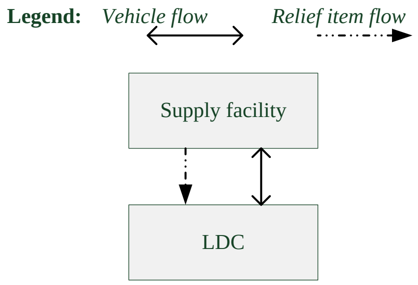


Figure 4.17. Simple example of the humanitarian logistics network in the OR model of Balcik et al. (2008)

The supply facility could have different counterparts in a real-world humanitarian logistics network; in fact, a supply facility could represent a stationary warehouse, a handling point, or a temporary warehouse. In any case, a supply facility is a facility located upstream from LDCs. Possible counterparts of a supply facility as defined in the model of Balcik et al. (2008) in the reference structure for humanitarian logistics networks (which was described in section 2.1) are highlighted in Figure 4.18. A LDC as defined in Balcik et al. (2008) has a distinct counterpart in this reference structure.

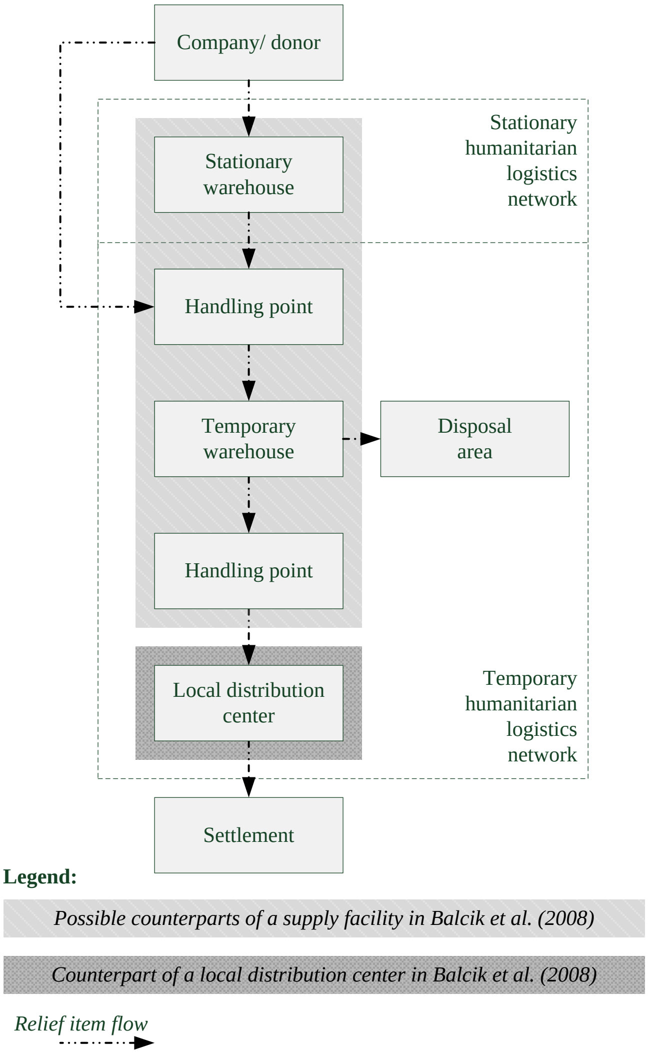


Figure 4.18. Counterparts of the facilities defined in Balcik et al. (2008) in the reference structure for humanitarian logistics networks

The supply facility is defined by the location it is assigned to, amounts of available relief items, and numbers of processed transportation vehicles. Each LDC is defined by the dedicated location it is assigned to, amounts of distributed relief items, amounts of stocked relief items, and numbers of processed transportation vehicles. Each transportation vehicle is characterized by its available transport volume and weight, its speed of travel, and the loads of relief items it transfers on certain routes. Each type of relief item is characterized by a volume and weight per unit. The amount of available relief items at the supply facility together with the transport volume, weight, and speed of a transportation vehicle are assumed to be already known by the humanitarian organization. The same is true for the weight and volume per unit of a relief item type. These attributes can be defined as static and deterministic and are – explicitly or implicitly – represented by parameters in the mathematical program. The speeds of transportation vehicles are implicitly represented by the parameters that describe the transportation times on routes, while the transport volume and weight per vehicle and the volume and weight per unit of a relief item type are implicitly represented by the parameters that describe the maximum loads of transportation vehicles.

The humanitarian organization decides about the quantities of relief items transferred by certain transportation vehicles on certain routes, the quantities of stocked and distributed relief items at LDCs, and the numbers of processed transportation vehicles at facilities. These values are explicitly or implicitly represented by decision variables in the mathematical program. The numbers of processed transportation vehicles at facilities can be derived from variables which describe the assignments of transportation vehicles to routes. How many relief items are distributed at LDCs can be derived from the variables which describe the percentages of unfulfilled demands at LDCs. Quantities of transferred relief items are positive real-valued numbers, flows of transportation vehicles are positive integer numbers, and routes for transportation vehicles can be chosen out of a discrete set. Therefore, the number of alternative solutions to the decision problem is continuous. The parameters and variables which describe attributes of logistics resources and relief items are outlined in Table 4.10.

The humanitarian organization must adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements in the environment. The following relationships are known to the organization:

- The amount of relief items that can be sent from the supply facility to the LDCs during a time period is limited to the supply facility's relief item stocks.
- Relief items can either be necessary once per time horizon or several times per time horizon; if they are necessary several times per time-horizon it is possible to stock them in the LDCs.
- There are no relief item stocks in the LDCs at the beginning of the time-horizon.
- The amount of relief items that can be distributed by a transportation vehicle depends on the vehicle's transport volume and weight and the volume and weight per relief item unit.
- The number of routes a transportation vehicle can perform per time period depends on the distances of routes, the routes' speed limitations, and the travel speed of the transportation vehicle.

In the mathematical program, the allowed use and interaction between resources, relief items, and elements in the environment are represented by constraints. The constraints that represent certain relationships are outlined in Table 4.10.

When setting up a humanitarian logistics network, the organization takes into account three critical aspects in order to identify the most advantageous network configuration. The configuration's input, the transportation resources, represents one crucial dimension. It is captured by the transportation costs – a metric belonging to the class of utilization metrics. On the other hand, the configuration's outputs – the delivered relief item quantity and the delivery time – represent key dimensions. The dimensions *delivered relief item quantity* and *delivery time* are both captured by the maximum relief item shortage costs. This metric belongs to the class of non-discrimination metrics and is calculated for each time period and for both types of relief items. Another metric capturing the dimension *delivered relief item quantity* is the amount of relief items transferred to LDCs. This metric belongs to the class of effectiveness metrics and is calculated at the end of the operation for those relief items which are needed only once per disaster response. The program's expressions for these metrics are outlined in Table 4.10. The following factors must be defined in order to determine the values of metrics: transportation costs of a route per transportation vehicle as well as shortage costs per 1% of unsatisfied demand for a relief item type at a location in a certain time period. The parameters for these factors are outlined in Table 4.10.

The organization intends to minimize transportation costs and minimize the maximum relief item shortage costs while ensuring complete fulfillment of certain relief item demands until the end of the time horizon. More exactly, the humanitarian organization means to minimize the input of transportation resources, to maximize the minimum quantity of delivered relief items of both types, to ensure complete fulfillment of relief item demands which occur only once (at the beginning of the time horizon), and to minimize the maximum delivery times of those relief items for which demand occurs only once. The parts of the program which realize these objectives and requirements are outlined in Table 4.10. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the decision problem captured in the OR model of Balcik et al. (2008).

Table 4.10. Problem structuring scheme for Balcik et al. (2008)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Location for a supply facility	Coordinates	Parameter $t^{t}_{\psi\vartheta}$
		Locations for LDCs	Coordinates	Parameter $t^{t}_{\psi\vartheta}$
			Relief item demand	Parameter dmd_{mr} , dmd_{mrt}
		Routes	Locations	Parameter $t^{t}_{\psi\vartheta}$
			Distance	Parameter $t^{t}_{\psi\vartheta}$
			Speed limitations	Parameter $t^{t}_{\psi\vartheta}$
Humanitarian organization	*Logistics resources and relief items*	Supply facility	Location for a supply facility	Parameter $t^{t}_{\psi\vartheta}$
			Transportation vehicles processed (DV)	Variable $y_{\psi\vartheta t}$
			Relief items stocked	Parameter spl_{rt}
		LDCs	Location for a LDC	Parameter $t^{t}_{\psi\vartheta}$
			Transportation vehicles processed (DV)	Variable $y_{\psi\vartheta t}$
			Relief items stocked (CV)	Variable x^{p}_{mrt}
			Relief items distributed (CV)	Variable β_{mrt}
		Transportation vehicles	Speed of travel	Parameter $t^{t}_{\psi\vartheta}$
			Transport volume	Parameter Ld_{ψ}
			Transport weight	Parameter Ld_{ψ}
			Routes used (DV)	Variable $y_{\psi\vartheta t}$

		Relief items transferred on routes (CV)	Variable $x^{\mathrm{t}}_{\psi\vartheta mrt}$
	Relief item types	Volume	Parameter Ld_{ψ}
		Weight	Parameter Ld_{ψ}
Use and interaction of logistics resources, relief items, and elements in environment	Amount of relief items that can be sent from the supply facility to the LDCs during a time period is limited to the supply facility's relief item stocks		Constraint set 4.61
	One type of relief item is needed once, at the beginning of the time horizon; it is not necessary to stock this relief item type in LDCs		Constraint set 4.58
	One type of relief item is needed several times per time horizon; it can be necessary to stock this relief item type in LDCs		Constraint set 4.59
	Relief item stocks of LDCs are zero at the beginning of the operation		Constraint set 4.65
	Amount of relief items that can be distributed by a transportation vehicle on a route depends on the vehicle's available transport volume and weight and the volume and weight per relief item		Constraint set 4.62
	Number of routes a transportation vehicle can visit per time period depends on the distances of routes, the routes' speed limitations, and the travel speed of the transportation vehicle		Constraint set 4.63
Key dimensions, metrics, objectives, and requirements	Input	Transportation resource: Transportation costs	Expression $\sum_{\psi\in\Psi}\sum_{\vartheta\in\Theta}\sum_{t\in T} c^{\mathrm{d}}_{\psi\vartheta} y_{\psi\vartheta t}$
	Outputs	Delivered relief item quantity:	
		- Maximum relief item shortage costs	Expression $\sum_{r\in R}\sum_{t\in T} MxSC_{rt}$

		- Transferred relief items	Expression $\sum_{\vartheta \mid m \in M_{\vartheta}} \sum_{\psi \in \Psi} \sum_{t \in T} x_{\psi \vartheta mrt}^{\mathrm{t}}$
		Delivery time: Maximum relief item shortage costs	Expression $\sum_{r \in R} \sum_{t \in T} MxSC_{rt}$
	Objectives and requirements	Minimizing input	Objective function 4.56
		Maximizing minimum delivered relief item quantity	Objective function 4.56, constraint sets 4.57, 4.58, 4.59
		Minimizing maximum delivery time	Objective function 4.56, constraint sets 4.57, 4.58
		Ensuring delivered relief item quantity	Constraint set 4.60
	Factors	Costs for driving a transportation vehicle on a route	Parameter $\boldsymbol{c}_{\psi \vartheta}^{\mathrm{d}}$
		Costs per 1% of unsatisfied demand for a relief item type at a location	Parameter $\boldsymbol{c}_{mrt}^{\mathrm{u}}$

Program code

Below is a possible translation of the OR model of Balcik et al. (2008) into program code, using the OPL language. This language is frequently used to code a MILP such as the one of Balcik et al. (2008). A MILP coded in this language can be automatically solved with the CPLEX solver. Two additional sets are defined in the program code compared to the original mathematical formulation in order to make sure that more than two types of relief items can be included into the program code. The original formulation only allows for two distinct types of relief items. The formulation below allows for as many relief item types as necessary. However, each type of relief item included has to be assigned either to class RT1 (representing those relief item types which are needed once, at the beginning of a disaster response) or to class RT2 (representing those relief item types which are needed several times per disaster response). Furthermore, the program code below requires a definition of an additional time period. If, for example, the actual planning horizon has a length of five time periods, six time periods would need to be defined in the program code. This additional time period is necessary in constraint (4.59) to calculate the excess inventory in the LDCs after transportation activities have stopped. Finally, the program code requires that there is a demand for each relief item type of class RT1 at each LDC at the beginning of the planning horizon; and that there is a demand for each relief item type of class RT2 at each LDC in each time period of the planning horizon. Otherwise, constraints (4.58) and (4.59) would be infeasible due to divisions by zero.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Balcik et al. (2008)
 * Creation Date: 19.01.2015 at 17:47:46
 *********************************************/
{int} TimePeriods = ...;
{string} TransportationVehicles = ...;
{string} Routes = ...;
{string} LocationsForLDCs = ...;
{string} LocationsOnRoutes[Routes] = ...;
{string} ReliefItems = ...;
{string} ReliefItemsTypes = {"RT1","RT2"};
{string} ReliefItemsOfType[ReliefItemsTypes] = ...;
float CostForDriving[Routes,TransportationVehicles] = ...;
float CostForShortage[ReliefItems,LocationsForLDCs,TimePeriods] = ...;
float Capacity[TransportationVehicles] = ...;
float Demand[ReliefItems,LocationsForLDCs,TimePeriods] = ...;
float Supply[ReliefItems,TimePeriods] = ...;
float TransportationTime[Routes,TransportationVehicles] = ...;
```

```
dvar float+ MaximumShortageCosts[ReliefItems,TimePeriods];
dvar float+ Prepositoned[ReliefItems,LocationsForLDCs,TimePeriods];
dvar float+ Transferred
[ReliefItems,LocationsForLDCs,Routes,TimePeriods,
TransportationVehicles];
dvar boolean Routing
[Routes,TransportationVehicles,TimePeriods];
dvar float+ PercentageDemandUnsatisfied
[ReliefItems,LocationsForLDCs,TimePeriods];

minimize sum(theta in Routes, psi in TransportationVehicles, t in TimePeriods:t<card(TimePeriods))
CostForDriving[theta,psi] * Routing[theta,psi,t]
 + sum(t in TimePeriods:t<card(TimePeriods), r in ReliefItems)
MaximumShortageCosts[r,t];

subject to {
ct57:
forall (m in LocationsForLDCs, rt in ReliefItemsTypes, r in ReliefItemsOfType[rt], t in TimePeriods:t<card(TimePeriods))
MaximumShortageCosts[r,t] >=
PercentageDemandUnsatisfied[r,m,t] * CostForShortage[r,m,t];

ct58:
forall (m in LocationsForLDCs, rt in ReliefItemsTypes:rt=="RT1", r in ReliefItemsOfType[rt], t in TimePeriods:t<card(TimePeriods))
PercentageDemandUnsatisfied[r,m,t] ==
(sum (t2 in TimePeriods)
Demand[r,m,t2] -
sum (theta in Routes:m in LocationsOnRoutes[theta], tI in 1..t, psi in TransportationVehicles)
Transferred[r,m,theta,tI,psi] ) /
sum (t2 in TimePeriods)
Demand[r,m,t2];

ct59:
forall (m in LocationsForLDCs, rt in ReliefItemsTypes:rt=="RT2", r in ReliefItemsOfType[rt],t in TimePeriods:t<card(TimePeriods))
PercentageDemandUnsatisfied[r,m,t] ==
(Demand[r,m,t] +
Prepositoned[r,m,t+1] -
sum (theta in Routes:m in LocationsOnRoutes[theta], psi in TransportationVehicles) Transferred[r,m,theta,t,psi] -
```

```
Prepositoned[r,m,t]) /
Demand[r,m,t];

ct60:
forall (m in LocationsForLDCs, rt in ReliefItemsTypes:rt=="RT1", r in ReliefItemsOfType[rt])
sum (theta in Routes:m in LocationsOnRoutes[theta], psi in TransportationVehicles, t in TimePeriods:t<card(TimePeriods))
Transferred[r,m,theta,t,psi] >=
sum (t in TimePeriods:t<card(TimePeriods))
Demand[r,m,t];

ct61:
forall (r in ReliefItems, t in TimePeriods:t<card(TimePeriods))
sum (theta in Routes, m in LocationsOnRoutes[theta], tI in 1..t, psi in TransportationVehicles)
Transferred[r,m,theta,tI,psi] <=
sum (tI in 1..t)
(Supply[r,tI]);

ct62:
forall (t in TimePeriods:t<card(TimePeriods), psi in TransportationVehicles, theta in Routes)
sum (m in LocationsOnRoutes[theta], r in ReliefItems)
Transferred[r,m,theta,t,psi] <=
Capacity[psi] * Routing[theta,psi,t];

ct63:
forall (t in TimePeriods:t<card(TimePeriods), psi in TransportationVehicles)
sum (theta in Routes)
Routing[theta,psi,t] * TransportationTime[theta,psi] <= 1;

ct64:
forall (m in LocationsForLDCs, r in ReliefItems, t in TimePeriods:t<card(TimePeriods))
0 <= PercentageDemandUnsatisfied[r,m,t] <= 1;

ct65:
forall (m in LocationsForLDCs, r in ReliefItems, t in TimePeriods:t==1)
Prepositoned[r,m,t] == 0;
}
```

4.3.2 Mathematical program of Özdamar et al. (2004) for supporting decisions about the modes, types, loads, and used arcs of transportation vehicles

Özdamar et al. (2004), in their publication entitled "Emergency Logistics Planning in Natural Disasters", present a mathematical program supporting the specification of transportation activities. On a functional level, the program can be characterized as a model for transportation planning; more exactly, as a service network design model because it determines the modes and types of transportation vehicles that operate on specific arcs (SteadieSeifi et al., 2014). Moreover, the program can be defined as a MILP given the use of the integer vehicle flow variables together with the real-valued relief item flow variables.

This section comprises the profile of the mathematical program. The profile contains a description of the mathematical formulation, a description of the underlying problem's structure, and a possible translation of the mathematical formulation into program code. Names of sets, parameters, and variables in the present notation of the mathematical formulation differ from the original notation in order to achieve a consistent notation within the toolkit. Özdamar et al. (2004) present a solution algorithm for their program which can be applied if the size of the problem overwhelms commercial solvers.

Mathematical formulation

The program's objective function (4.69) minimizes the amount of unsatisfied relief item demand at demand facilities during a given planning horizon. Constraint set (4.70) comprises the flow conservation constraints for demand facilities and transshipment facilities at the beginning of each time period; these constraints state that the amount of ingoing relief items until a certain moment should be equal to the demand of this facility until that moment (in the case of a demand facility) plus the amount of outgoing relief items until that moment. If this expression does not hold for a demand facility, a certain amount of unsatisfied demand levels the equation. Constraint set (4.71) ensures that the outflow of relief items at each supply facility until a certain moment cannot be bigger than the inflow of relief items until that moment plus the amount of relief items made available at this supply facility until that moment. Constraint set (4.72) permits transportation vehicles of specific modes to use only certain arcs of the transportation network. Constraint set (4.73) ensures that relief items cannot flow between the vehicle depot and other facilities while constraint set (4.74) limits the maximum flow of relief items between two facilities at a certain moment to the overall capacity of those transportations vehicles which go over the corresponding arc at that moment. Constraint set (4.75) balances the flow of vehicles over facilities at the beginning of each time period. Hence, the number of inflowing vehicles has to be equal to the number of outflowing and idle vehicles. Constraint set (4.76) caps the number of transportation vehicles which flow through the network to the number of vehicles that has been made available up to the actual moment. Constraint set (4.77) ensures non-negativity of the integer vehicle flow variables and constraint set (4.78) ensures non-negativity of the real-valued relief item flow variables.

Sets:

G	Set of locations
O	Set of locations where supply facilities are erected
P	Set of locations where transshipment facilities are erected
Q	Set of locations where demand facilities are erected
R	Set of relief item types
T	Set of time periods
v	Location where a vehicle depot is erected
W	Set of transportation modes
Z_w	Set of transportation vehicle types defined for transportation mode w

Parameters:

big	Big number
Ld_{z_w}	Maximum load of a transportation vehicle of type z_w
ld_r	Load by a unit of relief item type r
Nv_{gz_wt}	Number of transportation vehicles of type z_w added to the fleet at location g at the beginning of time period t
$splDmd_{grt}$	Units of relief item type r available or demanded at the beginning of time period t at location g; positive for supply and negative for demand

t^{t}_{ghw}	Time for transferring (t) relief items from location *g* to location *h* using transportation mode *w*; 0 for a non-existent arc

Variables:

x^{t}_{ghrwt}	Relief items of type r transferred (t) by transportation mode *w* from location *g* to location *h* at the beginning of time period *t*
x^{u}_{grt}	Relief item demand of type *r* unsatisfied (u) at location *g* at the beginning of time period *t*
$x^{\mathrm{d}}_{ghz_wt}$	Transportation vehicles of type z_w driving (d) from location *g* to location *h* at the beginning of time period *t*
$x^{\mathrm{w}}_{gz_wt}$	Transportation vehicles of type z_w waiting (w) at location *g* at the beginning of time period *t*

MILP:

(4.69) Minimize $\sum_{g\in Q}\sum_{r\in R}\sum_{t\in T} x^{\mathrm{u}}_{grt}$

s.t. (4.70)
$$\begin{aligned}&-\sum_{h\in G}\sum_{w\in W}\sum_{t'=1}^{t} x^{\mathrm{t}}_{hgrw,t'-t^{\mathrm{t}}_{hgw}}\\ &+\sum_{h\in G}\sum_{w\in W}\sum_{t'=1}^{t} x^{\mathrm{t}}_{ghrwt'} - x^{\mathrm{u}}_{grt} = \sum_{t'=1}^{t} splDmd_{grt'}\end{aligned} \qquad \forall g\in(P\cup Q), r\in R, t\in T$$

(4.71)
$$\begin{aligned}&-\sum_{h\in G}\sum_{w\in W}\sum_{t'=1}^{t} x^{\mathrm{t}}_{hgrw,t'-t^{\mathrm{t}}_{hgw}}\\ &+\sum_{h\in G}\sum_{w\in W}\sum_{t'=1}^{t} x^{\mathrm{t}}_{ghrwt'} \le \sum_{t'=1}^{t} splDmd_{grt'}\end{aligned} \qquad \forall g\in O, r\in R, t\in T$$

(4.72) $$x^{\mathrm{d}}_{ghz_wt} \le t^{\mathrm{t}}_{ghw} big \qquad \forall g,h\in G\setminus\{v\}, t\in T, w\in W, z_w\in Z_w$$

(4.73) $$x^{\mathrm{t}}_{gvrwt} + x^{\mathrm{t}}_{vgrwt} = 0 \qquad \forall g\in G\setminus\{v\}, r\in R, t\in T, w\in W$$

$$(4.74)\quad \sum_{z_w \in Z_w} x^{\mathrm{d}}_{ghz_wt} Ld_{z_w} \geq \sum_{r \in R} ld_r x^{\mathrm{t}}_{ghrwt} \qquad \forall g,h \in G, t \in T, w \in W$$

$$(4.75)\quad \begin{aligned} &\sum_{h \in G} \sum_{t'=1}^{t} x^{\mathrm{d}}_{hgz_w,t'-t^{t}_{hgw}} - x^{\mathrm{w}}_{gz_wt} \\ &= \sum_{h \in G} \sum_{t'=1}^{t} x^{\mathrm{d}}_{ghz_wt'} \end{aligned} \qquad \forall g \in G \setminus \{v\}, t \in T, w \in W, z_w \in Z_w$$

$$(4.76)\quad \sum_{t'=1}^{t} x^{\mathrm{d}}_{vgz_wt'} \leq \sum_{t'=1}^{t} Nv_{gz_wt'} \qquad \forall g \in G \setminus \{v\}, t \in T, w \in W, z_w \in Z_w$$

$$(4.77)\quad x^{\mathrm{d}}_{ghz_wt}, x^{\mathrm{w}}_{gz_wt} \geq 0, \text{ and integer} \qquad \forall g,h \in G, t \in T, w \in W, z_w \in Z_w$$

$$(4.78)\quad x^{\mathrm{t}}_{ghrwt}, x^{\mathrm{u}}_{grt} \geq 0 \qquad \forall g,h \in G, r \in R, t \in T, w \in W$$

Problem structure

In the following, the problem as captured in the OR model of Özdamar et al. (2004) is described based on the problem structuring scheme outlined in section 3.4. Firstly, the disaster environment is characterized. Following this, the humanitarian organization, which operates in this task environment, is described. The results of the problem structuring process are outlined in Table 4.11 (pp. 147ff).

The environment, in which the humanitarian logistics network is laid out, is a single-organizational disaster environment. The environment is characterized by three types of locations: locations for supply facilities, locations for transshipment facilities, and locations for demand facilities. Bidirectional arcs connect these locations with each other. All locations are characterized by coordinates while arcs are characterized by the two locations they connect, distances, speed limitations, and their applicabilities for certain modes of transportation. These attributes are implicitly represented by the parameters in the mathematical program which describe the transportation times between locations. Furthermore, locations for demand facilities are characterized by demands for specific types of relief items. Demands for relief items are represented by negative values of particular parameters. The same parameters can also describe available relief item supplies at locations for supply facilities. In that case their values are positive. Parameters which represent attributes of elements in the environment are outlined in Table 4.11 (p. 147).

The humanitarian organization has several inputs available to set up and run a humanitarian logistics network: supply facilities, transshipment facilities, demand facilities, a vehicle depot, transportation vehicles, and relief items. In Figure 4.19, a simple example of the humanitarian logistics network is depicted.

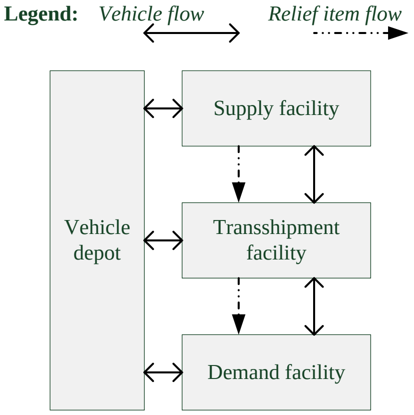


Figure 4.19. Simple example of the humanitarian logistics network in the OR model of Özdamar et al. (2004)

Supply facilities, transshipment facilities, and demand facilities could have different counterparts in a real-world humanitarian logistics network. A supply facility could represent a stationary warehouse, a handling point, or a temporary warehouse. A transshipment facility represents a facility located between stationary warehouses and LDCs. So, it could represent a handling point or a temporary warehouse. Finally, a demand facility could represent a temporary warehouse, a handling point, or a LDC. In Figure 4.20 (p. 144), the possible counterparts for supply facilities, transshipment facilities, and demand facilities are marked using the reference structure for humanitarian logistics networks as described in section 2.1. The vehicle depot defined in the OR model of Özdamar et al. (2004) has no counterpart in this reference structure.

A supply facility is defined by the location it is assigned to and the quantities of available relief items; a transshipment facility is defined by the location it is assigned to and the number of handled relief items; and a demand facility is defined by the location it is assigned to and the number of distributed relief items. The vehicle depot is characterized by the number of available transportation vehicles per mode and type. The humanitarian organization has already placed supply facilities, transshipment facilities, and demand facilities at dedicated locations. Furthermore, each type of transportation vehicle is characterized by the mode of transportation it belongs to, the available transport volume and weight per vehicle, a speed of travel, the number of vehicles on specific arcs (transportation vehicle flows), and the loads of relief items on specific arcs (relief item flows). Finally, each type of relief item is defined by a volume and weight per unit.

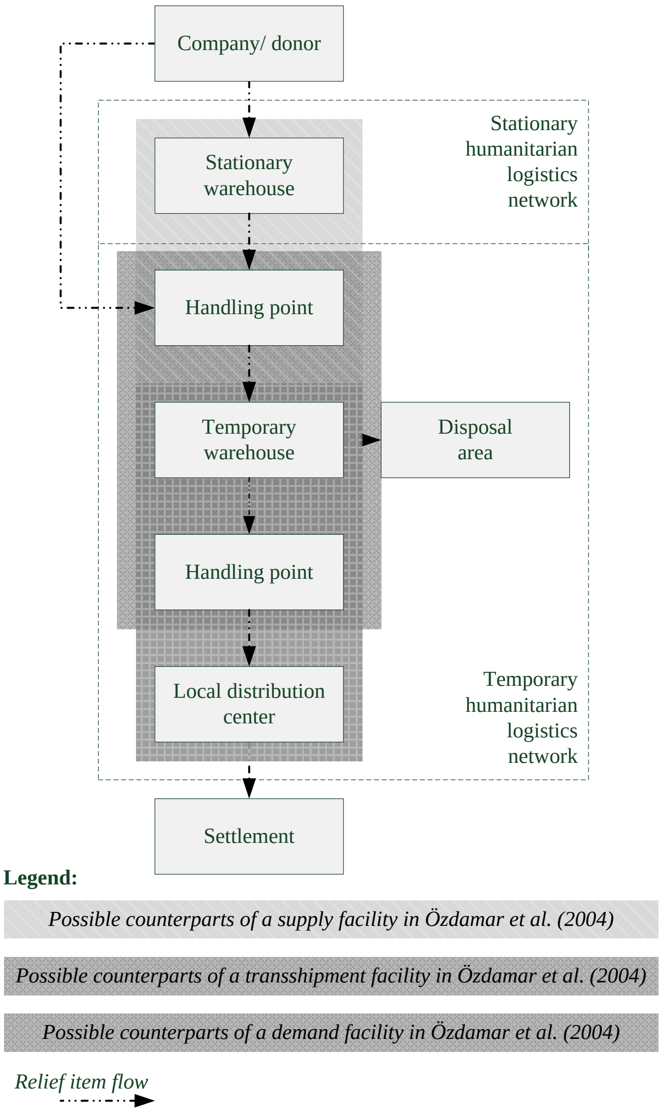


Figure 4.20. Counterparts of the facilities defined in Özdamar et al. (2004) in the reference structure for humanitarian logistics networks

Mode of vehicle types, transport volume and weight per vehicle of a certain type, and speed of travel are already fixed by the humanitarian organization. The same is true for the weight and volume per unit of a relief item type as well as for the relief item stocks at supply facilities and the numbers of additional transportation vehicles per mode and type that are available at the vehicle depot. These attributes are explicitly or implicitly represented by parameters in the mathematical program. Travel speeds are implicitly represented by the parameters that describe the transportation times between locations. Available transport volume and weight per vehicle of a certain type as well as weight and volume per relief item unit of a certain type are implicitly represented by the parameters that describe the maximum relief item loads of vehicles and the necessary loads for relief items, respectively. Furthermore, the numbers of additional transportation vehicles at the vehicle depot are implicitly represented by the parameters that describe the numbers of additional transportation vehicles at locations for demand, transshipment, and supply facilities. The parameters which describe logistics resources and relief items are outlined in Table 4.11.

The humanitarian organization intends to know the number of transportation vehicles of certain types and modes travelling over certain arcs as well as the quantities of relief items transferred by certain modes of transportation, the quantities of relief items handled by transshipment facilities, the quantities of distributed relief items at demand facilities, and the numbers of processed transportation vehicles at facilities. These values are explicitly or implicitly represented by decision variables in the mathematical program. The quantities of stocked, handled, and distributed relief items for a facility can be derived from the relief item flows between facilities. The quantities of processed transportation vehicles at facilities can be derived from the vehicle flows between facilities. Flows of transportation vehicles are allowed to take a positive integer number and flows of relief items are allowed to take a positive real-valued number. Therefore, the number of alternative solutions to the decision problem is continuous.

The humanitarian organization must adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements of the environment. The following relationships are known:

- The amount of inflowing relief items plus the relief item shortage at a demand facility has to be equal to the amount of outflowing relief items plus the relief item demand.
- The amount of inflowing relief items at a transshipment facility must be equal to the amount of outflowing relief items.
- The amount of outflowing relief items at a supply facility cannot exceed the amount of inflowing relief items plus the amount of available relief items.
- Volume and weight of a relief item, transport weight and volume of a specific type of transportation vehicle, and the number of vehicles of that type traveling over a certain arc restrict the quantity of relief items that can be transferred by that type of transportation vehicle over that arc.
- The number of ingoing transportation vehicles per type at a facility plus the number of transportation vehicles per type made available by the vehicle depot restrict the number of outgoing transportation vehicles per type at this facility.
- Transportation vehicles are not allowed to travel via the vehicle depot from one supply/ transshipment/ demand facility to another supply/ transshipment/ demand facility.

- Transportation vehicles can only use those arcs that are appropriate for the mode of transportation they belong to.

In the mathematical program, the allowed use and interaction between logistics resources, relief items, and elements in the environment are represented by constraints. The constraints which represent certain relationships are outlined in Table 4.11.

When setting up a humanitarian logistics network, the humanitarian organization as assumed in the model of Özdamar et al. (2004) takes into account two crucial dimensions in order to identify the most advantageous network configuration. The configuration's input – the amount of transportation resources – represents one key dimension. It is captured by the number of transportation vehicles of a certain type and mode. This metric belongs to the class of utilization metrics. The configuration's output – the delivered relief item quantity – represents the other key dimension of the humanitarian organization. This dimension is captured by the sum of the relief item shortages at demand facilities. This metric belongs to the class of effectiveness metrics. The mathematical program's expressions for these metrics are outlined in Table 4.11.

It is assumed that the organization intends to minimize relief item shortages while limiting the number of transportation vehicles. The parts of the mathematical program which represent this objective/ this requirement are outlined in Table 4.11. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the decision problem captured in the OR model of Özdamar et al. (2004).

Table 4.11. Problem structuring scheme for Özdamar et al. (2004)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Locations for supply facilities	Coordinates	Parameter t^{t}_{ghw}
		Locations for transshipment facilities	Coordinates	Parameter t^{t}_{ghw}
		Locations for demand facilities	Coordinates	Parameter t^{t}_{ghw}
			Relief item demand	Parameter $splDmd_{grt}$
		Arcs	Start location	Parameter t^{t}_{ghw}
			End location	Parameter t^{t}_{ghw}
			Distance	Parameter t^{t}_{ghw}
			Speed limitations	Parameter t^{t}_{ghw}
			Applicable for modes of transportation	Parameter t^{t}_{ghw}
Humanitarian organization	*Logistics resources and relief items*	Supply facilities	Location for a supply facility	Parameter t^{t}_{ghw}
			Transportation vehicles processed (DV)	Variable $x^{\mathrm{d}}_{ghz_w t}$
			Relief items stocked	Parameter $splDmd_{grt}$
			Relief items handled (CV)	Variable x^{t}_{ghrwt}
		Transshipment facilities	Location for a transshipment facility	Parameter t^{t}_{ghw}
			Transportation vehicles processed (DV)	Variable $x^{\mathrm{d}}_{ghz_w t}$
			Relief items handled (CV)	Variable x^{t}_{ghrwt}

	Demand facilities	Location for a demand facility	Parameter t^{t}_{ghw}
		Transportation vehicles processed (DV)	Variable $x^{\mathrm{d}}_{ghz_w t}$
		Relief items handled (CV)	Variable x^{t}_{ghrwt}
		Relief items distributed (CV)	Variable x^{t}_{ghrwt}
	Vehicle depot	Available transportation vehicles per mode and type	Parameter $Nv_{gz_w t}$
	Transportation vehicle types	Mode of transportation	Parameter $Nv_{gz_w t}$
		Speed of travel	Parameter t^{t}_{ghw}
		Transport volume	Parameter Ld_{z_w}
		Transport weight	Parameter Ld_{z_w}
		Vehicles on arcs (DV)	Variable $x^{\mathrm{d}}_{ghz_w t}$
		Relief items transferred on arcs (CV)	Variable x^{t}_{ghrwt}
	Relief item types	Weight	Parameter ld_r
		Volume	Parameter ld_r
Use and interaction of logistics resources, relief items, and elements in environment	The amount of inflowing relief items plus the relief item shortage at a demand facility has to be equal to the amount of outflowing relief items plus the relief item demand		Constraint set 4.70
	The amount of inflowing relief items at a transshipment facility must be equal to the amount of outflowing relief items		Constraint set 4.70
	The amount of outflowing relief items at a supply facility cannot exceed the amount of inflowing relief items plus the amount of available relief items		Constraint set 4.71
	Relief items cannot be transferred via the vehicle depot from one facility to another		Constraint set 4.73
	Transportation vehicles can only use those arcs that are appropriate for the corresponding mode of transportation		Constraint set 4.72

	Volume and weight of a relief item, transport weight and volume of a specific type of transportation vehicle, and the number of vehicles of that type traveling over a certain arc restrict the quantity of relief items that can be transferred by that type of transportation vehicle over that arc		Constraint set 4.74
	The number of ingoing transportation vehicles per type at a facility plus the number of transportation vehicles per type made available by the vehicle depot restrict the number of outgoing transportation vehicles per type at this facility		Constraint set 4.75
Key dimensions, metrics, objectives, and requirements	Input	Transportation resource: number of transportation vehicles	Expression $\sum_{t'=1}^{t} x^{d}_{vgz_w t'}$
	Output	Delivered relief item quantity: relief item shortages	Expression $\sum_{g\in Q}\sum_{r\in R}\sum_{t\in T} x^{u}_{grt}$
	Objective and requirement	Maximizing delivered relief item quantity	Objective function 4.69
		Limiting transportation resources	Constraint set 4.76

Program code

Below is a possible translation of the OR model of Özdamar et al. (2004) into program code, using the OPL language. This language is frequently used to code a MILP such as the one of Özdamar et al. (2004). MILPs coded in this language can be automatically solved with the CPLEX solver.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Özdamar et al. (2004)
 * Creation Date: 03.02.2015 at 14:34:57
 *********************************************/
{int} TimePeriods = ...;
{string} LocationsForSupplyFacilities = ...;
{string} LocationsForTransshipmentFacilitiesAndDemandFacilities = ...;
{string} ReliefItemTypes = ...;
{string} LocationForVehicleDepot = ...;
{string} ModesOfTransportation =  ...;
{string} TypesOfTransportationVehicles = ...;
float Big = 100000000000;
float CapacityAvailable
[ModesOfTransportation,TypesOfTransportationVehicles] = ...;
float CapacityNecessary
[ReliefItemTypes] = ...;
float NumberTransportationVehicles
[LocationsForSupplyFacilities     union     LocationsForTransshipmentFacilitiesAndDemandFacilities,ModesOfTransportation,
TypesOfTransportationVehicles,TimePeriods] = ...;
float SupplyDemand
[LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities,
ReliefItemTypes,TimePeriods] = ...;
int TransportationTime
[LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
LocationForVehicleDepot, LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
LocationForVehicleDepot, ModesOfTransportation] = ...;
dvar float+ Transferred
[LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
LocationForVehicleDepot,LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
```

```
LocationForVehicleDepot,ReliefItemTypes,ModesOfTransportation,
TimePeriods];
dvar float+ Shortage
[LocationsForTransshipmentFacilitiesAndDemandFacilities,
ReliefItemTypes,TimePeriods];
dvar int+ Driving
[LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
LocationForVehicleDepot,LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities union
LocationForVehicleDepot,ModesOfTransportation,
TypesOfTransportationVehicles,TimePeriods];
dvar int+ Waiting[LocationsForSupplyFacilities union
LocationsForTransshipmentFacilitiesAndDemandFacilities,
ModesOfTransportation,TypesOfTransportationVehicles,TimePeriods];

minimize
sum (pq in LocationsForTransshipmentFacilitiesAndDemandFacilities,
r in ReliefItemTypes, t in TimePeriods)
Shortage[pq,r,t];

subject to{
ct70:
forall(pq in LocationsForTransshipmentFacilitiesAndDemandFacilities, r in
ReliefItemTypes, t in TimePeriods)
- sum (g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, w in
ModesOfTransportation, tI in 1..t:tI-TransportationTime[g,pq,w]>0)
Transferred[g,pq,r,w,tI-TransportationTime[g,pq,w]] +
sum (g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, w in
ModesOfTransportation, tI in 1..t)
Transferred[pq,g,r,w,tI] -
Shortage[pq,r,t] ==
sum (tI in 1..t)
SupplyDemand[pq,r,tI];

ct71:
forall(o in LocationsForSupplyFacilities, r in ReliefItemTypes, t in TimePeriods)
- sum (g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, w in
ModesOfTransportation, tI in 1..t:tI-TransportationTime[g,o,w]>0)
Transferred[g,o,r,w,tI-TransportationTime[g,o,w]] +
```

```
sum (g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, w in ModesOfTransportation, tI in 1..t)
Transferred[o,g,r,w,tI] <=
sum (tI in 1..t)
SupplyDemand[o,r,tI];

ct72:
forall(g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities, h in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities, w in ModesOfTransportation, z in TypesOfTransportationVehicles, t in TimePeriods)
Driving[g,h,w,z,t] <=
TransportationTime[g,h,w] * Big;

ct73:
forall(g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities, v in LocationForVehicleDepot, r in ReliefItemTypes, w in ModesOfTransportation, t in TimePeriods)
Transferred[v,g,r,w,t] +
Transferred[g,v,r,w,t] == 0;

ct74:
forall(g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, h in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, w in ModesOfTransportation, t in TimePeriods)
sum (z in TypesOfTransportationVehicles)
Driving[g,h,w,z,t] * CapacityAvailable[w,z] >=
sum (r in ReliefItemTypes)
Transferred[g,h,r,w,t] * CapacityNecessary[r];

ct75:
forall(g in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities, w in ModesOfTransportation, z in TypesOfTransportationVehicles, t in TimePeriods)
sum (h in LocationsForSupplyFacilities union LocationsForTransshipmentFacilitiesAndDemandFacilities union LocationForVehicleDepot, tI in 1..t:tI-TransportationTime[h,g,w]>0)
Driving[h,g,w,z,tI-TransportationTime[h,g,w]] -
Waiting[g,w,z,t] ==
```

```
sum (h in LocationsForSupplyFacilities union LocationsForTransship-
mentFacilitiesAndDemandFacilities union LocationForVehicleDepot, tI in
1..t)
Driving[g,h,w,z,tI];

ct76:
forall(v in LocationForVehicleDepot, g in LocationsForSupplyFacilities un-
ion LocationsForTransshipmentFacilitiesAndDemandFacilities, w in Mode-
sOfTransportation, z in TypesOfTransportationVehicles, t in TimePeriods)
sum (tI in 1..t)
Driving[v,g,w,z,tI] <=
sum (tI in 1..t)
NumberTransportationVehicles[g,w,z,tI];
}
```

4.3.3 Mathematical program of Vitoriano et al. (2011) for supporting decisions about the types, loads, and used arcs of transportation vehicles

Vitoriano et al. (2011), in their publication entitled “A multi-criteria optimization model for humanitarian aid distribution”, present a mathematical program which supports the specification of transportation activities. On a functional level, the program can be characterized as a model for transportation planning; more exactly as a service network design model as it determines the types of transportation vehicles which transfer certain amounts of relief items over specific arcs (SteadieSeifi et al., 2014). The program can also be characterized as a MILP because of the use of binary, integer, and continuous variables. Finally, the program optimizes differences to target values. This kind of approach is called a “Goal Programming” approach (Williams, 2013, p. 27).

In this section, the mathematical program is profiled. This includes a description of the mathematical formulation, a description of the underlying problem, and a possible translation into program code. Names of sets, parameters, and variables in the present notation of the mathematical formulation differ from the original notation in order to achieve a consistent notation within the toolkit.

Mathematical formulation

The program’s objective function (5.79) minimizes deviations between variable values and corresponding target values. These deviations are normalized and weighted. Target values are defined for: total costs of the transportation activities, maximum delivery time of facilities, maximum percentage of unfulfilled demands at facilities, percentage of fulfilled demand at a priority facility, minimum probability of completely crossing a used arc, probability of completely crossing all used arcs, maximum ransack probability of a used arc, and probability of not being ransacked on any used arcs.

Constraint set (4.80) ensures relief item flow conservation at each facility; more exactly, it is required that the amount of available relief item supplies at the beginning of the transportation activities plus the amount of inflowing relief items during the operation must be equal to the amount of outflowing relief items during the operation plus the amount of relief items that remains at the facility after the transportation activities stop. Constraint set (4.81) defines an upper bound on the amount of relief items that can remain at a facility after the operation stops; this amount can exceed neither the original location-dependent relief item demand nor the original location-dependent relief item supply. Constraint (4.82) ensures that the total amount of relief items over all facilities at the end of the operation is equal to the total amount of available relief items at the beginning of the operation. Constraint set (4.83) ensures the conservation of vehicle flows at each facility: the number of available vehicles at the beginning of the operation plus the number of inflowing vehicles is equal to the number of outflowing vehicles plus the number of vehicles remaining at a facility after the operation stops. Constraint set (4.84) requires that the overall number of vehicles at the beginning of the operation has to be equal to the overall number of vehicles at the end of the operation. Constraint set (4.85) permits vehicles of a specific type to only use specific arcs. Constraint sets (4.86) and (4.87) calculate the delivery times of each facility after the operation has been started. The delivery time of a facility depends on the delivery time of the previously visited facility, the distance between the locations of the previous-visited facility and the visited facility, and the speed of the vehicle type used to overcome the distance respectively the speed limit on the corresponding arc. In order to determine if any transportation vehicle respectively if any transportation vehicle of a specific type travels between two facilities the constraint sets (4.88), (4.89), (4.90), and (4.91) are introduced. Constraint sets (4.86), (4.87), (4.88), (4.89), (4.90), and (4.91) are also used to prevent that facilities already visited by transportation vehicles are not reapproached during the operation (sub-cycle elimination constraints). Constraint set (4.92) requires transportation vehicles to carry relief items on the last leg of their travels and constraint sets (4.93) and (4.94) are introduced to determine if any transportation vehicle of a specific type ends its travels at a certain facility. Constraint set (4.95) assures that relief item flows are realized by vehicle flows and constraint set (4.96) determines that the amount of relief items transferred by a certain type of vehicle over a certain arc depends on the number of vehicles flowing over this particular arc and the available transport volume and weight per vehicle. Constraint (4.97) determines the number of relief items to be distributed during a response. Constraint (4.98) calculates the total costs of the operations. Costs are split into two terms: one term calculates the transportation costs due to the distance travelled and the other term calculates the transportation costs due to the transfer of loads. The transportation costs also cover the costs for the transportation vehicles' empty drives back to their point of origin. Constraint (4.99) calculates the difference between the actual total costs and a target value. Constraint set (4.100) determines the maximum delivery time of all facilities and constraint (4.101) calculates the difference between the actual maximum delivery time and a target value. Constraint set (4.102) computes the maximum percentage of unfulfilled demand of all locations and constraint (4.103) calculates the difference between the actual maximum percentage of unfulfilled demand and a target value. Constraint set (4.104) computes the percentage of fulfilled demand at the priority location and constraint (4.105) determines the difference between the actual percentage of fulfilled demand at the priority location and a target value. Constraint set (4.106) determines the minimum probability of completely crossing a used arc and constraint (4.107) calculates the difference between the actual minimum probability of completely crossing a used arc and a target value. Constraint set (4.108) captures the probability of completely crossing all arcs used during the response. This is not done directly by multiplying all probabilities for completely crossing an arc of those arcs that are used during the transportation activities – given that such a multiplication is a non-linear expression. Instead, the calculation of the probability of completely crossing all arcs used during the operation is linearized (and thereby approximated) by summing up all logarithmized probabilities of completely crossing an arc of those arcs that are used during transportation activities. The logarithmized total probability of completely crossing all used arcs is a negative value. Constraint (4.109) calculates the difference between the logarithmized total probability of completely crossing all used arcs and a target value. Constraint set (4.110) calculates the logarithmized maximum probability of being ransacked on a used arc depending on the number of vehicles flowing over it. Logarithms are also applied here because directly calculating the maximum probability of being ransacked on a used arc would involve non-linear expressions. Again, the logarithmized maximum probability of being ransacked on a used arc is a negative value. Constraint (4.111) calculates the difference between the actual logarithmized maximum probability of being ransacked on a used arc and a target value. Constraint (4.112) states that there is a probability of not being ransacked on an arc and that this probability rises with the number of transportation vehicles in a convoy and the number of convoys flowing over the arc. The constraint calculates the logarithmized probability of not being ransacked during an operation. Again, logarithms are applied as a direct calculation of the total probability of not being ransacked during an operation would involve non-linear expressions. The logarithmized probability of not being ransacked during an operation is a negative value. Constraint (4.113) calculates the difference between the logarithmized total probability of not being ransacked during an operation and a target value. Finally, the constraint sets (4.114), (4.115), (4.116), and (4.117) define the binary variables (necessary to capture whether a vehicle of a certain type or whether any vehicle uses a specific arc) as well as the non-negativity of the real-valued relief item flow variables and the integer vehicle flow variables.

Sets:

G	Set of locations
Z	Set of transportation vehicle types

Parameters:

big_1	Big number
big_2	Big number
big_3	Big number
big_4	Big number
big_5	Big number
big_6	Big number
c^{d}_{ghz}	Costs for driving (d) a transportation vehicle of type *z* from location *g* to location *h* per unit of length
c^{t}_{ghz}	Costs for the transportation (t) of a relief item unit with transportation vehicle type *z* from location *g* to location *h* per unit of length
crs_{gh}	Probability of completely crossing the arc between location *g* and location *h*
cvy	Maximum number of transportation vehicles in a convoy
d_{gh}	Distance between location *g* and location *h*
dmd_g	Units of relief items demanded at location *g*
Ld_z	Maximum load of a transportation vehicle of type *z*
Nr	Number of relief items to be distributed

Nv_{gz}	Number of transportation vehicles of type z available at location g
prt_g	0 if location g is a priority location, 1 otherwise
rnk_{gh}	Probability of being ransacked on arc between location g and location h
$rnkCvy_{gh}$	Probability of not being ransacked on arc between location g and location h if the number of vehicles going over it is the maximum size of a convoy
sMx_{gh}	Upper speed limit between location g and location h
sMx_z	Upper speed limit of a transportation vehicle of type z
spl_g	Units of relief items available at location g
TrC	Target total costs
$TrCrs$	Target probability of completely crossing all used arcs
$TrMnCrs$	Target minimum probability of completely crossing a used arc
$TrMxR$	Target maximum probability of being ransacked on a used arc
$TrMxRt$	Target maximum reaching time
$TrMxU$	Target maximum percentage of unfulfilled demand
TrP	Target percentage of fulfilled demand at priority node
TrR	Target probability of not being ransacked on all used arcs
use_{ghz}	0 if arc between location g and location h cannot be used by a transportation vehicle of type z, 1 otherwise
ω^{C}	Weight for total costs (C)
ω^{Crs}	Weight for probability of completely crossing all used arcs (Crs)

ω^{MnCrs}	Weight for minimum probability of crossing a used arc (MnCrs)
ω^{MxR}	Weight for maximum probability of being ransacked on a used arc (MxR)
ω^{MxRt}	Weight for maximum reaching time (MxRt)
ω^{MxU}	Weight for maximum percentage of unfulfilled demand (MxU)
ω^{P}	Weight for percentage of fulfilled demand at priority node (P)
ω^{R}	Weight for probability of not being ransacked on all used arcs (R)

Variables:

C	Total costs
Crs	Probability of completely crossing all used arcs
DC	Deviation: total costs from target value
$DCrs$	Deviation: probability of completely crossing all used arcs from target value
$DMnCrs$	Deviation: minimum probability of crossing a used arc from target value
$DMxR$	Deviation: maximum probability of being ransacked on a used arc from target value
$DMxRt$	Deviation: maximum reaching time from target value
$DMxU$	Deviation: maximum percentage of unfulfilled demand from target value
DP	Deviation: percentage of fulfilled demand at priority location from target value
DR	Deviation: probability of not being ransacked from target value
$MnCrs$	Minimum probability of crossing a used arc
MxR	Maximum probability of being ransacked on a used arc

$MxRt$	Maximum reaching time
MxU	Maximum percentage of unfulfilled demand
P	Percentage of fulfilled demand at priority location
R	Probability of not being ransacked on all used arcs
rt_g	Reaching time of location *g*
x_{gz}^{d}	Transportation vehicles of type *z* driving (d) to location *g* as their final destination
x_{ghz}^{d}	Transportation vehicles of type *z* driving (d) from location *g* to location *h*
x_{g}^{s}	Relief items staying (s) at location *g* at the end of the operation
x_{gh}^{t}	Relief items transferred (t) from location *g* to location *h*
x_{ghz}^{t}	Relief items transferred (t) by a transportation vehicle of type *z* from location *g* to location *h*
y_{gh}	1 if any transportation vehicle drives from location *g* to location *h*, 0 otherwise
y_{ghz}	1 if any transportation vehicle of type *z* drives from location *g* to location *h*, 0 otherwise
y_{gz}	1 if any transportation vehicle of type *z* has location *g* as its final destination, 0 otherwise

MILP:

(4.79) Minimize

$$\omega^{\mathrm{C}}\frac{DC}{TrC}+\omega^{\mathrm{MxRt}}\frac{DMxRt}{TrMxRt}+\omega^{\mathrm{MxU}}\frac{DMxU}{TrMxU}$$
$$+\omega^{\mathrm{P}}\frac{DP}{TrP}+\omega^{\mathrm{MnCrs}}\frac{DMnCrs}{TrMnCrs}+\omega^{\mathrm{Crs}}\frac{DCrs}{TrCrs}$$
$$+\omega^{\mathrm{MxR}}\frac{DMxR}{TrMxR}+\omega^{\mathrm{R}}\frac{DR}{TrR}$$

s.t. (4.80) $\sum_{h\in G|h\neq g} x_{hg}^{\mathrm{t}} + spl_g = \sum_{h\in G|h\neq g} x_{gh}^{\mathrm{t}} + x_g^{\mathrm{s}} \qquad \forall g\in G$

(4.81) $x_g^{\mathrm{s}} \le dmd_g + spl_g \qquad \forall g\in G$

(4.82) $\sum_{g\in G} x_g^{\mathrm{s}} = \sum_{g\in G} spl_g$

(4.83) $\sum_{h\in G|h\neq g} x_{hgz}^{\mathrm{d}} + Nv_{gz} = \sum_{h\in G|h\neq g} x_{ghz}^{\mathrm{d}} + x_{gz}^{\mathrm{d}} \qquad \forall g\in G, z\in Z$

(4.84) $\sum_{g\in G} x_{gz}^{\mathrm{d}} = \sum_{g\in G} Nv_{gz} \qquad \forall z\in Z$

(4.85) $x_{ghz|use_{ghz}=0}^{\mathrm{d}} = 0 \qquad \forall g,h\in G, z\in Z$

(4.86) $rt_h \ge rt_g + \frac{d_{gh}}{sMx_{gh}} - big_1(1-y_{gh}) \qquad \forall g,h\in G$

(4.87) $rt_h \ge rt_g + \frac{d_{gh}}{sMx_z} - big_2(1-y_{ghz}) \qquad \forall g,h\in G, z\in Z$

(4.88) $x_{ghz}^{\mathrm{d}} \le big_3 y_{ghz} \qquad \forall g,h\in G, z\in Z$

$$y_{ghz} \le x^{\mathrm{d}}_{ghz} \qquad \forall g,h \in G, z \in Z \tag{4.89}$$

$$y_{ghz} \le y_{gh} \qquad \forall g,h \in G, z \in Z \tag{4.90}$$

$$y_{gh} \le \sum_{z \in Z} y_{ghz} \qquad \forall g,h \in G \tag{4.91}$$

$$\sum_{z' \in Z} Ld_{z'} x^{\mathrm{d}}_{ghz'} - Ld_{z} \le x^{\mathrm{t}}_{gh} + big_4 (1 - y_{hz}) \qquad \forall g,h \in G, z \in Z \tag{4.92}$$

$$x^{\mathrm{d}}_{gz} \le big_5 y_{gz} \qquad \forall g \in G, z \in Z \tag{4.93}$$

$$y_{gz} \le x^{\mathrm{d}}_{gz} \qquad \forall g \in G, z \in Z \tag{4.94}$$

$$x^{\mathrm{t}}_{gh} = \sum_{z \in Z} x^{\mathrm{t}}_{ghz} \qquad \forall g,h \in G \tag{4.95}$$

$$x^{\mathrm{t}}_{ghz} \le Ld_{z} x^{\mathrm{d}}_{ghz} \qquad \forall g,h \in G, z \in Z \tag{4.96}$$

$$\sum_{g \in G | Dmd_g > 0} x^{\mathrm{s}}_{g} = Nr \tag{4.97}$$

$$C = \sum_{g \in G} \sum_{h \in G} \sum_{z \in Z} (2 c^{\mathrm{d}}_{ghz} d_{gh} x^{\mathrm{d}}_{ghz} + c^{\mathrm{t}}_{ghz} d_{gh} x^{\mathrm{t}}_{ghz}) \tag{4.98}$$

$$C - DC \le TrC \tag{4.99}$$

$$MxRt \ge rt_{g} \qquad \forall g \in G \tag{4.100}$$

$$MxRt - DMxRt \le TrMxRt \tag{4.101}$$

$$MxU \ge 1 - \frac{x^{\mathrm{s}}_{g}}{dmd_{g}} \qquad \forall g \in G / dmd_{g} > 0 \tag{4.102}$$

(4.103) $MxU - DMxU \leq TrMxU$

(4.104) $P = \dfrac{x_g^{\mathrm{s}}}{dmd_g} \qquad \forall g \in G \,/\, prt_g = 1$

(4.105) $P + DP \geq TrP$

(4.106) $MnCrs \leq crs_{gh} + 1 - y_{gh} \qquad \forall g, h \in G$

(4.107) $MnCrs + DMnCrs \geq TrMnCrs$

(4.108) $Crs = \sum_{g \in G} \sum_{h \in G} (y_{gh} (\log crs_{gh}))$

(4.109) $Crs + DCrs \geq TrCrs$

(4.110) $MxR \geq \sum_{z \in Z} x_{ghz}^{\mathrm{d}} \log(rnk_{gh}) - big_6 (1 - y_{gh}) \qquad \forall g, h \in G$

(4.111) $MxR - DMxR \leq TrMxR$

(4.112) $R = \sum_{g \in G} \sum_{h \in G} (\log(rnkCvy_{gh})(2 - \dfrac{\sum_z x_{ghz}^{\mathrm{d}}}{cvy} - 2(1 - y_{gh})))$

(4.113) $R + DR \geq TrR$

(4.114) $x_{ghz}^{\mathrm{d}}, x_{gz}^{\mathrm{d}} \geq 0$, and integer $\qquad \forall g, h \in G, z \in Z$

(4.115) $rt_g, x_g^{\mathrm{s}}, x_{gh}^{\mathrm{t}}, x_{ghz}^{\mathrm{t}} \geq 0 \qquad \forall g, h \in G, z \in Z$

(4.116) $y_{gh}, y_{gz}, y_{ghz} \in \{0,1\} \qquad \forall g, h \in G, z \in Z$

(4.117) $\begin{array}{l} C, DC, MxRt, DMxRt, MxU, DMxU, \\ P, DP, MnCrs, DMnCrs, DMxR, DR \geq 0 \end{array}$

Problem structure

In the following, the problem as captured in the OR model of Vitoriano et al. (2011) is described based on the problem structuring scheme outlined in section 3.4. Firstly, the disaster environment is characterized. Secondly, the characteristics of the humanitarian organization, which operates in the disaster environment, are described. The results of the problem structuring process are outlined in Table 4.12 (pp. 168ff).

The environment, in which a humanitarian logistics network is laid out, is a single-organizational disaster environment and consists of locations as well as bidirectional arcs between these locations. Different types of facilities can be erected at the locations. Each location is characterized by coordinates and a demand for relief items. Moreover, one of the locations is marked as the priority location. Each arc is characterized by the two locations it connects, a distance, speed limitations, applicability for certain transportation vehicle types, a probability of not being crossed completely (due to infrastructure damage), a probability of being ransacked, and a probability of not being ransacked if a convoy uses the arc. Attributes of locations and arcs are static and deterministic; and are explicitly or implicitly represented by parameters in the mathematical program. Coordinates of locations are implicitly represented by the parameters that describe the distances between locations (because coordinates have to be known to calculate these distances). The parameters which represent certain attributes of the environmental elements are outlined in Table 4.12.

The available inputs of the humanitarian organization to set up and run a humanitarian logistics network are: facilities that are used as supply facilities, transshipment facilities, and/ or demand facilities, a single relief item type, and different types of transportation vehicles. In Figure 4.21, a simple example of the humanitarian logistics network is presented. A facility that can be used as a supply facility, transshipment facility, and/ or demand facility can have several counterparts in a real-world humanitarian logistics network. Possible counterparts for such a facility are: a stationary warehouse, a handling point, a temporary warehouse, and/ or a LDC. Possible counterparts of a facility as defined in Vitoriano et al. (2011) in the reference structure for humanitarian logistics networks (as described in section 2.1) are shown in Figure 4.22 (p. 166).

Each facility is characterized by its location, by the amount of relief items stocked in the facility, by the amount of relief items handled in the facility, by the amount of relief items distributed at the facility, by the number of available vehicles per type, and by the number of processed vehicles per type. The humanitarian organization has erected facilities at certain locations. Furthermore, each vehicle type is characterized by the available transport volume and weight per vehicle, a speed of travel, a number of vehicles on specific arcs (transportation vehicle flows), and loads of relief items on specific arcs (relief item flows). Finally, the single type of relief item is defined by its weight and volume per unit. Relief item stocks at facilities, the number of available vehicles at facilities, the available transport volume, transport weight, and travel speed per vehicle of a certain type together with the weight and volume per relief item unit are assumed to be already known by the humanitarian organization. These attributes can be defined as being static and deterministic and are – implicitly or explicitly – represented by parameters in the mathematical program. The available transport volume and weight per vehicle of a certain type as well as the volume and weight per relief item unit are implicitly represented by the parameters which describe the numbers of relief items certain types of vehicles can load.

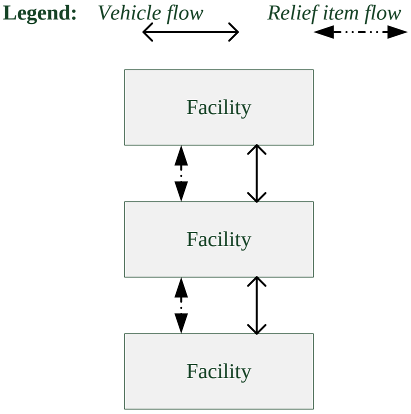


Figure 4.21. Simple example of the humanitarian logistics network in the OR model of Vitoriano et al. (2011)

The humanitarian organization decides about the numbers of transportation vehicles of certain types travelling over certain arcs, the quantities of relief items moved by certain types of vehicles, the quantities of relief items handled and distributed at facilities, and the numbers of processed transportation vehicles at facilities. These attributes are explicitly or implicitly represented by decision variables in the mathematical program. Quantities of stocked, handled, and distributed relief items at facilities can be derived from the relief item flows between facilities; and the numbers of processed transportation vehicles at facilities can be derived from the vehicle flows between facilities. The flows of transportation vehicles may take a positive integer number while the flows of relief items may take a positive real-valued number. Given that flows of relief items can take a positive real-valued number, the number of alternative solutions to the problem is continuous. The parameters and variables which represent attributes of logistics resources and relief items are outlined in Table 4.12.

The assumed humanitarian organization must adhere to specific rules when using the logistics resources and relief items as well as when interacting with the elements of the environment. The following relationships are known to the organization:

- At each facility, the available amount of stocked relief items from the beginning of the transportation activities plus the amount of inflowing relief items

during the operation must be equal to the amount of outflowing relief items during the operation plus the amount of relief items that remains at the facility for distribution after the transportation activities stopped.
- The amount of relief items that can remain at a facility for distribution after the transportation activities stopped cannot exceed the sum of original location-dependent demand plus the facility's relief item stock from the beginning of the operation.
- The total amount of relief items from the beginning of the operation is equal to the total amount of relief items at the end of the operation.
- At each facility, the number of available vehicles of a certain type at the beginning of the operation plus the number of inflowing vehicles during the operation must be equal to the number of outflowing vehicles during the operation plus the number of vehicles staying at the facility at the end of the operation.
- The overall number of transportation vehicles of a certain type at the beginning of the operation is equal to the overall number of vehicles of this type at the end of the operation.
- Transportation vehicles of a specific type can only be used on specific arcs.
- Transportation vehicles are not allowed to reapproach any already visited location
- Relief item flows are realized by transportation vehicle flows.
- The amount of relief items transferred by a certain type of transportation vehicles over a certain arc depends on the number of vehicles flowing over this arc, on the available transport volume and weight per vehicle, and the volume and weight per relief item unit.

In the mathematical program, the permitted use and interaction between logistics resources, relief items, and elements in the environment are represented by the constraints. The constraints which represent these relationships are outlined in Table 4.12.

When setting up a humanitarian logistics network, the humanitarian organization takes into account several critical dimensions in order to identify the most advantageous configuration. The configuration's input – the amount of transportation resources – is one critical aspect. It is measured by the transportation costs that are associated with a certain configuration and by the number of transportation vehicles driving on arcs. These metrics belong to the class of utilization metrics. A configuration's output is broken down to the key dimensions *delivered relief item quantity*, *delivery time*, and *workforce safety and security*. In order to quantify the dimension *delivered relief item quantity*, the maximum percentage of unfulfilled demand of all locations is calculated. This is a metric to measure the non-discrimination of beneficiaries. Another metric used to measure the dimension *delivered relief item quantity* is the fulfilled demand at the priority location, which is an impartiality metric. Finally, the dimension *delivered relief item quantity* is measured by the total amount of relief items arriving at demand facilities, which is an effectiveness metric. In order to quantify the dimension *delivery times*, the maximum delivery time of all facilities is calculated – again, a non-discrimination metric. Furthermore, the dimension *workforce safety and security* is measured by four metrics: security is captured by the probability of not being ransacked on any used arcs and the maximum probability of suffering an attack on a used arc; and safety is captured by the probability of completely crossing all used arcs and the minimum probability of completely crossing a used arc. The mathematical expressions for these metrics are outlined in Table 4.12.

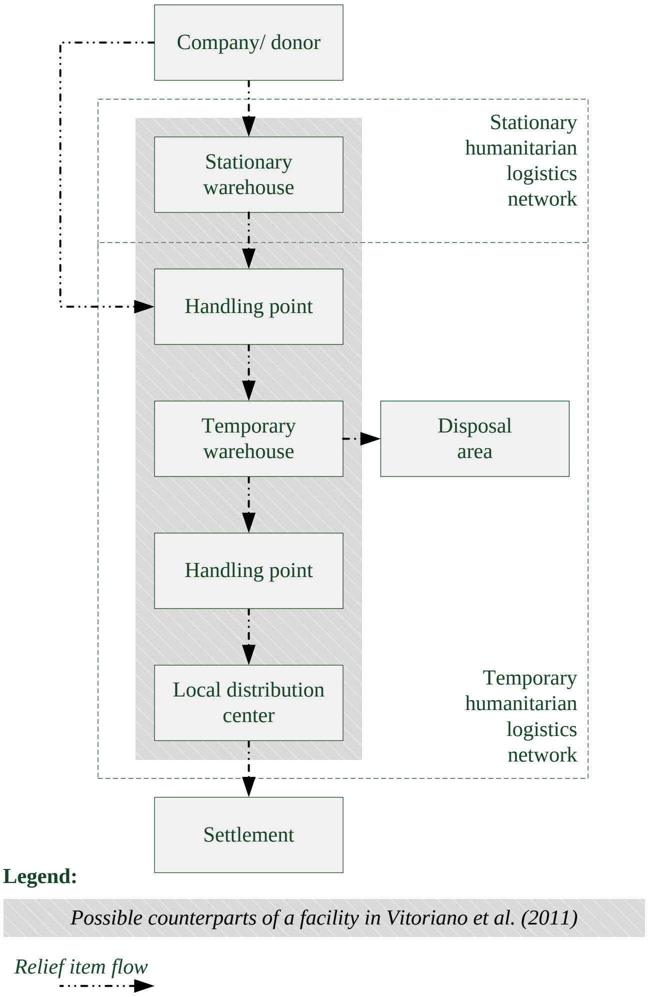


Figure 4.22. Counterparts of a facility defined in Vitoriano et al. (2011) in the reference structure for humanitarian logistics networks

The humanitarian organization has target values for certain metrics and intends to minimize the weighted, normalized deviations between actual values and the corresponding target values. More exactly, the humanitarian organization intends to minimize the difference between the actual value of the transportation costs and a target value, to minimize the difference between the actual quantity of delivered relief items to a particular demand facility (the one at the priority location) and a target value, to minimize the difference between the actual minimum quantity of delivered relief items at the other demand facilities and a target value, to minimize the difference between the actual maximum delivery time and a target value, to minimize the differences between the actual values for workforce safety/ security and target values, and to minimize the differences between the actual minimum values for workforce safety/ security and target values. The humanitarian organization has to define weights and target values for these metrics. The parameters which represent these weights and target values are outlined in Table 4.12. Moreover, the organization requires that transportation vehicles transfer relief items on the last legs of their travels in order to cap the usage of transportation resources. Finally, the organization ensures that the total amount of relief items arriving at demand facilities is equal to a certain value, which is selected by the organization and is represented by a parameter in the mathematical program. Generally speaking, maximizing the efficiency of the humanitarian logistics network is the overarching objective of the problem that is captured in the OR model of Vitoriano et al. (2011).

Table 4.12. Problem structuring scheme for Vitoriano et al. (2011)

Category	Properties (DV: discrete variable, CV: continuous variable)			Mathematical representation
Disaster environment		Humanitarian organization		
		Disaster		
		Locations	Coordinates	Parameter d_{gh}
			Relief item demand	Parameter dmd_{g}
			Priority	Parameter prt_{g}
		Arcs	Start location	Parameter d_{gh}
			End location	Parameter d_{gh}
			Distance	Parameter d_{gh}
			Speed limitations	Parameter sMx_{gh}
			Applicable for transportation vehicle types	Parameter use_{ghz}
			Probability of crossing completely	Parameter crs_{gh}
			Probability of being ransacked	Parameter rnk_{gh}
			Probability of not being ransacked if a convoy uses the arc	Parameter $rnkCvy_{gh}$
Humanitarian organization	*Logistics resources and relief items*	Facilities	Location	Parameter d_{gh}
			Available transportation vehicles	Parameter Nv_{gz}
			Transportation vehicles processed (DV)	Variable x^{d}_{ghz}
			Relief items stocked	Parameter spl_{g}
			Relief items handled (CV)	Variable x^{t}_{gh}
			Relief items distributed (CV)	Variable x^{s}_{g}

	Transportation vehicle types	Speed of travel	Parameter sMx_z
		Transport volume	Parameter Ld_z
		Transport weight	Parameter Ld_z
		Vehicles on arcs (DV)	Variable x^{d}_{ghz}
		Maximum number of vehicles in convoy	Parameter cvy
		Relief items transferred on arcs (CV)	Variable x^{t}_{ghz}
	Relief item types	Volume	Parameter Ld_z
		Weight	Parameter Ld_z
Use and interaction of logistics resources, relief items, and elements in environment	At each facility, the available amount of relief items stocked at the beginning of the transportation activities plus the amount of inflowing relief items during the operation must be equal to the amount of outflowing relief items during the operation plus the amount of relief items that remains at the facility for distribution after the transportation activities stopped		Constraint set 4.80
	The amount of relief items that can remain at a facility for distribution after the transportation activities stopped cannot exceed the sum of the original location-dependent demand plus the relief item stocks at the facility from the beginning of the operation		Constraint set 4.81
	The total amount of relief items from the beginning of the operation is equal to the total amount of relief items at the end of the operation.		Constraint 4.82
	At each facility, the number of available vehicles of a certain type at the beginning of the operation plus the number of inflowing vehicles during the operation must be equal to the number of outflowing vehicles during the operation plus the number of vehicles remaining at the facility at the end of the operation		Constraint set 4.83
	Overall number of transportation vehicles of a certain type at the beginning of the operation is equal to the overall number of vehi-		Constraint set 4.84

	cles at the end of the operation		
	Transportation vehicles of a specific type can only be used on specific arcs		Constraint set 4.85
	Transportation vehicles are not allowed to reapproach any already visited location		Constraint sets 4.86, 4.87, 4.88, 4.89, 4.90, 4.91
	Relief items flows are realized by transportation vehicle flows		Constraint set 4.95
	The amount of relief items transferred by a certain type of transportation vehicle over a certain arc depends on the number of vehicles flowing over this arc, on the available transport volume and weight per vehicle, and the volume and weight per relief item unit.		Constraint set 4.96
Key dimensions, metrics, targets, and requirements	Input	Transportation resources: - Transportation costs, - Number of vehicles driving on arcs	 Expression C Expression $\sum_{z\in Z} x^{d}_{ghz}$
	Outputs	Delivered relief item quantity: - Maximum percentage of unfulfilled demand - Percentage of fulfilled demand at priority location	 Expression MxU Expression P
		Delivery times: Maximum reaching time of facilities	Expression $MxRt$
		Workforce safety & security: - Probability of crossing all used arcs completely - Minimum probability of crossing a used arc completely - Probability of not being ransacked on all used arcs - Maximum probability of being ransacked on a used arc	 Expression Crs Expression $MnCrs$ Expression R Expression MxR

Requirements	Ensuring output (total amount of relief items arriving at demand facilities)	Constraint 4.97
	Limiting inputs (Transportation vehicles can only operate if they transfer relief items on their last legs)	Constraint sets 4.92, 4.93, 4.94
Targets	Minimizing difference inputs to target value	Objective function 4.79, constraints 4.98, 4.99
	Minimizing difference delivered relief item quantity to target value at priority location	Objective function 4.79, constraint (set) 4.104, 4.105
	Minimizing difference minimum quantity of delivered relief items to target value	Objective function 4.79, constraint (set) 4.102, 4.103
	Minimizing difference maximum delivery times to target value	Objective function 4.79, constraint (set) 4.100, 4.101
	Minimizing differences workforce safety and security to target values	Objective function 4.79, constraints 4.108, 4.109, 4.112, 4.113
	Minimizing differences minimum workforce safety and security to target values	Objective function 4.79, constraints 4.106, 4.107, 4.110, 4.111
Factors and bounds	Target total transportation costs	Parameter TrC
	Target probability of crossing all used arcs completely	Parameter $TrCrs$
	Target minimum probability of crossing a used arc	Parameter $TrMnCrs$
	Target maximum probability of being ransacked on a used arc	Parameter $TrMxR$
	Target maximum reaching time	Parameter $TrMxRt$
	Target maximum percentage of unfulfilled demand	Parameter $TrMxU$
	Target percentage of fulfilled demand at priori-	Parameter TrP

ty location	
Target probability of not being ransacked on all used arcs	Parameter TrR
Weight for total transportation costs	Parameter ω^{C}
Weight for probability of crossing all used arcs completely	Parameter ω^{Crs}
Weight for minimum probability of crossing a used arc	Parameter ω^{MnCrs}
Weight for maximum probability of being ransacked on a used arc	Parameter ω^{MxR}
Weight for maximum reaching time	Parameter ω^{MxRt}
Weight for maximum percentage of unfulfilled demand	Parameter ω^{MxU}
Weight for percentage of fulfilled demand at priority location	Parameter ω^{P}
Weight for probability of not being ransacked on all used arcs	Parameter ω^{R}
Total amount of relief items to be distributed	Parameter Nr

Program code

Below is a possible translation of the OR model of Vitoriano et al. (2011) into program code, using the OPL language. This language is frequently used to code a MILP such as the one of Vitoriano et al. (2011). MILPs coded in this language can be automatically solved with the CPLEX solver. The program code below (as the mathematical formulation) prohibits transportation vehicles to reapproach any already visited location. Therefore, the solver will not find a feasible solution if transportation vehicles have to go forth and back during a disaster response because the available transportation capacity is too low. Furthermore, there are three differences in the presented program code compared to the original mathematical formulation. As stated before, the logarithmized probability of completely crossing all used arcs, the logarithmized maximum probability of being ransacked on a used arc, and the logarithmized probability of not being ransacked on any used arc are negative values. Therefore, the three targets for these values in constraints (4.109), (4.111), and (4.113) are explicitly marked as negative.

```
/*********************************************
 * OPL 12.5.1.0 Model
 * Author: Henning Gösling based on Vitoriano et al. (2011)
 * Creation Date: 26.11.2014 at 12:32:15
 *********************************************/
{string} Locations = ...;
{string} TypesOfTransportationVehicles = ...;
float BigNumber1 = ...;
float BigNumber2 = ...;
float BigNumber3 = ...;
float BigNumber4 = ...;
float BigNumber5 = ...;
float BigNumber6 = ...;
float CostsForDriving
[Locations,Locations,TypesOfTransportationVehicles] = ...;
float CostsForTransportation
[Locations,Locations,TypesOfTransportationVehicles] = ...;
float Capacity[TypesOfTransportationVehicles] = ...;
float CrossingProbability[Locations,Locations] = ...;
float Distance[Locations,Locations] = ...;
float Demand[Locations] = ...;
float NumberMaximumConvoy = ...;
float NumberReliefItems = ...;
float NumberTransportationVehicles
[Locations,TypesOfTransportationVehicles] = ...;
float Priority[Locations] = ...;
```

```
float RansackProbability[Locations,Locations] = ...;
float NotRansackProbabiltiy[Locations,Locations] = ...;
float UpperSpeedLimitArc[Locations,Locations] = ...;
float UpperSpeedLimitTransportationVehicle
[TypesOfTransportationVehicles] = ...;
float Supply[Locations] = ...;
float TargetCosts = ...;
float TargetCrs = ...;
float TargetMnCrs = ...;
float TargetMxR = ...;
float TargetMxRt = ...;
float TargetMxU = ...;
float TargetP = ...;
float TargetR = ...;
float Useable[Locations,Locations,TypesOfTransportationVehicles] = ...;
float WeightCosts = ...;
float WeightCrs = ...;
float WeightMnCrs = ...;
float WeightMxR = ...;
float WeightMxRt = ...;
float WeightMxU = ...;
float WeightP = ...;
float WeightR = ...;
dvar float+ Costs;
dvar float Crs;
dvar float+ DCosts;
dvar float+ DCrs;
dvar float+ DMnCrs;
dvar float+ DMxR;
dvar float+ DMxRt;
dvar float+ DMxU;
dvar float+ DP;
dvar float+ DR;
dvar float+ MnCrs;
dvar float MxR;
dvar float+ MxRt;
dvar float+ MxU;
dvar float+ P;
dvar float R;
dvar float+ ReachingTime[Locations];
dvar int+ DrivingFinalDestination
[Locations,TypesOfTransportationVehicles];
dvar int+ Driving[Locations,Locations,TypesOfTransportationVehicles];
dvar float+ Staying[Locations];
```

```
dvar float+ Transferred[Locations,Locations];
dvar float+ TransferredByTransportationVehicleType
[Locations,Locations,TypesOfTransportationVehicles];
dvar boolean ArcUsed[Locations,Locations];
dvar boolean ArcUsedByTransportationVehicleType
[Locations,Locations,TypesOfTransportationVehicles];
dvar boolean LocationFinalDestination
[Locations,TypesOfTransportationVehicles];

minimize

(DCosts/TargetCosts) * WeightCosts +
(DCrs/TargetCrs) * WeightCrs +
(DMnCrs/TargetMnCrs) * WeightMnCrs +
(DMxR/TargetMxR) * WeightMxR +
(DMxRt/TargetMxRt) * WeightMxRt +
(DMxU/TargetMxU) * WeightMxU +
(DP/TargetP) * WeightP +
(DR/TargetR) * WeightR;

subject to{
ct80:
forall(g in Locations)
sum (h in Locations:h!=g)
Transferred[h,g] +
Supply[g] ==
sum (h in Locations:h!=g)
Transferred[g,h] +
Staying[g];

ct81:
forall(g in Locations)
Staying[g] <= Demand[g] + Supply[g];

ct82:
sum (g in Locations)
Staying[g] ==
sum (g in Locations)
Supply[g];

ct83:
forall(g in Locations, z in TypesOfTransportationVehicles)
sum (h in Locations:h!=g)
Driving[h,g,z] +
```

```
NumberTransportationVehicles[g,z] ==
sum (h in Locations:h!=g)
Driving[g,h,z] +
DrivingFinalDestination[g,z];

ct84:
forall(z in TypesOfTransportationVehicles)
sum (g in Locations)
NumberTransportationVehicles[g,z] ==
sum (g in Locations)
DrivingFinalDestination[g,z];

ct85:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
if (Useable[g,h,z] == 0)
Driving[g,h,z] == 0;

ct86:
forall(g in Locations, h in Locations)
ReachingTime[h] >=
ReachingTime[g] +
Distance[g,h]/UpperSpeedLimitArc[g,h] -
BigNumber1 *
(1 - ArcUsed[g,h]);

ct87:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
ReachingTime[h] >=
ReachingTime[g] +
Distance[g,h]/UpperSpeedLimitTransportationVehicle[z] -
BigNumber2 *
(1 - ArcUsedByTransportationVehicleType[g,h,z]);

ct88:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
Driving[g,h,z] <=
BigNumber3 * ArcUsedByTransportationVehicleType[g,h,z];

ct89:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
ArcUsedByTransportationVehicleType[g,h,z] <=
Driving[g,h,z];

ct90:
```

```
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
ArcUsedByTransportationVehicleType[g,h,z] <=
ArcUsed[g,h];

ct91:
forall(g in Locations, h in Locations)
ArcUsed[g,h] <=
sum (z in TypesOfTransportationVehicles)
ArcUsedByTransportationVehicleType[g,h,z];

ct92:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
sum (zI in TypesOfTransportationVehicles)
Capacity[zI] * Driving[g,h,zI] -
Capacity[z] <=
Transferred[g,h] +
BigNumber4 *
(1 - LocationFinalDestination[h,z]);

ct93:
forall(g in Locations, z in TypesOfTransportationVehicles)
DrivingFinalDestination[g,z] <=
BigNumber5 * LocationFinalDestination[g,z];

ct94:
forall(g in Locations, z in TypesOfTransportationVehicles)
LocationFinalDestination[g,z] <=
DrivingFinalDestination[g,z];

ct95:
forall(g in Locations, h in Locations)
Transferred[g,h] ==
sum (z in TypesOfTransportationVehicles)
TransferredByTransportationVehicleType[g,h,z];

ct96:
forall(g in Locations, h in Locations, z in TypesOfTransportationVehicles)
TransferredByTransportationVehicleType[g,h,z] <=
Capacity[z] * Driving[g,h,z];

ct97:
sum (g in Locations: Demand[g]>0)
Staying[g] == NumberReliefItems;
```

```
ct98:
Costs == sum(g in Locations, h in Locations, z in TypesOfTransportation-
Vehicles)
(2 * CostsForDriving[g,h,z] * Distance[g,h] * Driving[g,h,z] +
CostsForTransportation[g,h,z] * Distance[g,h] *
TransferredByTransportationVehicleType[g,h,z] );

ct99:
Costs - DCosts <=
TargetCosts;

ct100:
forall (g in Locations)
MxRt >=
ReachingTime[g];

ct101:
MxRt -
DMxRt <=
TargetMxRt;

ct102:
forall (g in Locations: Demand[g]>0)
MxU >=
1 - (Staying[g]/Demand[g]);

ct103:
MxU -
DMxU <=
TargetMxU;

ct104:
forall (g in Locations)
if (Priority[g] == 1)
P == Staying[g]/Demand[g];
ct105:
P +
DP >=
TargetP;

ct106:
forall (g in Locations, h in Locations)
MnCrs <=
CrossingProbability[g,h] +
```

```
1 - ArcUsed[g,h];
ct107:
MnCrs +
DMnCrs >=
TargetMnCrs;

ct108:
Crs ==
sum (g in Locations, h in Locations)
(log (CrossingProbability[g,h] ) * ArcUsed[g,h]);

ct109:
Crs + DCrs >=
-TargetCrs;

ct110:
forall (g in Locations, h in Locations)
MxR >=
(log (RansackProbability[g,h])) *
sum(z in TypesOfTransportationVehicles)
Driving[g,h,z]  -
BigNumber6 * (1 - ArcUsed[g,h]);

ct111:
MxR -
DMxR <=
-TargetMxR;

ct112:
R == sum (g in Locations, h in Locations)
((log (NotRansackProbabiltiy[g,h]) *
(2 - ((sum(z in TypesOfTransportationVehicles)
Driving[g,h,z]) /
NumberMaximumConvoy ) -
2 * (1 - ArcUsed[g,h]))));

ct113:
R +
DR >=
-TargetR;
}
```

4.4 Conclusions concerning the content of the online OR toolkit for humanitarian logistics

So far, the proposed structure of the online OR toolkit for humanitarian logistics includes nine published mathematical programs, as shown in Figure 4.23 (for section 4.1), Figure 4.24 (section 4.2), and Figure 4.25 (section 4.3). Due to the nature of the present work, chapter 4 can be interpreted as a shortened, paper version of the online toolkit. It is a shortened version, given that not all OR models identified in section 3.3 were included.

As stated in section 3.4 (pp. 31ff), the online OR toolkit for humanitarian logistics should have several functions. It should help

1. practitioners (in the field of humanitarian logistics) to find, adapt, and combine available OR models for their specific problem(s);
2. practitioners to convert an OR model into a computerized model;
3. practitioners to build a database for the computerized model;
4. practitioners to interact with academics, whereby academics could help practitioners to adapt and apply their model while practitioners could give feedback on the OR model's assumptions (conceptual model validation) and on its usefulness for the practitioners' use cases (operational validation) which can then be used again by academics to update their OR model; and
5. academics to analyze available OR models whereby identifying open research questions and reducing the risk of redundant or useless model building.

Obviously, the hierarchies shown in Figure 4.23, Figure 4.24, and Figure 4.25 provide ways for practitioners to find an appropriate OR model. Guidance is given based on the phase in the disaster management cycle, on the task the practitioner wants to support using an OR model in a specific phase, on the attributes of a specific logistical resource an OR model can help to specify (or on the key dimensions, objectives, and requirements used to determine the most advantageous configuration of these attributes), as well as on the OR methodology that was used to capture a certain problem. Problems are expressed in mathematical and machine-readable form. Additionally, problems are analyzed based on a structuring scheme that was developed in chapter 3. This scheme was applicable to capture different types of mathematical programs for humanitarian logistics in a consistent way; more exactly, it was shown that the scheme can capture programs of the following categories: IPs, MILPs, stochastic programs, goal programs, location models, service network design models, and route enumeration models.

The problem structuring scheme can be used by practitioners to obtain a complete understanding of a problem captured in an OR model; i.e. of the environment wherein the problem takes place, of the fixed and variable attributes of the organizational resources, of the allowed interactions between organizational resources and the elements in the environment, and of the performance measures of the organization. A complete understanding is necessary in order to adapt an available

OR model – and the available program code constitutes a starting point for the necessary programming effort due to the adaption. However, if practitioners are fully satisfied with an available OR model, the program code enables them to apply the model directly, without any additional programming effort.

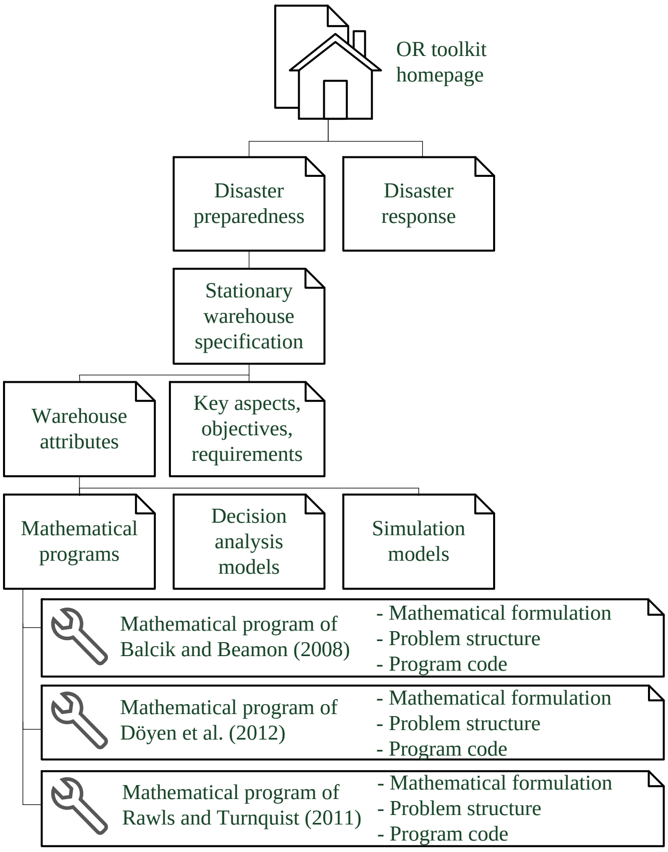


Figure 4.23. Content of the stationary warehouse specification toolkit

The problem structuring scheme also helps practitioners understand whether a certain model can only be applied in response to a certain type of disaster or whether it can be applied in response to any type of disaster. None of the included models specifically concentrates on a certain type of disaster. Unfortunately, some of the corresponding publications have titles which could be misleading for practitioners searching for useful OR models. This is most obviously the case with the model of Murali et al. (2012). Even though the title is “Facility location under demand uncertainty: Response to a large-scale bio-terror attack”, the problem structuring framework reveals that the model does not include any assumptions that would prohibit the model’s application in response to other disasters than terror attacks. Horner and Downs (2010) also use a possibly prohibitive title: “Optimizing hurricane disaster relief goods distribution: model development and application with respect to planning strategies". Their model includes the assumption that beneficiaries are notified of their nearest local distribution center (LDC). This indeed might be easier to do if a disaster can be anticipated – such as a hurricane. However, the model can also be applied in response to other disasters as long as this assumption holds.

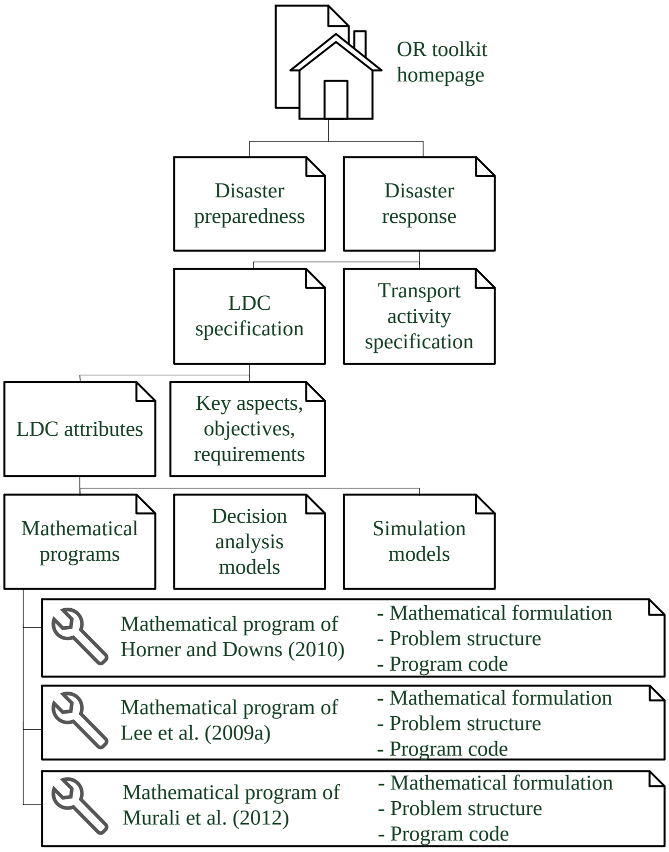


Figure 4.24. Content of the local distribution center specification toolkit

The problem structuring scheme is also of use to understand the links between different OR models. For example, the model of Balcik and Beamon (2008) helps specify the location and relief item stock of one or more stationary warehouses while a necessary piece of information in order to run the model of Murali et al. (2012) is the quantity of available relief items at a supply facility. The model of Murali et al. (2012) supports decisions regarding the locations of LDCs. Finally, the necessary information to run the model of Balcik et al. (2008) include the location of a supply facility – e.g. the location of a stationary warehouse as determined in the OR model of Balcik and Beamon (2008) – and a set of locations for LDCs.

Figure 4.26 gives an overview of the interconnections between the included OR models. An arrow is drawn between two OR models if any output of the one OR model can be used as an input for the other OR model. As shown in Figure 4.26, the included OR models are highly interwoven. Generally speaking:

- OR models supporting the specification of stationary warehouses can provide those OR models with information supporting the specification of LDCs; only the OR model of Lee et al. (2009a) supports the specification of LDCs without information about a supply facility.
- OR models supporting the specification of stationary warehouses and OR models supporting the specification of LDCs can provide those OR models with information that support the specification of transportation activities.

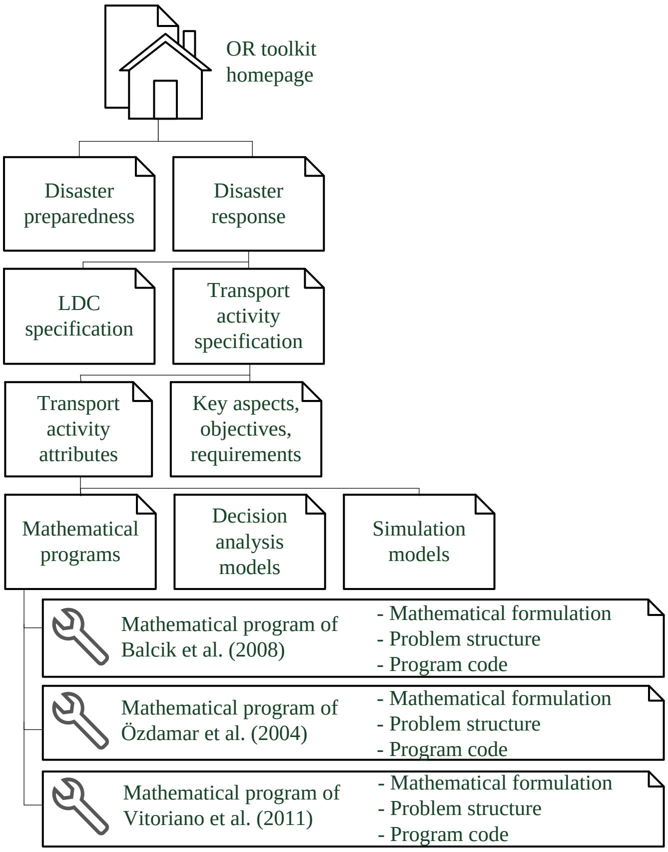


Figure 4.25. Content of the transport specification toolkit

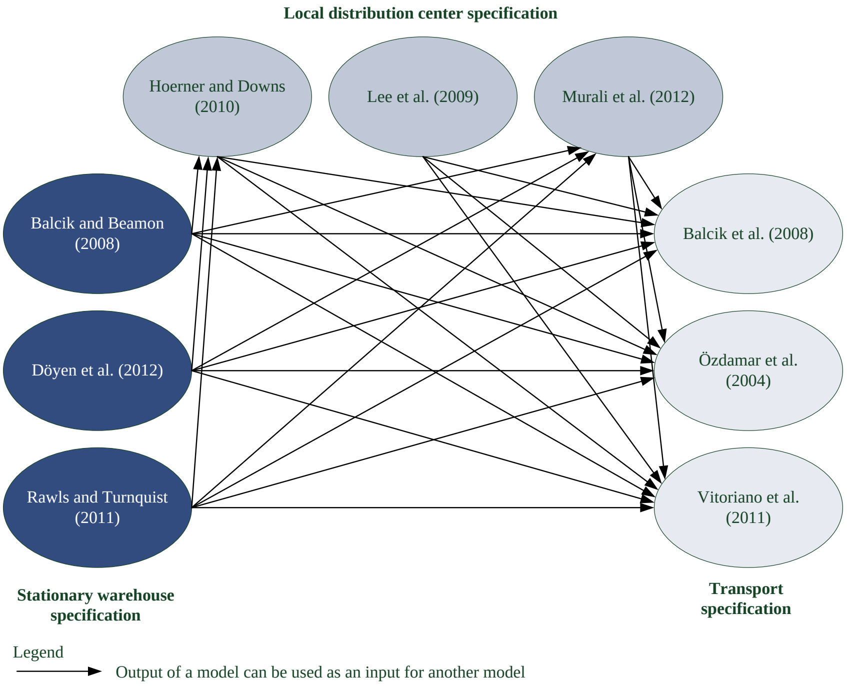


Figure 4.26. Interconnections between OR models included in the toolkit

The problem structuring scheme is also useful in order to help practitioners to distinguish between the different environmental elements and organizational resources which need to be specified in order to run a particular OR model. Often, the necessary numeric data regarding environmental elements and organizational resources is not explicitly stated in the original mathematical formulation. For example, a certain parameter in the OR model of Balcik and Beamon (2008) describes the time needed to fulfil a relief item demand at a certain location. Data on different elements and resources is necessary in order to calculate this parameter: the coordinates of the stationary warehouse location and the demand location, the distance between these location, speed limitations on the arc, the maximum speeds of the available transportation vehicle types, the transport volume and weight per vehicle of a certain type, the number of available vehicles per type, and the volume and weight per unit of the necessary relief items. Hence, the problem structuring scheme uncovers the numeric data about the environmental elements and organizational resources that is necessary to run an OR model – and if a database of a humanitarian organization would provide this data, an OR model could be applied automatically. Even more, a relational database that would be structured in accordance with the model profiles of all OR models already included in the online OR toolkit and implemented with a database management system such as

Microsoft Access, Oracle, or 4th Dimension, would enable humanitarian organizations to apply all these models automatically. Generally speaking, this would support the experimentation phase of the model development process, because there would be no need for manual data handling. The translation of the problem structuring schemes into a database structure can be supported by five principles developed by Fourer (1997):

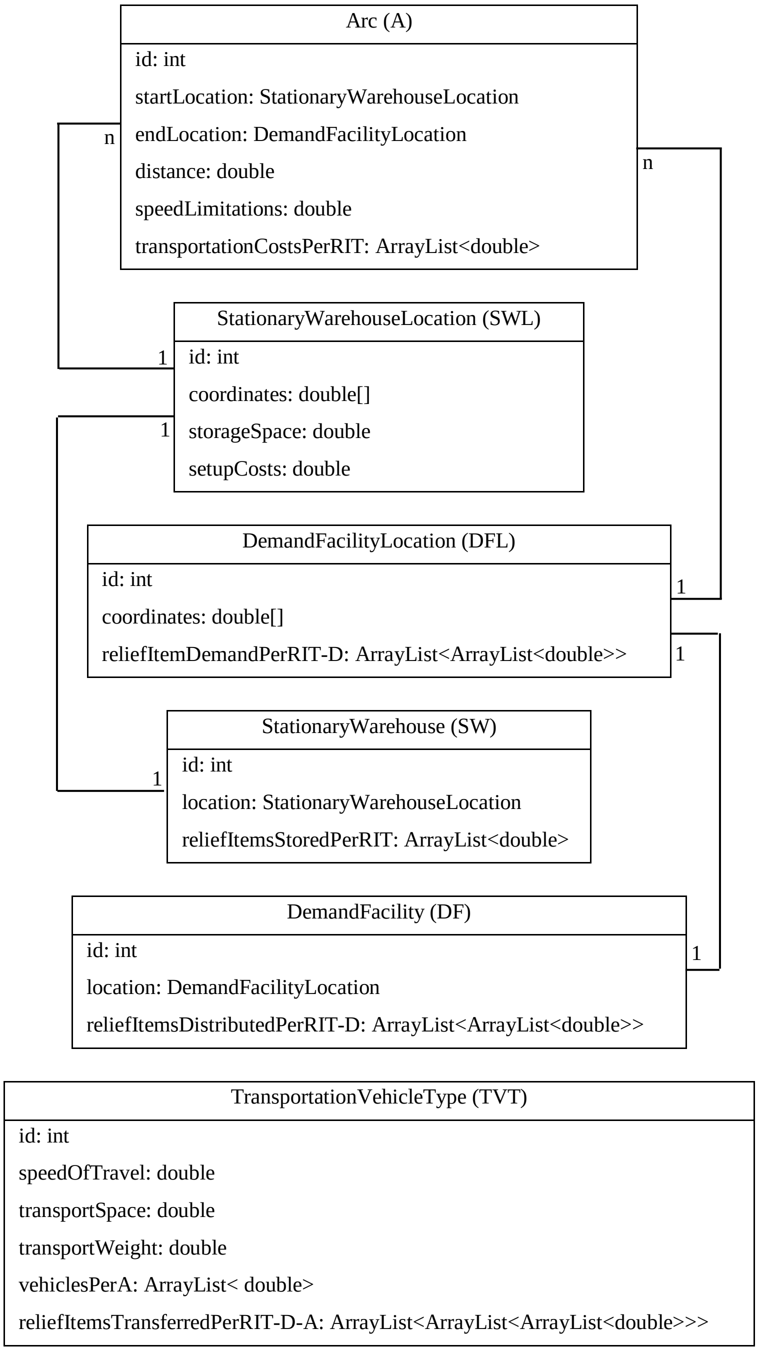
- for each set in the model, there is a corresponding file in the database,
- each file has a number of key fields equal to the dimension of the set,
- each file has as many data fields as there are attributes of the set's members,
- each member has a value for each attribute, and
- an attribute value of a member can correspond to a key field of another file.

For example, each of the eight different sets defined in the model profile of Balcik and Beamon (2008) – disasters, locations for stationary warehouses, locations for demand facilities, arcs, stationary warehouses, demand facilities, transportation vehicle types, and relief item types – would relate to a unique class in a relational database. In the case of the arc-class, the number of key fields would be equal to the dimension of the corresponding set, i.e. the number of arcs defined. Moreover, the arc-class would have five data fields (start location, end location, distance, speed limitations, and transportation costs). Each member of the arc-class would have a record, i.e. a value for its start location, end location, distance, speed limitations, and transportation costs. Start and end location are represented by keys belonging to certain records in the classes for stationary warehouse locations and demand facility locations, respectively. Table 4.13 shows the structure of the classes that contain the environmental and organizational data to run the OR model of Balcik and Beamon (2008). Data about certain factors (e.g. transportation costs for arcs and importance weights for relief items) can be integrated into these eight classes. However, two additional classes have to be defined to capture data about the coverage levels and budgets. The class diagram is shaped using the Unified Modeling Language (UML).

Table 4.13. UML classes containing data to run the OR model of Balcik and Beamon (2008)

Disaster (D)
id: int probabilityOfOccurrence: double

ReliefIitemType (RIT)
id: integer volume: double weight: double procurementHoldingCostsPerSWL: ArrayList<double> importanceFactor: double


Arc (A)
id: int
startLocation: StationaryWarehouseLocation
endLocation: DemandFacilityLocation
distance: double
speedLimitations: double
transportationCostsPerRIT: ArrayList<double>
n
n
StationaryWarehouseLocation (SWL)
id: int
coordinates: double[]
storageSpace: double
setupCosts: double
1
1
DemandFacilityLocation (DFL)
id: int
coordinates: double[]
reliefItemDemandPerRIT-D: ArrayList<ArrayList<double>>
1
1
StationaryWarehouse (SW)
id: int
location: StationaryWarehouseLocation
reliefItemsStoredPerRIT: ArrayList<double>
1
DemandFacility (DF)
id: int
location: DemandFacilityLocation
reliefItemsDistributedPerRIT-D: ArrayList<ArrayList<double>>
1
TransportationVehicleType (TVT)
id: int
speedOfTravel: double
transportSpace: double
transportWeight: double
vehiclesPerA: ArrayList< double>
reliefItemsTransferredPerRIT-D-A: ArrayList<ArrayList<ArrayList<double>>>

CoverageLevel (CL)
id: int
upperDistanceLimit: double
lowerDistanceLimit: double
importanceWeight: double

Budget (B)
id: int
disasterPreparedness: double
disasterResponse: double

Finally, the available OR models can be analyzed based on the problem structuring schemes. In other words, the schemes can be used to determine which aspects are and which aspects are not captured in a model's mathematical formulation. For example, the quantity of distributed relief items, the quality of distributed relief items, the delivery times of relief items, and the beneficiaries' distances to LDCs are key dimensions often considered in the analyzed OR models for humanitarian logistics. Only one model (Vitoriano et al., 2011) takes social effects into account. Environmental and financial effects as defined in Table 2.3 (p. 16) are not considered in any of those models in chapter 4.

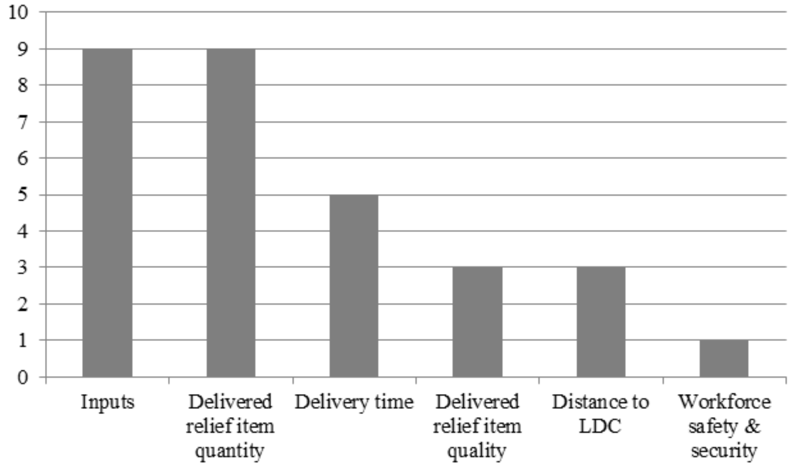


Figure 4.27. Exemplary analysis – number of times a key dimension, as defined in Table 2.3, is considered in the OR models that are included in the toolkit

Based on a complete online OR toolkit for humanitarian logistics (with all available models characterized based on the problem structuring scheme) the current state of the used key dimensions in OR models for humanitarian logistics could be presented – and if a complete toolkit would be updated regularly, the development of used key dimensions could be tracked over time. Figure 4.27 shows an exemplary analysis of the key dimensions in the OR models which were analyzed in chapter 4. Generally, a complete OR toolkit would allow researchers to analyze the available models in order to identify open research questions as well as sufficiently covered topics. Thereby the risk of redundant model building would be reduced.

To conclude, the abridged paper version of the proposed online OR toolkit for humanitarian logistics – as presented in this chapter – can be used by practitioners to find, adapt, and combine available OR models for humanitarian logistics (function 1, p. 180), to apply an available OR model by using the program code (function 2), to develop a relational database for such an OR model (function 3) as well as for academics to analyze the available OR models in order to identify open research questions and sufficiently covered topics (function 5).

5 An application of the online OR toolkit for humanitarian logistics

In this chapter, one function of the toolkit is described in detail: the combination of available OR models for humanitarian logistics. For this purpose, a case study is used, one that takes place in the Philippines, which is a country vulnerable to tropical storms, floods, landslides, earthquakes, and tsunamis (EM-DAT, n.d.a). Table 5.1 lists the worst natural disasters in the Philippines between 1900 and 2015 sorted by the numbers of affected people (EM-DAT, n.d.a) – almost all of the disasters were storms. Figure 5.1 (p. 190) shows the regions in the Philippines generally at risk of storms of specific intensities.

Table 5.1. Worst natural disasters in the Philippines between 1900 and 2015 sorted by the numbers of total affected people (EM-DAT, n.d.a)

Disaster	Date	Affected people
Storm	8. November 2013	16,106,870
Storm	4. December 2012	6,246,664
Storm	12. November 1990	6,159,569
Storm	24. September 2009	4,901,763
Storm	21. June 2008	4,785,460
Storm	29. September 2009	4,478,491
Flood	6. August 2012	4,451,725
Storm	12. December 2014	4,150,400
Storm	21. October 1998	3,902,424
Storm	27. September 2006	3,842,406

This case study focuses on the warehousing and distribution of plastic tarpaulins. Plastic tarpaulins are important immediately after a disaster occurs. For example, after an earthquake hit the Indonesian island of Java in May 2006, these items were distributed so that the sick, weak, young, and elderly were under cover as rain was falling each night following the earthquake. The distribution of tarps started 10 hours after the earthquake took place (UNHABITAT et al., n.d., p. 49). When stocked in warehouses, plastic tarpaulins should be kept out of the sun, away from rodents, and in a dry location (IFRC and Oxfam, 2007, p. 15).

In the following, the toolkit is used to (1) set up a system of stationary warehouses for stocking plastic tarpaulins in the disaster preparedness phase, (2) set up a system of LDCs during a specific disaster response while taking into account the decisions made under (1), and (3) specify transportation activities between stationary warehouses and LDCs during a specific disaster response while taking into account the decisions made under (1) and (2).

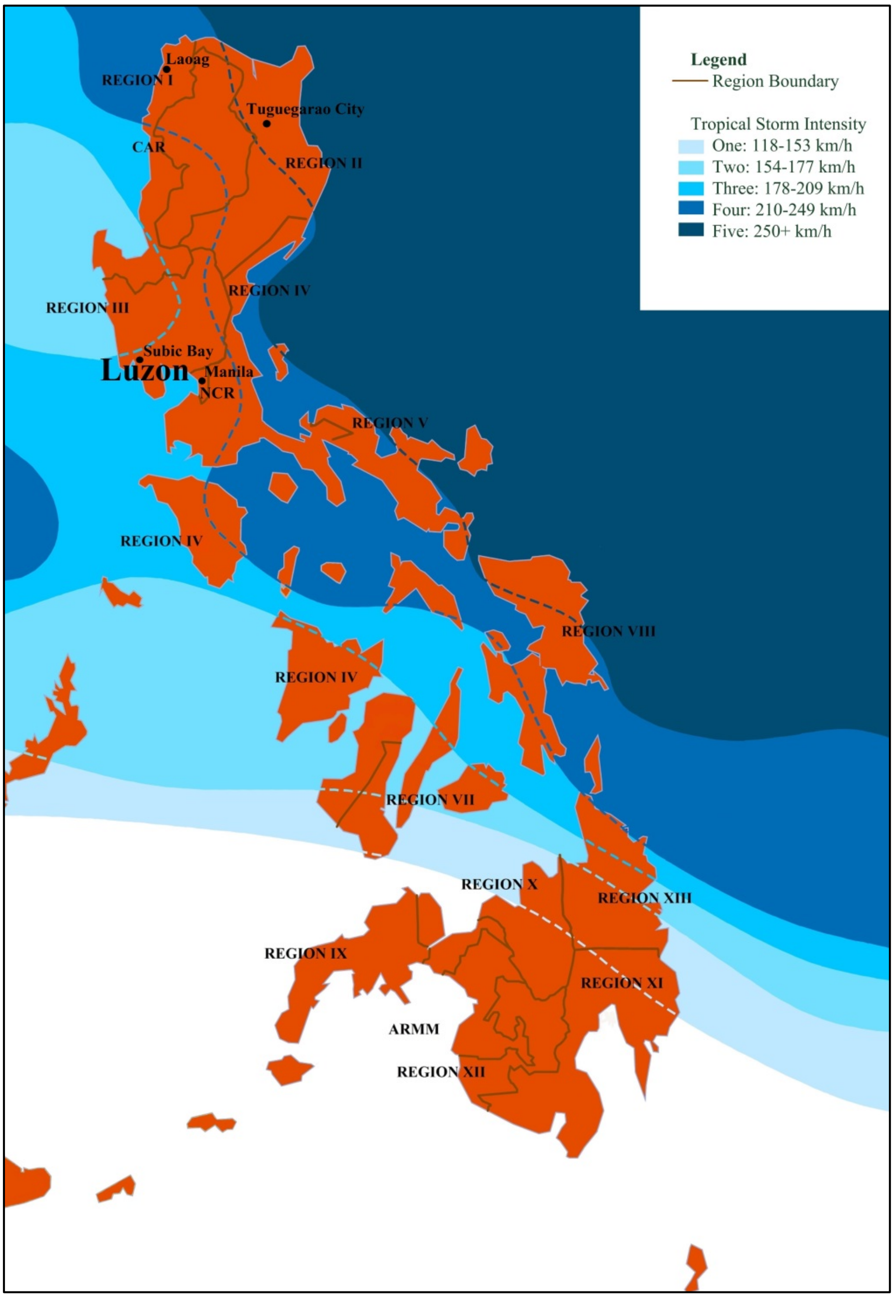


Figure 5.1. Map of the Philippines (adapted from UNOCHA, 2011b)

5.1 Application of the stationary warehouse specification toolkit

The toolkit is used to set up a system of stationary warehouses on Luzon, the largest and most populous island of the Philippines (Figure 5.1). Luzon is at risk of being hit by tropical storms of category five with wind speeds of more than 250 km/h. The island is divided into seven regions: National Capital Region (NCR), Cordillera Administrative Region (CAR), Ilocos Region (Region I), Cagayan Valley (Region II), Central Luzon (Region III), and Calabarzon (Region IV), and Bicol Region (Region V).

Following the OR toolkit structure presented in chapter 4, the OR models of Balcik and Beamon (2008), Döyen et al. (2012), and Rawls and Turnquist (2011) are available for determining a system of stationary warehouses. In this case study, the mathematical program of Balcik and Beamon (2008) is used. Three types of data needs to be gathered according to the model's profile (Table 4.2, pp. 53ff): data about the elements in the environment, data about the available logistics resources and relief items, and data about certain factors (e.g. costs) and bounds (e.g. budgets) necessary to determine the most advantageous configuration. Table 5.2 gives an overview on the data to be gathered. The last column of Table 5.2 indicates how the data relates to the parameters of the OR model.

Firstly, data about environmental elements is needed. Possible disasters are identified using Figure 5.1. A region on Luzon island is a possible disaster area, if this region is – according to this map – at risk of getting hit by a tropical storm with the highest (category 5) or the second-highest (category 4) intensity. Each possible disaster has a probability of occurrence of 10% within the next 10 years (UNOCHA, 2011b). Laoag International Airport, Manila International Airport, and Subic Bay International Airport are selected as potential locations of a stationary warehouse for plastic tarpaulins; each with a maximum storage space of 100,000 m³. The locations of Laoag, Subic Bay, and Manila on Luzon are marked in Figure 5.1. Locations for demand facilities (from where relief items are distributed to downstream facilities and/ or directly to beneficiaries) are the principal cities of those regions which may be possibly hit by a tropical storm of category four or five: Baguio (Region CAR), San Fernando-La Union (Region I), Tuguegarao City (Region II), San Fernando-Pampanga (Region III), Calamba (Region IV), and Legazpi (Region V). Roadways have a certain distance, speed limitations, and lay between potential locations of stationary warehouses and locations of potential demand. Distances are calculated using Google Maps. Speeds are assumed to be limited to 30 km/h during a disaster response due to infrastructure damages. Available data for the category-five typhoon Pablo, which hit the southern Region XI in December 2012, is used to calculate the number of plastic tarpaulins needed at locations for demand facilities in the case of a typhoon. Region XI, having a population of 4,468,563 million people, received 10,233 emergency shelter kits in the aftermath of Pablo (UNHCR et al., 2014); that translates to 0.0023 emergency shelter kits per person. Based on this proportion, the number of plastic tarpaulins for each possible disaster is estimated.

Table 5.2. Necessary data for applying the OR model of Balcik and Beamon (2008)

Category	Data	OR model representation
Disasters	Probability of occurrence	Parameter prb_s
Locations for stationary warehouses	Coordinates	Parameter t_{irs}^{sf}
	Storage space	Parameter $SpcW_i$
Locations for demand facilities	Coordinates	Parameter t_{irs}^{sf}
	Relief item demands in disasters	Parameter dmd_{rs}
Arcs	Start location	Parameter t_{irs}^{sf}
	End location	Parameter t_{irs}^{sf}
	Distance	Parameter t_{irs}^{sf}
	Speed limitation	Parameter t_{irs}^{sf}
Demand facilities	Demand facility location	Parameter t_{irs}^{sf}
Transportation vehicle types	Speed of travel	Parameter t_{irs}^{sf}
	Transport space	Parameter t_{irs}^{sf}
	Transport weight	Parameter t_{irs}^{sf}
	Vehicles on arcs	Parameter t_{irs}^{sf}
Relief item types	Volume	Parameter $spcW_r$
	Weight	Parameter t_{irs}^{sf}
Factors and bounds	Setup costs per location for a stationary warehouses	Parameter C_i^{s}
	Transportation costs between locations per relief item type unit	Parameter c_{irs}^{t}
	Procurement and holding costs per relief item type unit and location for a stationary warehouses	Parameter c_{ir}^{ah}
	Upper time limit per coverage level	Parameter tMx_{a_r}
	Lower time limit per coverage level	Parameter tMn_{a_r}
	Importance factor per coverage level	Parameter ω_{a_r}
	Importance factor per relief item type	Parameter ω_r
	Budget in the disaster preparedness phase	Parameter bgt^{P}
	Budget in the disaster response phase	Parameter bgt^{R}

Secondly, data about the available logistics resources and relief items is needed. The transportation vehicle type used during a possible disaster is assumed to be a large truck with a standard 40 feet container as its transporter unit. Ten large trucks are available per roadway. The maximum transport volume is 65 m³ per vehicle and maximum transport weight is 26 t per vehicle (PAHO, 2001, p. 127). The volume of an emergency shelter kit is 0.0122 m³ and its weight is 4.2 kg (IFRC, n.d.a).

Thirdly, the necessary factors and bounds needed to calculate the performance of a certain configuration of stationary warehouses must be determined. The necessary factors and bounds are: budgets for the disaster preparedness phase (US$250,000) and response phase (US$500,000), transportation costs between two locations per relief item unit (US$0.05 per km), procurement and holding costs per relief item unit (US$15 at each potential location for a warehouse), warehouse setup costs at a potential location (US$100,000 at Laoag International Airport, US$200,000 at Manila International Airport, and US$100,000 at Subic Bay International Airport), upper and lower time limits describing a certain coverage level (0-5.99 hours for coverage level “high”, 6-11.99 hours for coverage level “medium”, and 12-∞ hours for coverage level “low”), as well as weights that describe the importance of coverage levels (3 for coverage level “high”, 2 for coverage level “medium”, and 1 for coverage level “low”) and a weight that describes the importance of plastic tarpaulins for beneficiaries (1 for category “very important”).

Table A.1 (Appendix) captures the data necessary to apply the program code presented in section 4.1.1. The results of the application to the case study are shown in Table A.2 (Appendix). Accordingly, a stationary warehouse is set up at the International Airport of Subic Bay and 10,000 emergency shelter kits are prepositioned in this stationary warehouse. Results were obtained using the CPLEX Optimization Studio version 12.5.1.

5.2 *Application of the local distribution center specification toolkit*

It is assumed that the island of Luzon was hit by a typhoon. In response, a system of LDCs is set up in Tuguegarao City, a city in the north of Cagayan Valley (Region II). A map of Tuguegarao City is shown in Figure 5.2 and the location of Tuguegarao City on Luzon is marked in Figure 5.1.

The system of LDCs can be supplied by the stationary warehouse located at the Subic Bay airport and stocked with 10,000 emergency shelter kits. Using the toolkit presented in chapter 4, the OR models of Horner and Downs (2010), Lee et al. (2009a), and Murali et al. (2012) can be applied to set up a system of LDCs in Tuguegarao City. Taking a look at the needed data to apply these OR models, it can be stated that:

- the OR model of Horner and Downs (2010) takes the location of a supply facility into account;

- the OR model of Lee et al. (2009a) takes neither the location nor the stocks of a supply facility into account; and
- the OR model of Murali et al. (2012) takes the stocks of a supply facility into account.

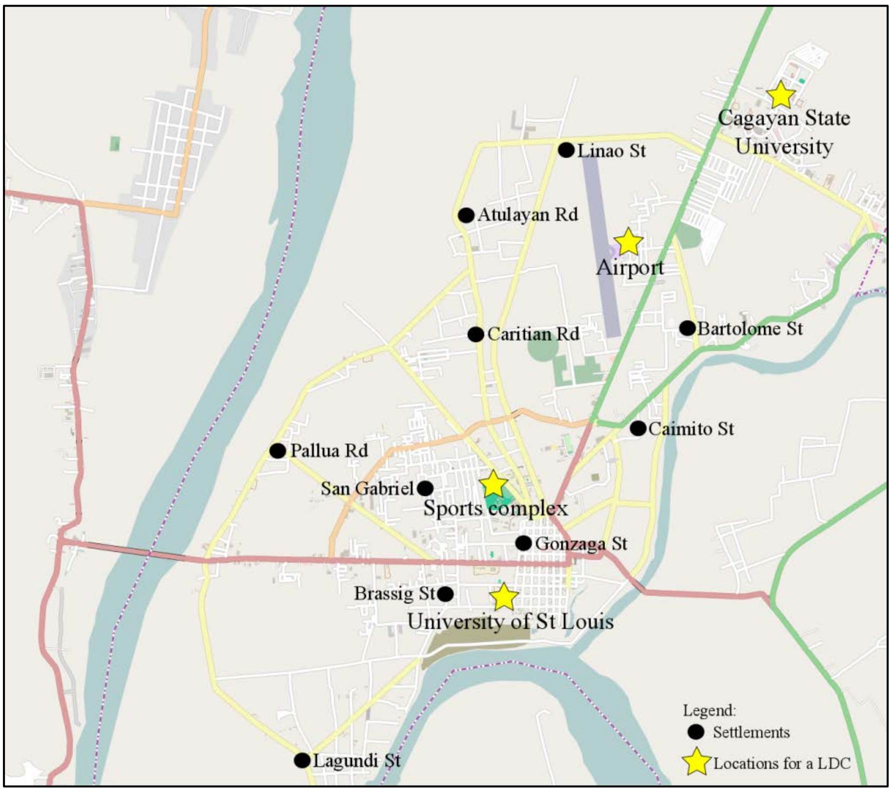


Figure 5.2. Map of Tuguegarao City (adapted from Open Steet Map, n.d.)

Therefore, in order to make use of the available information about the warehouse (i.e. the location and/ or stock of the stationary warehouse at the Subic Bay airport), the model of Horner and Downs (2010) (in order to make use of the information about the warehouse's location) or the model of Murali et al. (2012) (in order to make use of the information about the warehouse's stock) can be used. The latter is chosen given the distances are almost identical (ca. 468 km by road according to Google Maps) between the supply facility at Subic Bay airport and potential locations of LDCs within Tuguegarao City. Hence, the location of the supply facility would not have any impact on the configuration of the LDC system. In the following, the model of Murali et al. (2012) is used to install LDCs in Tuguegarao City. Three types of data need to be gathered according to the model's profile (Table 4.8, pp.119f): data about the elements in the environment, about the logistics resources and relief items, and about certain bounds necessary to determine the most advantageous configuration of LDCs. Table 5.3 outlines the data to be gathered. The last column indicates how the data relates to the parameters of the OR model.

Table 5.3. Necessary data for applying the OR model of Murali et al. (2012)

Category	Data	OR model representation
Disaster		
Locations for LDCs	Coordinates	Parameter d_{bm}
Settlements	Coordinates	Parameter d_{bm}
	Relief item demand	Parameter dmd_b
Arcs	Start location	Parameter d_{bm}
	End location	Parameter d_{bm}
	Distance	Parameter d_{bm}
Supply facility	Relief items stocked	Parameter spl
Aid workers	Working time	Parameter $CapD_m$
	Number at locations for a LDC	Parameter $CapD_m$
Relief item	Time for distribution	Parameter $CapD_m$
Factors and bounds	Number of LDCs to be erected	Parameter Nf
	Duration of disaster response	Parameter $CapD_m$
	Upper distance limit per coverage level	Parameter dMx_a
	Maximum percentage of demand at a settlement to be satisfied from LDCs that provide a certain coverage level	Parameter shr_a

Firstly, data about the elements in the environment is gathered. Locations for LDCs in Tuguegarao City are the sports complex, the airport, the University of St Louis, and the Cagayan State University. Locations for LDCs are marked by a star in the map of Tuguegarao City (Figure 5.2). Settlement locations (each represented by a single coordinate) and the corresponding demands for emergency shelter kits are assumed to be: San Gabriel (200 kits), Bassig Street (600 kits), Gonzaga Street (400 kits), Lagundi Street (300 kits), Pallua Road (100 kits), Caimito Street (100 kits), Bartolome Street (100 kits), Atulayan Road (100 kits), Linao-Carig Road (300 kits), and Caritian Highway (200 kits). Each arc between a location for a LDC and a settlement location describes a footpath. Walking distances were calculated using Google Maps.

Secondly, data on the available logistics resources and relief items needs to be gathered. Each location for a LDC is characterized by a capacity to distribute 504 emergency shelter kits per day. More exactly, each location is characterized by three available aid workers. Each aid worker is capable of working seven hours a day and each aid worker needs 2.5 minutes for the distribution of one emergency shelter kit.

Thirdly, the bounds necessary to calculate the performance of a certain configuration of LDCs are determined: they are, number of LDCs to be erected (one LDC), upper (and thereby lower) distance limits of coverage levels (0-2.99 km for a “high” coverage level, 3-4.99 km for a “medium” coverage level, and 5-7 km for a “low” coverage level), and the maximum percentage of a settlement’s demand that can be satisfied from LDCs providing a certain coverage level (maximum 100% demand satisfaction from LDCs providing “high” coverage, maximum 50% from LDCs providing “medium” coverage, and maximum 10% from LDCs providing “low” coverage). The assumed planning horizon for the disaster response is five days.

Table A.3 (Appendix) comprises the data that is necessary to apply the OR model of Murali et al. (2012); i.e. to apply the corresponding program code presented in section 4.2.3. The results of the application to the case study are shown in Table A.4 (Appendix). Accordingly, a LDC is set up at the sport complex. Results were obtained using the CPLEX Optimization Studio version 12.5.1.

5.3 Application of the transport specification toolkit

The specification of transportation activities between the stationary warehouse at the Subic Bay airport and the LDCs, which are opened throughout Luzon in response to the typhoon, can also be supported by the toolkit presented in chapter 4. It is assumed that 23 LDCs are opened in the aftermath of the typhoon – including the one in Tuguegarao City that was specified in section 5.2. Using the toolkit, the models of Balcik et al. (2008), Özdamar et al. (2004) and Vitoriano et al. (2011) could be chosen. While the OR models of Özdamar et al. (2004) and Vitoriano et al. (2011) only differ between supply facilities, transshipment facilities, and demand facilities, Balcik et al. (2008) explicitly focus on the last leg of transportation activities between some sort of supply facility (e.g. a stationary warehouse) and LDCs. This is why the model of Balcik et al. (2008) is selected to specify the transportation activities between the single stationary warehouse at the Subic Bay airport and the 23 LDCs located all over Luzon island. Three types of data need to be gathered according to the model’s profile (Table 4.10, pp. 133ff): data concerning the elements in the environment, the available logistics resources and relief items, and the necessary factors to determine the most advantageous configuration. Table 5.4 gives an overview on the data to be gathered. The last column indicates how the data relates to the parameters of the OR model.

Firstly, data about the elements in the environment must be gathered. The location of the supply facility is the Subic Bay airport. Locations for LDCs on regional scale are Alaminos, Aurora, Bambang, Bongabon, Cabagan, Cabanatuan, Caiguran, Daguapan City, Dipaculao, Iba, Lamut, Maddela, Malolos City, Maria Aurora, Munoz, Roxas, San Miguel, Santa Cruz, Santiago City, Talavera, Tarlac City, Tuguegarao City, and Tumauini. There is a certain demand for emergency shelter kits at each location. Each route is characterized by the locations on the route, a distance, and speed limitations. The first route, with a total distance of 566 km, goes along the locations of Malolos City, San Miguel, Cabanatuan, Tarlac City, Daguapan City, Alaminos, Santa Cruz, and Iba; the second route, with a total distance of 885 km, along the locations of Tarlac City, Bongabon, Maria Aurora, Dipaculao, Caiguran, Maddela, Lamut, Bambang, Muñoz, and Talavera; and the third route, with a total distance of 1095 km, along the locations of Tarlac City, Tuguegarao City, Cabagan, Tumauini, Roxas, Aurora, and Santiago City. Distances were calculated using Google Maps. Speed limits are fixed to 50 km/h due to some damages of the road infrastructure.

Table 5.4. Necessary data for applying the OR model of Balcik et al. (2008)

Category	Data	OR model representation
Location for a supply facility	Coordinates	Parameter $t_{\psi\vartheta}$
Locations for LDCs	Coordinates	Parameter $t_{\psi\vartheta}$
	Relief item demand	Parameter dmd_{mr}
Routes	Locations	Parameter $t_{\psi\vartheta}$
	Distance	Parameter $t_{\psi\vartheta}$
	Speed limitations	Parameter $t_{\psi\vartheta}$
Supply facility	Location for a supply facility	Parameter $t_{\psi\vartheta}$
	Relief items stocked	Parameter spl_{rt}
LDCs	Location for a LDC	Parameter $t_{\psi\vartheta}$
Transportation vehicles	Speed of travel	Parameter $t_{\psi\vartheta}$
	Transport space	Parameter Ld_{ψ}
	Transport weight	Parameter Ld_{ψ}
Relief item types	Volume	Parameter Ld_{ψ}
	Weight	Parameter Ld_{ψ}
Factors	Costs for driving a transportation vehicle on a route	Parameter $c^{\mathrm{d}}_{\psi\vartheta}$
	Costs per 1% of unsatisfied demand for a relief item type at a location	Parameter c^{u}_{mrt}

Secondly, data about the available logistics resources and relief items has to be gathered. The stationary warehouse at the Subic Bay airport is the starting and end point of each route. At the beginning of the first day, 10,000 emergency shelter kits are stocked in the warehouse – as determined in section 5.1. At the beginning of the third, fourth, and fifth day, 5,000 additional emergency shelter kits arrive at the airport. Five large trucks are available at the airport; each vehicle has a standard 40-feet container as its transporter unit. Thus, the transport volume is 65 m³ and the transport weight is 26 t per vehicle (PAHO, 2001, p. 127). Still, the volume of an emergency shelter kit is 0.0122 m³ and its weight is 4.2 kg (IFRC, n.d.a).

Finally, costs factors are necessary for calculating the performance of the transportation activities. Transportation costs are set to US$400 if a transportation vehicle operates on route #1, US$600 on route #2, and US$800 on route #3. Shortage costs occurring at demand facilities are set to US$500 per 1% unfulfilled demand at the end of the first time period, US$1,000 at the end of the second time period, US$2,000 at the end of the third time period, US$4,000 at the end of the fourth time period, and US$10,000 at the end of the fifth time period.

Table A.5 (Appendix) gives an overview on the data that is necessary to apply the program code presented in section 4.3.1. The results of the application to the case study are shown in Table A.6. Accordingly, transportation vehicle #1 operates on route #1 in time period 1 with a load of 1,650 emergency shelter kits, transportation vehicle #3 operates on route #1 in time period 4 with a load of 900 kits, transportation vehicle #4 operates on route #2 in time period 1 with a load of 3,900 kits, and transportation vehicle #5 operates on route #3 in time period 1 with a load of 4,450 kits as well as on route #1 in time period 3 with a load of 5,000 kits. Results were obtained using the CPLEX Optimization Studio version 12.5.1.

5.4 *Conclusions concerning an application of the online OR toolkit for humanitarian logistics*

The filled-out problem structuring schemes can be used to identify links between available OR models for humanitarian logistics. Several combinations are possible based on the included OR models. In this chapter, one combination was described; that of Balcik and Beamon (2008), Murali et al. (2012), and Balcik et al. (2008). Figure 5.3 shows the combination of OR models as presented in this chapter.

After combining OR models, a practitioner as the toolkit-user can evaluate the usefulness of particular combinations. Even more, the toolkit-user can judge – based on the models' profiles – about the usefulness of certain components of the models and about the applicability of the models' result for a specific disaster response (function 4, p. 180). To be precise, the toolkit-user can perform the conceptual model validation and the operational validation of the overall model development process (Figure 3.1, p. 20). For example, the user could judge the usefulness of certain constraints in a mathematical program (conceptual model validation) or judge the usefulness of selecting the sports stadium as the location for a LDC in Tuguegarao City in section 5.2 (operational validation). The evaluation can be supported by available frameworks such as the one of Caplice and Sheffi (1994) for the evaluation of metrics used in logistics systems or the one of

Galindo and Batta (2013b) for the evaluation of assumptions made in OR models for disaster management. Based on the judgements, academics could update or remove their OR models from the online toolkit.

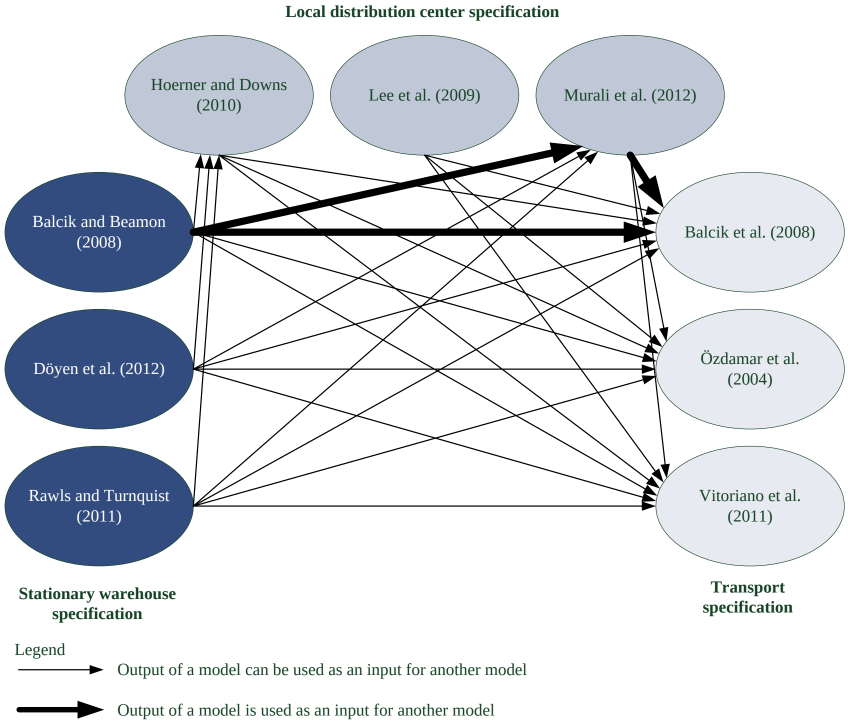


Figure 5.3. Exemplary combination of OR models as presented in chapter 5

6 Conclusions and outlook

The present work is a step towards a ready-to-use online OR toolkit for humanitarian logistics. Such a toolkit should be implemented as a website and should enable practitioners to tap the full potential of the available, published OR models for humanitarian logistics. Moreover, it should help bridge the gap between practitioner needs and academic results. A gap between academic results in the field of OR and practitioner needs (in general, in disaster management, and in humanitarian logistics) has been identified multiple times (e.g. by Ackoff, 1987; Galindo and Batta, 2013b; Ormerod, 2002; Overmeer et al., 1997; Schulenberg, 2014; Sodhi and Tang, 2008; and Ortuño et al., 2013). Ormerod (2002) suggests that academics share their discoveries on some sort of market, and suggests that practitioners seek – on that market – available approaches to the problem they are addressing. An online OR toolkit, as outlined in the present work, could provide such a market for OR models in the field of humanitarian logistics. In this sense, it can be regarded as a web-based, inter-organizational market for decision technologies, envisioned by Bhargava et al. (1997). There has been no attempt yet to develop a platform to support practitioners in applying published OR models for humanitarian logistics. Furthermore, there has been no attempt to arrange published OR models of any particular focus by some sort of electronic market for decision technologies; although there are several OR handbooks available for different fields of application.

In the present work, a structure for an online OR toolkit is proposed (section 3.4). More exactly, a hierarchical outline of the corresponding website is developed. The hierarchical outline guides toolkit-users to the model which best addresses their needs. The following seven steps were executed to arrive at the OR toolkit's hierarchical outline:

1. Definition of the crucial time frames of humanitarian logistics (i.e. disaster preparedness phase and disaster response phase) – in chapter 2.
2. Definition of the non-temporary and temporary elements of a humanitarian logistics network – in section 2.1.
3. Definition of the tasks that occur within the two time frames to set up and run a humanitarian logistics network (e.g. stationary warehouse specification in disaster preparedness) – in section 2.2.
4. Definition of the critical dimensions and metrics to judge the performance of a humanitarian logistics network – in section 2.3.
5. Definition of a problem structuring scheme to analyze completely and consistently the organizational problems captured in OR models – in section 3.1.
6. Definition of the OR methodologies that are commonly used in the field of disaster management – in section 3.2.
7. Sorting the available OR models that support the tasks of humanitarian logistics – in section 3.3.

A problem structuring scheme (step 5) is necessary to identify the problem components (i.e. environmental elements, organizational resources, and performance measures) that are captured in the mathematical expressions of OR models and that may vary across available OR models. Obviously, only those problem components which vary across models can help toolkit-users in the selection process when there is more than one model available for a certain task. So far, the problem structuring scheme has proved to be applicable to structure the underlying problems of several types of mathematical programs. Further research is necessary to show if simulation models and decision analysis models can also be captured by this scheme. Only recently, articles containing a simulation model (Mulyono and Ishida, 2014) and a decision analysis model (Roh et al., 2015) were published that have a focus on humanitarian logistics. Hence, these two OR models could provide a starting point for further research regarding the applicability of the proposed problem structuring scheme to other OR models than mathematical programs. Moreover, the problem structuring scheme was only applied to analyze OR models for humanitarian logistics. While the general structure of the scheme indicates its use also for other fields of application, this should still be validated by future research.

In the present work, the proposed structure for an online OR toolkit for humanitarian logistics was partly filled with available OR models (chapter 4). Due to the nature of the present work, this results into a shortened, paper version of the toolkit. This shortened version:

- helps practitioners determine the cornerstones of any humanitarian logistics network and the interactions in between; i.e. the planning of stationary warehouses (section 4.1), LDCs (section 4.2), and transportation activities (section 4.3);
- helps practitioners find, adapt, and combine available OR models for their specific problem(s), thereby reducing the practitioners' own modeling effort;
- helps practitioners convert an OR model into a computerized model, thereby reducing the practitioners' own implementation effort;
- helps practitioners build a database for a computerized model, thereby reducing the practitioners' own experimentation effort; and
- helps academics analyze available OR models whereby open research questions can be identified and the risk of redundant or useless OR model building can be reduced.

While this work is a step towards a ready-to-use toolkit, some more steps have to be made in order to develop the corresponding website. First, the information architecture as presented in this work must be validated by potential real users, e.g. by conducting workshops with groups of practitioners. Second, design sketches of the user interfaces need to be drawn. Based on information architecture and design sketches, a detailed specification of the necessary technologies can be made. The Web Style Guide of Lynch and Horton (n.d.b) includes a complete list of actions necessary to design and construct a ready-to-use website. Only after the OR toolkit for humanitarian logistics is online, can one of its central functions be validated; namely, supporting practitioners to catch up with academics as the OR model developers, whereby academics assist practitioners to adapt and apply their models while practitioners give feedback on the OR models' assumptions (conceptual model validation) and usefulness for their use cases (operational validation). The feedback can then be used again by the academics to update or remove their OR models. In the long run, the online OR toolkit for humanitarian logistics should be hosted by an established scientific association that has a focus on disaster management and that is trusted by academics (e.g. the ISCRAM community). Academics could then, out of altruistic motives, add their models to the toolkit – apart from presenting them at conferences or publishing them in a scientific journal.

An online OR toolkit with several more models would support several more tasks than specifying stationary warehouses, LDCs, and transportation activities (see Table 3.5, p. 27) – and would prevent academics from building redundant OR models. However, even by supporting only some selected problems in the field of humanitarian logistics, the presented paper version of the toolkit can be used to specify the cornerstones and the interactions of any humanitarian logistics network. How three of the included OR models can be combined to set up and run a small-scale humanitarian logistics network was demonstrated in chapter 5 using a case study applied to the Philippines.

An online OR toolkit as outlined in this work is a website that enables practitioners and academics to exchange information about available OR models ("web as media"). The final experimentations are executed locally and to perform these experiments, the practitioner would require the corresponding desktop applications (e.g. CPLEX Optimization Studio). In the long run, the online toolkit could make use of the web service concept. A web service is defined as a software system running on a remote server which can be accessed through a web browser. In the case of the online OR toolkit, a web service could allow for the remote experimentations on a computerized model to determine the most advantageous configuration of a humanitarian logistics network ("web as computer") (Bhargava et al., 2007; Valente and Mitra, 2007).

Furthermore, the online OR toolkit should interconnect with web-based projects which support practitioners in the field of humanitarian logistics. The Sahana Eden software provides an open-source, web-based inter-organizational platform for humanitarian organizations to store and share their data about disasters, facilities, human resources, relief item stocks, and other assets (SAHANA, n.d.). The Digital Humanitarian Network is a group of volunteers that analyzes data, monitors mainstream and social media, and creates maps in the aftermath of a disaster, and provides the gathered information to humanitarian organizations (DHNetwork, n.d.). Certainly, a ready-to-use online OR toolkit for humanitarian logistics should make use of data that is stored on the Sahana Eden platform or that is generated by the Digital Humanitarian Network.

Indeed, a ready-to-use online OR toolkit for humanitarian logistics can be of use for both academics and practitioners. The present work is a step towards such a toolkit. Generally speaking, the present work has three original contributions:

- an information architecture of an online OR toolkit for humanitarian logistics;
- a problem structuring scheme (as part of the information architecture) to completely capture the inserted OR models' underlying problems in a consistent way; and
- an arrangement of available OR models which can be used to specify the cornerstones of a humanitarian logistics network as well as the transportation activities in between.

7 Summary

There are several disasters per year that affect millions of people and trigger the need for relief items such as food, blankets, or tents. Humanitarian logistics networks organize the flow of relief items from various suppliers to the people in need. In the last ten years, several OR models were published by academics in scientific journals that could support decision-makers to set up and run humanitarian logistics networks. The models' practical application, however, is hampered because humanitarian organizations typically lack necessary resources and are often not included in the model development process. In this thesis, the concept and structure of an online OR toolkit for humanitarian logistics are proposed. Such a toolkit should enable practitioners to tap the full potential of published OR models.

Two major steps were necessary for the structuring of the toolkit. In the first step, characteristics of disaster management and humanitarian logistics were identified (chapter 2) and, in the second step, characteristics of available OR models for humanitarian logistics were described (chapter 3). A humanitarian logistics network consists of the necessary facilities, technical equipment, aid workers, and transportation vehicles to distribute relief items within an environment affected by a disaster. Transport corridors may be broken, unsafe, or unsecure, failed communication systems remove the logical links between the actors, and locations of beneficiaries may be dynamic or unknown in such an environment (section 2.1). Several tasks must be performed in order to set up the non-temporary parts of the network during the disaster preparedness phase and its temporary parts during the disaster response phase (section 2.2). The performance of a certain network can be determined by measuring a configuration's input of logistical resources and relief items as well as by measuring a configuration's many effects on beneficiaries, workforce, society, environment, and donation levels (section 2.3).

OR models are conceptual representations of organizational decision problems. Problems are converted into OR models during a modeling process, OR models are computerized during an implementation process, and computerized models are solved during an experimentation process. The components of an organizational problem must be captured in the corresponding OR model's formulation. These components are: an environment where the task takes place, fixed and variable attributes of organizational resources, permitted interactions between resources and environment, and performance measures of the organization to determine whether a certain solution to a task is better than other solutions (section 3.1). OR methodologies are used to convert organizational problems into OR models. Mathematical programming, decision analysis, and simulation are the methodologies most often used in the field of disaster management (section 3.2). However, a review of available OR models for humanitarian logistics revealed that mostly mathematical programs were published in peer-reviewed scientific journals; and that most of the published programs are models for planning transportation activities (section 3.3).

After conceptualizing the fields of humanitarian logistics and OR, and after collecting available OR models for humanitarian logistics, the structure of an online OR toolkit for humanitarian logistics was determined (section 3.4). According to the structure, available models are first separated into those for tasks in the disaster preparedness phase and those for tasks in the disaster response phase. Second, models are assigned to the specific task they support – e.g. specifying the locations and relief item stocks of stationary warehouses. Third, models are assigned to the underlying OR methodology. Finally, each model is characterized by its mathematical formulation, by a translation of the mathematical formulation into a suitable program code, and by a description of the underlying problem. A problem structuring scheme is developed as part of the toolkit's structure in order to consistently and completely describe problems that are captured in OR models for humanitarian logistics.

The proposed structure of the online toolkit is filled with nine published mathematical programs in chapter 4. These programs support the specification of stationary warehouses (Balcik and Beamon, 2008; Döyen et al., 2012; Rawls and Turnquist, 2011), of LDCs (Horner and Downs, 2010; Lee et al., 2009a; Murali et al., 2012), and of transportation activities (Balcik et al., 2008; Özdamar et al., 2004; Vitoriano et al., 2011). Thereby, the cornerstones of any humanitarian logistics network can be specified with the present version of the toolkit: stationary warehouses as sources of relief items, LDCs as the sinks of relief items, and transportation activities in order to realize the flow of relief items from sources to sinks. It is shown that the proposed problem structuring scheme can completely characterize different types of mathematical programs in a consistent way. Moreover, it is indicated how the proposed structure of the toolkit can support academics in identifying open research questions – as well as support practitioners in finding, adapting, implementing, building databases for, and combining available OR models for humanitarian logistics.

How practitioners could use the toolkit to combine available OR models is demonstrated in chapter 5. Exemplarily, a humanitarian logistics network in the Philippines is designed. Therefore, three of the models that were included in the toolkit (Balcik and Beamon, 2008, Murali et al., 2012; Balcik et al., 2008) are applied to set up a stationary warehouse in the disaster preparedness phase, to set up a LDC in response to a typhoon, and to determine the transportation activities in response to a typhoon. After applying a certain combination of models, the toolkit-user is able to judge about the combination's usefulness. Furthermore, the toolkit-user can make judgments about the usefulness of certain parts of an OR model based on the problem structuring scheme. However, judgments about models and model combinations can only arrive digitally at responsible academics after the present version of the toolkit is transformed into an online platform. Only then, the toolkit can – virtually – bring together academics and practitioners.

Consequently, future work is directed towards the technical implementation of the OR toolkit for humanitarian logistics as a website. After the website is online, other available OR models for humanitarian logistics should be assigned to the toolkit structure in order to broaden the toolkit’s focus (e.g. by including available inventory models or models for the specification of temporary handling points). As a long term goal, the online toolkit could make use of the web service concept to allow practitioners to apply the included models through web browsers instead of desktop applications.

References

Ackoff, R.L., 1956. The Development of Operations Research as a Science. Operations Research 4 (3), 265–295. 10.1287/opre.4.3.265.

Ackoff, R.L., 1978. The art of problem solving: Accompanied by Ackoff's fables. Wiley, New York, NY.

Ackoff, R.L., 1987. Presidents' Symposium: OR, A Post Mortem. Operations Research 35 (3), 471–474. 10.2307/170549.

Adıvar, B., Mert, A., 2010. International disaster relief planning with fuzzy credibility. Fuzzy Optimization and Decision Making 9 (4), 413–433. 10.1007/s10700-010-9088-8.

Afshar, A., Haghani, A., 2012. Modeling integrated supply chain logistics in real-time large-scale disaster relief operations. Socio-Economic Planning Sciences 46 (4), 327–338. 10.1016/j.seps.2011.12.003.

Alp Ertem, M., Buyurgan, N., 2011. An auction ‐ based framework for resource allocation in disaster relief. Journal of Humanitarian Logistics and Supply Chain Management 1 (2), 170 ‐ 188. 10.1108/20426741111158412.

Altay, N., Green, W.G., 2006. OR/MS research in disaster operations management. European Journal of Operational Research 175 (1), 475–493. 10.1016/j.ejor.2005.05.016.

American Red Cross, 2013. Superstorm Sandy - OneYear Update - October 2013. American Red Cross. https://s3.amazonaws.com/s3.documentcloud.org/documents/1017587/one-year-report-m23216738-superstorm-sandy-one.pdf?_ga=1.33618145.1739699996.1425460821. Accessed 14 April 2015.

Anaya-Arenas, A.M., Renaud, J., Ruiz, A., 2014. Relief distribution networks: a systematic review. Annals of Operations Research 223 (1), 53–79. 10.1007/s10479-014-1581-y.

Angelis, V., Mecoli, M., Nikoi, C., Storchi, G., 2007. Multiperiod integrated routing and scheduling of World Food Programme cargo planes in Angola. Computers & Operations Research 34 (6), 1601–1615. 10.1016/j.cor.2005.07.012.

Arnold, D., 2008. Handbuch Logistik, 3rd ed. Springer, Berlin.

Balcik, B., Beamon, B.M., 2008. Facility location in humanitarian relief. International Journal of Logistics Research and Applications 11 (2), 101–121. 10.1080/13675560701561789.

Balcik, B., Beamon, B.M., Krejci, C.C., Muramatsu, K.M., Ramirez, M., 2010. Coordination in humanitarian relief chains: Practices, challenges and opportunities. International Journal of Production Economics 126 (1), 22–34. 10.1016/j.ijpe.2009.09.008.

Balcik, B., Beamon, B.M., Smilowitz, K., 2008. Last Mile Distribution in Humanitarian Relief. Journal of Intelligent Transportation Systems 12 (2), 51–63. 10.1080/15472450802023329.

Barbarosoğlu, G., Arda, Y., 2004. A two-stage stochastic programming framework for transportation planning in disaster response. Journal of the Operational Research Society 55 (1), 43–53. 10.1057/palgrave.jors.2601652.

Barbarosoğlu, G., Özdamar, L., Çevik, A., 2002. An interactive approach for hierarchical analysis of helicopter logistics in disaster relief operations. European Journal of Operational Research 140 (1), 118–133. 10.1016/S0377-2217(01)00222-3.

Barnhart, C., Smith, B., 2012. Quantitative Problem Solving Methods in the Airline Industry. Springer US, Boston, MA.

Barzinpour, F., Esmaeili, V., 2014. A multi-objective relief chain location distribution model for urban disaster management. The International Journal of Advanced Manufacturing Technology 70 (5-8), 1291–1302. 10.1007/s00170-013-5379-x.

Batta, R., Kwon, C., 2013. Handbook of OR/MS Models in Hazardous Materials Transportation. Springer New York, New York, NY.

Beamon, B.M., Balcik, B., 2008. Performance measurement in humanitarian relief chains. International Journal of Public Sector Management 21 (1), 4–25. 10.1108/09513550810846087.

Beamon, B.M., Kotleba, S.A., 2006. Inventory management support systems for emergency humanitarian relief operations in South Sudan. The International Journal of Logistics Management 17 (2), 187–212. 10.1108/09574090610689952.

Berkoune, D., Renaud, J., Rekik, M., Ruiz, A., 2012. Transportation in disaster response operations. Socio-Economic Planning Sciences 46 (1), 23–32. 10.1016/j.seps.2011.05.002.

Bhargava, H.K., Krishnan, R., Müller, R., 1997. Decision support on demand: Emerging electronic markets for decision technologies. Decision Support Systems 19 (3), 193–214. 10.1016/S0167-9236(96)00056-5.

Bhargava, H.K., Power, D.J., Sun, D., 2007. Progress in Web-based decision support technologies. Decision Support Systems 43 (4), 1083–1095. 10.1016/j.dss.2005.07.002.

Bodin, L., Golden, B., 1981. Classification in vehicle routing and scheduling. Networks 11 (2), 97–108. 10.1002/net.3230110204.

Bookbinder, J.H., 2013. Handbook of Global Logistics. Springer New York, New York, NY.

Bozorgi-Amiri, A., Jabalameli, M.S., Mirzapour Al-e-Hashem, S.M.J., 2013. A multi-objective robust stochastic programming model for disaster relief logistics under uncertainty. OR Spectrum 35 (4), 905-933. 10.1007/s00291-011-0268-x.

Bradley, S.P., Hax, A.C., Magnanti, T.L., 1977. Applied mathematical programming. Addison-Wesley Pub. Co., Reading, MA.

Camacho-Vallejo, J.F., González-Rodríguez, E., Almaguer, F., González-Ramírez, R.G., 2014. A bi-level optimization model for aid distribution after the occurrence of a disaster. Journal of Cleaner Production. 10.1016/j.jclepro.2014.09.069.

Campbell, A.M., Jones, P.C., 2011. Prepositioning supplies in preparation for disasters. European Journal of Operational Research 209 (2), 156–165. 10.1016/j.ejor.2010.08.029.

Campbell, A.M., Vandenbussche, D., Hermann, W., 2008. Routing for Relief Efforts. Transportation Science 42 (2), 127–145. 10.1287/trsc.1070.0209.

Caplice, C., Sheffi, Y., 1994. A Review and Evaluation of Logistics Metrics. The International Journal of Logistics Management 5 (2), 11–28. 10.1108/09574099410805171.

Carter, C.R., Jennings, M.M., 2002. Logistics social responsibility: An integrative framework. Journal of Business Logistics 23 (1), 145–180. 10.1002/j.2158-1592.2002.tb00020.x.

Caunhye, A.M., Nie, X., Pokharel, S., 2012. Optimization models in emergency logistics: A literature review. Socio-Economic Planning Science 46 (1), 4–13. 10.1016/j.seps.2011.04.004.

Chang, M., Tseng, Y., Chen, J., 2007. A scenario planning approach for the flood emergency logistics preparation problem under uncertainty. Transportation Research Part E: Logistics and Transportation Review 43 (6), 737–754. 10.1016/j.tre.2006.10.013.

Checkland, P., Poulter, J., 2010. Soft systems methodology, in: Reynolds, M., Holwell, S. (Eds.), Systems approaches to managing change: A practical guide. Springer, pp. 191–242.

Consuelos Salas, L., Robles Cárdenas, M., Zhang, M., 2012. Inventory policies for humanitarian aid during hurricanes. Socio-Economic Planning Sciences 46 (4), 272–280. 10.1016/j.seps.2012.02.002.

Crainic, T.G., Laporte, G., 1997. Planning models for freight transportation. European Journal of Operational Research 97 (3), 409–438. 10.1016/S0377-2217(96)00298-6.

Crainic, T.G., 1998. A Survey of Optimization Models for Long-haul Freight Transportation. Centre de recherche sur les transports (C.R.T.).

Daft, R.L., Wiginton, J.C., 1979. Language and Organization. The Academy of Management Review 4 (2), 179–191. 10.2307/257772.

Dai, J., Wang, S., Yang, X., 1994. Computerized support systems for emergency decision making. Annals of Operations Research 51 (7), 313–325. 10.1007/BF02048553.

Das, R., Hanaoka, S., 2014. Relief inventory modelling with stochastic lead-time and demand. European Journal of Operational Research 235 (3), 616–623. 10.1016/j.ejor.2013.12.042.

Davis, L.B., Samanlioglu, F., Qu, X., Root, S., 2013. Inventory planning and coordination in disaster relief efforts. International Journal of Production Economics 141 (2), 561–573. 10.1016/j.ijpe.2012.09.012.

Denton, B.T., 2013. Handbook of Healthcare Operations Management. Springer New York, New York, NY.

DHNetwork, n.d. About. http://digitalhumanitarians.com/about. Accessed 7 May 2015.

Dilley, M., 2005. Natural disaster hotspots: A global risk analysis. World Bank, Washington, D.C.

Döyen, A., Aras, N., Barbarosoğlu, G., 2012. A two-echelon stochastic facility location model for humanitarian relief logistics. Optimization Letters 6 (6), 1123–1145. 10.1007/s11590-011-0421-0.

Duncan, R.B., 1972. Characteristics of Organizational Environments and Perceived Environmental Uncertainty. Administrative Science Quarterly 17 (3), 313–327. 10.2307/2392145.

Eden, C., 1988. Cognitive mapping. European Journal of Operational Research 36 (1), 1–13. 10.1016/0377-2217(88)90002-1.

ELRHA, n.d. Guide to constructing effective partnerships. http://www.elrha.org/wp-content/uploads/2015/01/effective-partnerships-report.pdf. Accessed 12 March 2015.

EM-DAT, n.d.a. Country Profile. http://www.emdat.be/country_profile/index.html. Accessed 17 April 2015.

EM-DAT, n.d.b. Explanatory notes. http://www.emdat.be/explanatory-notes. Accessed 4 March 2015.

EM-DAT, n.d.c. Home. http://www.emdat.be/. Accessed 4 March 2015.

Falasca, M., Zobel, C.W., 2011. A two-stage procurement model for humanitarian relief supply chains. Journal of Humanitarian Logistics and Supply Chain Management 1 (2), 151–169. 10.1108/20426741111188329.

Fourer, R., 1997. Database structures for mathematical programming models. Decision Support Systems 20 (4), 317–344. 10.1016/S0167-9236(97)00007-9.

Galindo, G., Batta, R., 2013a. Prepositioning of supplies in preparation for a hurricane under potential destruction of prepositioned supplies. Socio-Economic Planning Sciences 47 (1), 20–37. 10.1016/j.seps.2012.11.002.

Galindo, G., Batta, R., 2013b. Review of recent developments in OR/MS research in disaster operations management. European Journal of Operational Research 230 (2), 201–211. 10.1016/j.ejor.2013.01.039.

Geoffrion, A.M., 1987. An Introduction to Structured Modeling. Management Science 33 (5), 547–588. 10.2307/2632287.

Görmez, N., Köksalan, M., Salman, F.S., 2010. Locating disaster response facilities in Istanbul. Journal of the Operational Research Society 62 (7), 1239–1252. 10.1057/jors.2010.67.

Gösling, H., Geldermann, J., 2014a. A Framework to Compare OR Models for Humanitarian Logistics. Procedia Engineering 78, 22–28. 10.1016/j.proeng.2014.07.034.

Gösling, H., Geldermann, J., 2014b. Decisions and decision criteria in humanitarian logistics, in: Langton, S., Morton, A., Geiger, M.J., Siebert, J. (Eds.), Proceedings of the Joint GOR- and DASIG-Conference 2013. Shaker-Verlag, Aachen, pp. 1–8.

Gösling, H., Geldermann, J., 2014c. Methodological tool kit for humanitarian logistics. Proceedings of the 11th International ISCRAM Conference, 190–194.

Greeno, J.G., 1976. Indefinite goals in well-structured problems. Psychological Review 83 (6), 479–491. 10.1037/0033-295X.83.6.479.

Gu, Y., 2011. Research on Optimization of Relief Supplies Distribution Aimed to Minimize Disaster Losses. Journal of Computers 6 (3). 10.4304/jcp.6.3.603-609.

Haghani, A., Oh, S., 1996. Formulation and solution of a multi-commodity, multi-modal network flow model for disaster relief operations. Transportation Research Part A: Policy and Practice 30 (3), 231–250. 10.1016/0965-8564(95)00020-8.

Harmer, A., Cotterrell, L., 2005. Diversity in donorship: The changing lanscape of official humanitarian aid. Humanitarian Policy Group, Overseas Development Institute, London.

Harvey, A., 1970. Free for All—Factors Making for Implementation Success and Failure. Management Science 16 (6), B-312. 10.1287/mnsc.16.6.B312.

Herrmann, J.W., 2013. Handbook of Operations Research for Homeland Security. Springer New York, New York, NY.

HIF, 2014. UNOCHA: The Humanitarian Exchange Language Reaches Alpha. Humanitarian Innovation Fund. http://www.elrha.org/project/the-humanitarian-exchange-language-initiative/. Accessed 4 March 2015.

Hillier, F.S., Lieberman, G.J., 2010. Introduction to operations research, 9th ed. McGraw-Hill, New York, NY.

Holguín-Veras, J., Jaller, M., van Wassenhove, L., Pérez, N., Wachtendorf, T., 2012. On the unique features of post-disaster humanitarian logistics. Journal of Operations Management 30 (7–8), 494–506. 10.1016/j.jom.2012.08.003.

Holguín-Veras, J., Pérez, N., Jaller, M., van Wassenhove, L., Aros-Vera, F., 2013. On the appropriate objective function for post-disaster humanitarian logistics models. Journal of Operations Management 31 (5), 262–280. 10.1016/j.jom.2013.06.002.

Horner, M.W., Downs, J.A., 2010. Optimizing hurricane disaster relief goods distribution: model development and application with respect to planning strategies. Disasters 34 (3), 821–844. 10.1111/j.1467-7717.2010.01171.x.

Hu, Z., 2011. A container multimodal transportation scheduling approach based on immune affinity model for emergency relief. Expert Systems with Applications 38 (3), 2632–2639. 10.1016/j.eswa.2010.08.053.

Huang, K., Jiang, Y., Yuan, Y., Zhao, L., 2015. Modeling multiple humanitarian objectives in emergency response to large-scale disasters. Transportation Research Part E: Logistics and Transportation Review 75, 1–17. 10.1016/j.tre.2014.11.007.

Huang, M., Smilowitz, K., Balcik, B., 2012. Models for relief routing: Equity, efficiency and efficacy. Transportation Research Part E: Logistics and Transportation Review 48 (1), 2–18. 10.1016/j.tre.2011.05.004.

IASC, 2012. Multi-Cluster/Sector Initial Rapid Assessment (MIRA): Provisional Version March 2012. Inter-Agency Standing Committee. https://docs.unocha.org/sites/dms/CAP/mira_final_version2012.pdf. Accessed 21 November 2013.

IFRC, n.d.a. Emergency Items Catalogue. http://procurement.ifrc.org/catalogue/overview.aspx?volume=3&groupcode=301&page=introduction. Accessed 14 April 2015.

IFRC, n.d.b. Global fleet solutions for humanitarian action. http://www.ifrc.org/PageFiles/91193/Fleet%20leaflet.pdf?epslanguage=en. Accessed 4 May 2015.

IFRC, n.d.c. Humanitarian logistics. http://www.ifrc.org/what-we-do/logistics/. Accessed 14 April 2015.

IFRC, n.d.d. Types of disasters: Definition of hazard. http://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/definition-of-hazard/. Accessed 14 April 2015.

IFRC, n.d.e. What is a disaster? http://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/what-is-a-disaster/. Accessed 30 October 2014.

IFRC, Oxfam, 2007. plastic sheeting: A guide to the specification and use of plastic sheeting in humanitarian relief. http://www.plastic-sheeting.org/ref/Plastic_Sheeting_2007.pdf. Accessed 4 May 2015.

IFRC, 2008. Relief ERU Field Manual. https://www-secure.ifrc.org/DMISII/Pages/03_response/0306_eru/030602_eru_relief/146900_relief%20ERU_EN_LR.pdf. Accessed 12 February 2014.

IFRC, 2010. Haiti erthquake 2010: One-year progress report. http://www.ifrc.org/Global/Publications/disasters/208400-First%20anniversary%20Haiti%20EQ%20operation%20report_16b.pdf. Accessed 4 March 2015.

IFRC, 2013. DREF final report - Zambia: Floods. http://www.ifrc.org/docs/Appeals/13/MDRZM008FR.pdf. Accessed 12 February 2014.

Ince, D.C., Hatton, L., Graham-Cumming, J., 2012. The case for open computer programs. Nature 482 (7386), 485–488. 10.1038/nature10836.

Jia, H., Ordóñez, F., Dessouky, M., 2007a. A modeling framework for facility location of medical services for large-scale emergencies. IIE Transactions 39 (1), 41–55. 10.1080/07408170500539113.

Jia, H., Ordóñez, F., Dessouky, M., 2007b. Solution approaches for facility location of medical supplies for large-scale emergencies. Computers & Industrial Engineering 52 (2), 257–276. 10.1016/j.cie.2006.12.007.

Keeney, R.L., Raiffa, H., 1993. Decisions with multiple objectives: Preferences and value tradeoffs. Cambridge University Press, Cambridge, New York, NY.

Klose, A., Drexl, A., 2005. Facility location models for distribution system design. European Journal of Operational Research 162 (1), 4–29. 10.1016/j.ejor.2003.10.031.

Kovacevic, R.M., Pflug, G.C., Vespucci, M.T., 2013. Handbook of Risk Management in Energy Production and Trading. Springer US, Boston, MA.

Kovács, G., Spens, K., 2007. Humanitarian logistics in disaster relief operations. International Journal of Physical Distribution & Logistics Management 37 (2), 99–114. 10.1108/09600030710734820.

Kovács, G., Spens, K., 2009. Identifying challenges in humanitarian logistics. International Journal of Physical Distribution & Logistics Management 39 (6), 506–528. 10.1108/09600030910985848.

LaTorre, L.E., Dolinskaya, I.S., Smilowitz, K.R., 2012. Disaster relief routing: Integrating research and practice. Socio-Economic Planning Science 46 (1), 88–97. 10.1016/j.seps.2011.06.001.

Law, A.M., Kelton, W.D., 1982. Simulation modeling and analysis. McGraw-Hill, New York, NY.

Lee, E.K., Chen, C., Pietz, F., Benecke, B., 2009a. Modeling and Optimizing the Public-Health Infrastructure for Emergency Response. Interfaces 39 (5), 476–490. 10.1287/inte.1090.0463.

Lee, E.K., Smalley, H.K., Zhang, Y., Pietz, F., Benecke, B., 2009b. Facility location and multi-modality mass dispensing strategies and emergency response for biodefence and infectious disease outbreaks. International Journal of Risk Assessment and Management 12 (2/3/4), 311. 10.1504/IJRAM.2009.025925.

Li, L., Jin, M., Zhang, L., 2011. Sheltering network planning and management with a case in the Gulf Coast region. International Journal of Production Economics 131 (2), 431–440. 10.1016/j.ijpe.2010.12.013.

Lin, Y., Batta, R., Rogerson, P.A., Blatt, A., Flanigan, M., 2011. A logistics model for emergency supply of critical items in the aftermath of a disaster. Socio-Economic Planning Sciences 45 (4), 132–145. 10.1016/j.seps.2011.04.003.

Lin, Y., Batta, R., Rogerson, P.A., Blatt, A., Flanigan, M., 2012. Location of temporary depots to facilitate relief operations after an earthquake. Socio-Economic Planning Sciences 46 (2), 112–123. 10.1016/j.seps.2012.01.001.

Logistics Cluster, n.d. About the logistics cluster. http://logcluster.org/logistics-cluster. Accessed 23 April 2014.

Logistics Cluster, 2014. Ebola Outbreak: Logistics Cluster: Situation Update. 26 September 2014. http://www.logcluster.org/sites/default/files/logistics_cluster_ebola_outbreak_situation_update_140926.pdf. Accessed 17 April 2015.

Logistics Cluster, 2015. Mozambique Floods: Situation Update. (23 February 2015). http://reliefweb.int/sites/reliefweb.int/files/resources/logistics_cluster_mozambique_floods_situation_update_150222_fin.pdf. Accessed 17 April 2015.

Lynch, P.J., Horton, S., n.d.a. Web Style Guide. http://webstyleguide.com/wsg3/3-information-architecture/2-organizing-information.html. Accessed 9 March 2015.

Lynch, P.J., Horton, S., n.d.b. Web Style Guide: The Site Development Process. http://webstyleguide.com/wsg3/1-process/7-development-process.html. Accessed 9 March 2015.

Maxwell, D., Bailey, S., Harvey, P., Walker, P., Sharbatke-Church, C., Savage, K., 2012. Preventing corruption in humanitarian assistance: perceptions, gaps and challenges. Disasters 36 (1), 140–160. 10.1111/j.1467-7717.2011.01245.x.

McCoy, J.H., Brandeau, M.L., 2011. Efficient stockpiling and shipping policies for humanitarian relief: UNHCR's inventory challenge. OR Spectrum 33 (3), 673-698. 10.1007/s00291-011-0237-4.

Mete, H.O., Zabinsky, Z.B., 2010. Stochastic optimization of medical supply location and distribution in disaster management. International Journal of Production Economics 126 (1), 76–84. 10.1016/j.ijpe.2009.10.004.

Muhanna, W.A., Pick, R.A., 1994. Meta-Modeling Concepts and Tools for Model Management: A Systems Approach. Management Science 40 (9), 1093–1123. 10.1287/mnsc.40.9.1093.

Mulvey, J.M., Vanderbei, R.J., Zenios, S.A., 1995. Robust Optimization of Large-Scale Systems. Operations Research 43 (2), 264–281. 10.1287/opre.43.2.264.

Mulyono, N.B., Ishida, Y., 2014. Humanitarian logistics and inventory model based on probabilistic cellular automata. International Journal of Innovative Computing, Information and Control 10 (1), 357–372.

Murali, P., Ordóñez, F., Dessouky, M., 2012. Facility location under demand uncertainty: Response to a large-scale bio-terror attack. Socio-Economic Planning Sciences 46 (1), 78–87. 10.1016/j.seps.2011.09.001.

Najafi, M., Eshghi, K., Dullaert, W., 2013. A multi-objective robust optimization model for logistics planning in the earthquake response phase. Transportation Research Part E: Logistics and Transportation Review 49 (1), 217–249. 10.1016/j.tre.2012.09.001.

Naji-Azimi, Z., Renaud, J., Ruiz, A., Salari, M., 2012. A covering tour approach to the location of satellite distribution centers to supply humanitarian aid. European Journal of Operational Research 222 (3), 596–605. 10.1016/j.ejor.2012.05.001.

Neely, A., Gregory, M., Platts, K., 1995. Performance measurement system design. International Journal of Operations & Production Management 15 (4), 80–116. 10.1108/01443579510083622.

NEOS, n.d. NEOS Guide: Companion Site to the NEOS Server. http://www.neos-guide.org/. Accessed 20 March 2015.

Nikbakhsh, E., Zanjirani Farahani, R., 2011. Humanitarian Logistics Planning in Disaster Relief Operations, in: Logistics Operations and Management. Elsevier, pp. 291–332.

Nolz, P.C., Semet, F., Doerner, K.F., 2011. Risk approaches for delivering disaster relief supplies. OR Spectrum 33 (3), 543-569. 10.1007/s00291-011-0258-z.

NRC, 2008. The camp management toolkit. Norwegian Refugee Council. http://www.nrc.no/arch/_img/9295458.pdf. Accessed 12 February 2014.

Olsen, G.R., Carstensen, N., Høyen, K., 2003. Humanitarian Crises: What Determines the Level of Emergency Assistance? Media Coverage, Donor Interests and the Aid Business. Disasters 27 (2), 109–126. 10.1111/1467-7717.00223.

Open Steet Map, n.d. Tuguegarao City. http://www.openstreetmap.org/#map=14/17.6212/121.7129&layers=H. Accessed 23 March 2015.

Ormerod, R.J., 2002. On the Nature of OR: Taking Stock. The Journal of the Operational Research Society 53 (5), 475–491. 10.2307/823016.

Ortuño, M.T., Cristóbal, P., Ferrer, J.M., Martín-Campo, F.J., Muñoz, S., Tirado, G., Vitoriano, B., 2013. Decision Aid Models and Systems for Humanitarian Logistics. A Survey, in: Vitoriano, B., Montero, J., Ruan, D. (Eds.), Decision Aid Models for Disaster Management and Emergencies, vol. 7. Atlantis Press, Paris, pp. 17–44.

Ortuño, M.T., Tirado, G., Vitoriano, B., 2011. A lexicographical goal programming based decision support system for logistics of Humanitarian Aid. TOP 19 (2), 464–479. 10.1007/s11750-010-0138-8.

Overmeer, W., Corbett, C.J., Salomon, M., 1997. Intractable problems in discussing OR practice at a scientific conference: Reflections on a panel discussion at EURO XIV. European Journal of Operational Research 99 (1), 197–206. 10.1016/S0377-2217(96)00392-X.

Özdamar, L., 2011. Planning helicopter logistics in disaster relief. OR Spectrum 33 (3), 655-672. 10.1007/s00291-011-0259-y.

Özdamar, L., Alp Ertem, M., 2015. Models, solutions and enabling technologies in humanitarian logistics. European Journal of Operational Research 244 (1), 55–65. 10.1016/j.ejor.2014.11.030.

Özdamar, L., Demir, O., 2012. A hierarchical clustering and routing procedure for large scale disaster relief logistics planning. Transportation Research Part E: Logistics and Transportation Review 48 (3), 591–602. 10.1016/j.tre.2011.11.003.

Özdamar, L., Ekinci, E., Küçükyazici, B., 2004. Emergency Logistics Planning in Natural Disasters. Annals of Operations Research 129 (1-4), 217-245. 10.1023/B:ANOR.0000030690.27939.39.

PAHO, 2001. Humanitarian supply management and logistics in the health sector. Pan American Health Organization; World Health Organization, Washington, D.C.

Paton, D., 2003. Stress in disaster response: a risk management approach. Disaster Prevention and Management 12 (3), 203–209. 10.1108/09653560310480677.

Pauwels, N., Van De Walle, B., Hardeman, F., Soudan, K., 2000. The implications of irreversibility in emergency response decisions. Theory and Decision 49 (1), 25-51. 10.1023/A:1005155426945.

PedrazaMartinez, A.J., Stapleton, O., van Wassenhove, L., 2011. Field vehicle fleet management in humanitarian operations: A case-based approach. Journal of Operations Management 29 (5), 404–421. 10.1016/j.jom.2010.11.013.

Penuel, K.B., Statler, M., 2011. Encyclopedia of disaster relief. Sage Publications, Thousand Oaks, CA.

Rath, S., Gutjahr, W.J., 2014. A math-heuristic for the warehouse location–routing problem in disaster relief. Computers & Operations Research 42, 25–39. 10.1016/j.cor.2011.07.016.

Raufi, M.H., 2014. Food distribution report in Sayad district Sar-e-pul province. ISLAMIC RELIEF AFGHANISTAN. http://www.humanitarianresponse.info/system/files/documents/files/IRA%20 Emergency%20Response%20to%20the%20Flood%20affectees%20in%20Sare-e-Pul%20Province.pdf. Accessed 4 May 2015.

Rawls, C.G., Turnquist, M.A., 2011. Pre-positioning planning for emergency response with service quality constraints. OR Spectrum 33 (3), 481-498. 10.1007/s00291-011-0248-1.

Rawls, C.G., Turnquist, M.A., 2012. Pre-positioning and dynamic delivery planning for short-term response following a natural disaster. Socio-Economic Planning Sciences 46 (1), 46–54. 10.1016/j.seps.2011.10.002.

reliefweb, n.d.a. National Disaster Management Authorities. http://reliefweb.int/topics/ndm-authorities.

reliefweb, n.d.b. Typhoon Haiyan - Nov 2013. http://reliefweb.int/disaster/tc-2013-000139-phl. Accessed 14 April 2015.

Roh, S., Pettit, S., Harris, I., Beresford, A., 2015. The pre-positioning of Warehouses at regional and local levels for a Humanitarian Relief Organisation. International Journal of Production Economics. 10.1016/j.ijpe.2015.01.015.

Rottkemper, B., Fischer, K., Blecken, A., Danne, C., 2011. Inventory relocation for overlapping disaster settings in humanitarian operations. OR Spectrum 33 (3), 721-749. 10.1007/s00291-011-0260-5.

Rushton, A., Croucher, P., Baker, P., 2006. The handbook of logistics and distribution management, 3rd ed. Kogan Page, London, Philadelphia, PA.

Russell, S.J., Norvig, P., Davis, E., 2010. Artificial intelligence: A modern approach, 3rd ed. Prentice Hall, Upper Saddle River, NJ.

SAHANA, n.d. What Does Sahana Eden Do? http://en.flossmanuals.net/sahana-eden/what-is-sahana-eden/. Accessed 20 March 2015.

Salmerón, J., Apte, A., 2010. Stochastic Optimization for Natural Disaster Asset Prepositioning. Production and Operations Management 19 (5), 561–574. 10.1111/j.1937-5956.2009.01119.x.

Sargent, R.G., 2005. Verification and validation of simulation models. Proceedings of the 37th conference on Winter simulation, 130–143.

Schulenberg, T., 2014. Annual Report 2013 of the Institute for Nuclear and Energy Technologies. KIT Scientific Publishing, Karlsruhe, Online-Ressource.

Schulz, S.F., Heigh, I., 2009. Logistics performance management in action within a humanitarian organization. Management Research News 32 (11), 1038–1049. 10.1108/01409170910998273.

Shapiro, D.L., Kirkman, B.L., Courtney, H.G., 2007. Perceived Causes and Solutions of the Translation Problem in Management Research. The Academy of Management Journal 50 (2), 249–266. 10.2307/20159853.

Sharfman, M.P., Dean, J.W., 1991. Conceptualizing and Measuring the Organizational Environment: A Multidimensional Approach. Journal of Management 17 (4), 681–700. 10.1177/014920639101700403.

Shen, Z., Dessouky, M.M., Ordóñez, F., 2009. A two-stage vehicle routing model for large-scale bioterrorism emergencies. Networks 54 (4), 255–269. 10.1002/net.20337.

Silver, E.A., 1981. Operations Research in Inventory Management: A Review and Critique. Operations Research 29 (4), 628–645. 10.2307/170382.

Simon, H.A., Newell, A., 1958. Heuristic Problem Solving: The Next Advance in Operations Research. Operations Research 6 (1), 1–10. 10.2307/167397.

Sodhi, M.S., Tang, C.S., 2008. The OR/MS Ecosystem: Strengths, Weaknesses, Opportunities, and Threats. Operations Research 56 (2), 267–277. 10.1287/opre.1080.0519.

Sphere Project, 2011. Humanitarian charter and minimum standards in humanitarian response, 3rd ed. Sphere Project, Rugby.

SteadieSeifi, M., Dellaert, N.P., Nuijten, W., van Woensel, T., Raoufi, R., 2014. Multimodal freight transportation planning: A literature review. European Journal of Operational Research 233 (1), 1–15. 10.1016/j.ejor.2013.06.055.

Suzuki, Y., 2012. Disaster-Relief Logistics With Limited Fuel Supply. Journal of Business Logistics 33 (2), 145–157. 10.1111/j.0000-0000.2012.01047.x.

Tatham, P., Banomyong, R., Sopadang, A., 2010. Using Monte Carlo simulation to refine emergency logistics response models: a case study. International Journal of Physical Distribution & Logistics Management 40 (8/9), 709–721. 10.1108/09600031011079346.

Tomasini, R.M., van Wassenhove, L.N., 2009. Humanitarian logistics. Palgrave Macmillan, Houndmills, Basingstoke, New York, NY.

Tzeng, G., Cheng, H., Huang, T., 2007. Multi-objective optimal planning for designing relief delivery systems. Transportation Research Part E: Logistics and Transportation Review 43 (6), 673–686. 10.1016/j.tre.2006.10.012.

UNHABITAT, UNHCR, IFRC, n.d. Shelter Projects 2008. http://www.sheltercasestudies.org/shelterprojects2008/ref/UN_Habitat_shelter_projects_2008.pdf. Accessed 17 April 2015.

UNHCR, IFRC, UNHABITAT, 2014. Shelter Projects 2013-2014. http://reliefweb.int/sites/reliefweb.int/files/resources/Shelterprojects_2013-14.pdf. Accessed 4 May 2015.

UNHRD, n.d. HUBs. http://www.unhrd.org/?page_id=91. Accessed 12 March 2015.

UNOCHA, 2011a. OCHA Annual Report. http://www.unocha.org/annualreport/2011/strategic-plan/objective-1_4. Accessed 4 March 2015.

UNOCHA, 2011b. Philippines: composite hazard map. http://www.preventionweb.net/files/4179_ochaphlhazardv3110606.pdf. Accessed 17 April 2015.

Valente, P., Mitra, G., 2007. The evolution of web-based optimisation: From ASP to e-Services. Decision Support Systems 43 (4), 1096–1116. 10.1016/j.dss.2005.07.003.

van Wassenhove, L., 2006. Humanitarian Aid Logistics: Supply Chain Management in High Gear. The Journal of the Operational Research Society 57 (5), 475–489. 10.2307/4102445.

Veinott, A.F., 1966. The Status of Mathematical Inventory Theory. Management Science 12 (11), 745–777. 10.2307/2627742.

Vitoriano, B., Ortuño, T., Tirado, G., 2009. HADS, a goal programming-based humanitarian aid distribution system. Journal of Multi-Criteria Decision Analysis 16 (1-2), 55–64. 10.1002/mcda.439.

Vitoriano, B., Ortuño, T., Tirado, G., Montero, J., 2011. A multi-criteria optimization model for humanitarian aid distribution. Journal of Global Optimization 51 (2), 189-208. 10.1007/s10898-010-9603-z.

Wakolbinger, T., Toyasaki, F., 2011. Impacts of funding systems on humanitarian operations, in: Christopher, M., Tatham, P. (Eds.), Humanitarian logistics. Meeting the challenge of preparing for and responding to disasters, 1st ed. Kogan Page, London, Philadelphia, PA, pp. 34–46.

Wallace, W.A., Balogh, F., 1985. Decision Support Systems for Disaster Management. Public Administration Review 45, 134–146. 10.2307/3135008.

Wang, H., Du, L., Ma, S., 2014. Multi-objective open location-routing model with split delivery for optimized relief distribution in post-earthquake. Transportation Research Part E: Logistics and Transportation Review 69, 160–179. 10.1016/j.tre.2014.06.006.

WFP, 2002. Emergency Field Operations Pocketbook. http://www.unicef.org/emerg/files/WFP_manual.pdf. Accessed 21 March 2015.

WFP, 2015. WFP Ebola response: Common service in Guinea, Liberia and Sirra Leone. 09 - 15 February 2015. http://www.logcluster.org/sites/default/files/attachments/wfp_ebola_response_common_services_sitrep_150220_v6.pdf. Accessed 17 April 2015.

Williams, H.P., 2013. Model building in mathematical programming, 5th ed. Wiley, Chichester, West Sussex.

Wohlgemuth, S., Oloruntoba, R., Clausen, U., 2012. Dynamic vehicle routing with anticipation in disaster relief. Socio-Economic Planning Sciences 46 (4), 261–271. 10.1016/j.seps.2012.06.001.

World Bank, 2010. Natural Hazards, UnNatural Disasters. World Bank; United Nations, Washington, D.C.

Yan, S., Shih, Y., 2009. Optimal scheduling of emergency roadway repair and subsequent relief distribution. Computers & Operations Research 36 (6), 2049–2065. 10.1016/j.cor.2008.07.002.

Yang, F., Yuan, Q., Du, S., Liang, L., 2014. Reserving relief supplies for earthquake: a multi-attribute decision making of China Red Cross. Annals of Operations Research. 10.1007/s10479-014-1749-5.

Ye, Y., Liu, N., 2014. Humanitarian logistics planning for natural disaster response with Bayesian information updates. Journal of Industrial and Management Optimization 10 (3), 665–689. 10.3934/jimo.2014.10.665.

Yi, W., Özdamar, L., 2007. A dynamic logistics coordination model for evacuation and support in disaster response activities. European Journal of Operational Research 179 (3), 1177–1193. 10.1016/j.ejor.2005.03.077.

Yushimito, W., Jaller, M., Ukkusuri, S., 2012. A Voronoi-Based Heuristic Algorithm for Locating Distribution Centers in Disasters. Networks and Spatial Economics 12 (1), 21-39. 10.1007/s11067-010-9140-9.

Zimmermann, H., 2005. Operations research: Methoden und Modelle, 1st ed. Vieweg, Wiesbaden.

Appendix

Table A.1 Data gathered for the application of the OR model of Balcik and Beamon (2008) to the Philippines case study

Category	Elements	Properties
Disasters	Possible typhoon Region CAR	10% probability of occurrence
	Possible typhoon Region I	10% probability of occurrence
	Possible typhoon Region II	10% probability of occurrence
	Possible typhoon Region III	10% probability of occurrence
	Possible typhoon Region IV	10% probability of occurrence
	Possible typhoon Region V	10% probability of occurrence
Locations for stationary warehouses	Laoag airport	18°10′41″N, 120°31′55″E
		100,000 m³
	Manila airport	14°30′30″N, 121°1′11″E
		100,000 m³
	Subic Bay airport	14°47′39″N, 120°16′15″E
		100,000 m³
Locations for demand facilities	Baguio (CAR)	16°25’ N, 120°36° E
		3,719 emergency shelter kits
	San Fernando-La Union (Region I)	16°37’ N, 120°19° E
		10,921 emergency shelter kits
	Tuguegarao City (Region II)	17°37’ N, 121°43 E
		7,427 emergency shelter kits
	San Fernando-Pampanga (Region III)	15°02’ N, 120°41 E
		23,317 emergency shelter kits
	Calamba (Region IV)	14°13’ N, 121°10 E
		29,003 emergency shelter kits
	Legazpi (Region V)	13°08’ N, 123°44 E
		12,467 emergency shelter kits
Arcs	Arc 1	Laoag airport
		Baguio
		282 km
		30 km/h
	Arc 2	Laoag airport
		San Fernando-La Union
		223 km
		30 km/h

Arc 3	Laoag airport
	Tuguegarao
	311 km
	30 km/h
Arc 4	Laoag airport
	San Fernando-Pampanga
	428 km
	30 km/h
Arc 5	Laoag airport
	Calamba
	545 km
	30 km/h
Arc 6	Laoag airport
	Legazpi
	962 km
	30 km/h
Arc 7	Manila airport
	Baguio
	259 km
	30 km/h
Arc 8	Manila airport
	San Fernando-La Union
	281 km
	30 km/h
Arc 9	Manila airport
	Tuguegarao
	498 km
	30 km/h
Arc 10	Manila airport
	San Fernando-Pampanga
	83 km
	30 km/h
Arc 11	Manila airport
	Calamba
	46 km
	30 km/h

	Arc 12	Manila airport
		Legazpi
		463 km
		30 km/h
	Arc 13	Subic Bay airport
		Baguio
		230 km
		30 km/h
	Arc 14	Subic Bay airport
		San Fernando-La Union
		252 km
		30 km/h
	Arc 15	Subic Bay airport
		Tuguegarao
		469 km
		30 km/h
	Arc 16	Subic Bay airport
		San Fernando-Pampanga
		64 km
		30 km/h
	Arc 17	Subic Bay airport
		Calamba
		181 km
		30 km/h
	Arc 18	Subic Bay airport
		Legazpi
		598 km
		30 km/h
Demand facilities	Demand facility 1 (DF1)	Baguio (CAR)
	Demand facility 2 (DF2)	San Fernando-La Union (Region I)
	Demand facility 3 (DF3)	Tuguegarao (Region II)
	Demand facility 4 (DF4)	San Fernando-Pampanga (Region III)
	Demand facility 5 (DF5)	Calamba (Region IV)
	Demand facility 6 (DF6)	Legazpi (Region V)
Transportation vehicle types	Long truck	90 km/h
		65 m³
		26 t
		10 vehicles on each arc

Relief item types	Emergency shelter kit	0.0112 m^3
		4.2 kg
Factors and bounds	Setup costs per location for a stationary warehouse	US$100,000 at Laoag airport
		US$200,000 at Manila airport
		US$100,000 at Subic Bay airport
	Transportation costs between locations per relief item type unit	US$0.05 per emergency shelter kit and km
	Procurement and holding costs per relief item type unit and location for a stationary warehouse	US$15 per emergency shelter kit at Laoag airport
		US$15 per emergency shelter kit at Manila airport
		US$15 per emergency shelter kit at Subic Bay airport
	Lower time limit per coverage level	0 h for coverage level “high”
		6 h for coverage level “medium”
		12 h for coverage level “low”
	Upper time limit per coverage level	5.99 h for coverage level “high”
		11.99 h for coverage level “medium”
		∞ for coverage level “low”
	Importance factor per coverage level	3 for coverage level “high”
		2 for coverage level “medium”
		1 for coverage level “low”
	Importance factor per relief item type	1 for category “very important”
	Budget in the disaster preparedness phase	US$250,000
	Budget in the disaster response phase	US$500,000

```
/***********************************************
 * OPL 12.5.1.0 Data Set for the Philippines case study
 * Author: Henning Gösling
 * Creation Date: 15.01.2015 at 13:59:46
 **********************************************/
Scenarios =
{TyphoonRCAR, TyphoonRI, TyphoonRII, TyphoonRIII, TyphoonRIV,
TyphoonRV};
LocationsForStationaryWarehouses =
{LaoagAirport, ManilaAirport, SubicBayAirport};
ReliefItemTypes = {EmergencyShelterKit};
CoverageLevels = {high,medium,low};
BudgetPreparedness = 250000;
BudgetResponse = 500000;
CostForAquiringAndHolding = [[15],[15],[15]];
CostForTransferring = [[[14.10,11.15,15.55,21.40,27.25,48.10]],
[[12.95,14.05,24.90,4.15,2.30,23.15]],
[[11.50,12.60,21.45,3.2,9.05,29.90]]];
Demand = [[3719,10921,7427,23317,29003,12467]];
CostSetupWarehouseAt = [100000,200000,100000];
Probability = [0.1,0.1,0.1,0.1,0.1,0.1];
SpaceAvailable = [100000,100000,100000];
SpaceNecessary = [0.0112];
TimeSatisfyingDemand = [[[9.4,7.4,10.4,14.3,18.2,32.1]],
[[8.6,9.4,16.6,2.8,1.5,15.4]]
[[7.7,8.4,15.6,2.1,6,20]]];
LowerTimeLimit = [[0],[6],[12]];
UpperTimeLimit = [[5.99],[11.99],[1000]];
ImportanceFactorReliefItemType = [1];
ImportanceFactorCoverageLevelReliefItemType = [[3],[2],[1]];
```

Table A.2 Solution for the Philippines case study determined with the OR model of Balcik and Beamon (2008)

Category	Elements	Properties
Stationary warehouses	Stationary warehouse 1 (SW1)	Subic Bay airport
		10,000 stocked emergency shelter kits
Demand facilities	DF1	3,719 distributed emergency shelter kits
	DF2	10,000 distributed emergency shelter kits
	DF3	7,427 distributed emergency shelter kits
	DF4	10,000 distributed emergency shelter kits
	DF5	10,000 distributed emergency shelter kits
	DF6	10,000 distributed emergency shelter kits
Transportation vehicle types	Large truck	3,719 transferred emergency shelter kits from SW1 to DF1
		10,000 transferred emergency shelter kits from SW1 to DF2
		7,427 transferred emergency shelter kits from SW1 to DF3
		10,000 transferred emergency shelter kits SW1 to DF4
		10,000 transferred emergency shelter kits from SW1 to DF5
		10,000 transferred emergency shelter kits from SW1 to DF6
Inputs	Warehousing resources: warehouse setup costs	US$100,000
	Relief items: procurement cost (incl. holding costs)	US$150,000
	Transportation resources: transportation costs in disasters	US$42,768 SW1 to DF1
		US$126,000 SW1 to DF2
		US$159,309 SW1 to DF3
		US$32,000 SW1 to DF4
		US$90,500 SW1 to DF5
		US$299,000 SW1 to DF6
Outputs	Delivered relief item quantity: percentage of fulfilled demand	100 % satisfied at DF1
		91.6 % satisfied at DF2
		100 % satisfied at DF3
		42.9 % satisfied at DF4
		34.5 % satisfied at DF5
		80.2% satisfied at DF6

	Delivered relief item quality: percentage of fulfilled demand	100% satisfied DF1 of “very important“ relief items
		91.6% satisfied DF2 of “very important“ relief items
		100% satisfied DF3 of “very important“ relief items
		42.9% satisfied DF4 of “very important“ relief items
		34.5% satisfied DF5 of “very important“ relief items
		80.2% satisfied DF6 of “very important“ relief items
	Delivery time: demand facility coverage level	Coverage level “medium” DF1
		Coverage level “medium” DF2
		Coverage level “low” DF3
		Coverage level “high” DF4
		Coverage level “medium” DF5
		Coverage level “low” DF6
Objectives and requirements	Limiting inputs in preparedness phase	Buffer 0
	Limiting inputs in response phase	Buffer US$457,232
		Buffer US$374,000
		Buffer US$340,691
		Buffer US$468,000
		Buffer US$409,500
		Buffer US$201,000
	Maximizing outputs	Objective function value 9,486.5

Table A.3 Data gathered for the application of the OR model of Murali et al. (2012) to the Philippines case study

Category	Elements	Properties
Disaster		
Locations for LDCs	Tuguegarao City sports complex	17°37'14.9"N 121°43'24.7"E
	Tuguegarao City airport	17°38'35.3"N 121°44'08.5"E
	University of St Louis	17°36'36.7"N 121°43'22.2"E
	Cagayan State University	17°39'30.7"N 121°45'03.9"E
Settlements	San Gabriel	17°37'13.0"N 121°42'57.4"E
		200 emergency shelter kits
	Bassig Street	17°36'37.3"N 121°43'07.7"E
		600 emergency shelter kits
	Gonzaga Street	17°36'54.6"N 121°43'31.8"E
		400 emergency shelter kits
	Lagundi Street	17°35'39.8"N 121°42'12.5"E
		300 emergency shelter kits
	Pallua Road	17°37'29.0"N 121°42'02.1"E
		100 emergency shelter kits
	Caimito Street	17°37'35.5"N 121°44'12.5"E
		100 emergency shelter kits
	Bartolome Street	17°38'08.1"N 121°44'33.0"E
		100 emergency shelter kits
	Atulayan Road	17°38'47.8"N 121°43'06.4"E
		100 emergency shelter kits
	Linao-Carig Road	17°39'13.1"N 121°43'43.5"E
		300 emergency shelter kits
	Caritian Highway	17°38'00.7"N 121°43'15.1"E
		200 emergency shelter kits
Arcs	Arc 1	Tuguegarao City sports complex
		San Gabriel
		1.8 km
	Arc 2	Tuguegarao City sports complex
		Bassig Street
		2 km
	Arc 3	Tuguegarao City sports complex
		Gonzaga Street
		0.9 km

Arc 4	Tuguegarao City sports complex Lagundi Street 4.5 km
Arc 5	Tuguegarao City sports complex Pallua Road 3.2 km
Arc 6	Tuguegarao City sports complex Caimito Street 2.2 km
Arc 7	Tuguegarao City sports complex Bartolome Street 3.2 km
Arc 8	Tuguegarao City sports complex Atulayan Road 3.3 km
Arc 9	Tuguegarao City sports complex Linao-Carig Road 4.1 km
Arc 10	Tuguegarao City sports complex Caritian Highway 1.6 km
Arc 11	Tuguegarao City airport San Gabriel 5.2 km
Arc 12	Tuguegarao City airport Bassig Street 5.2 km
Arc 13	Tuguegarao City airport Gonzaga Street 4 km
Arc 14	Tuguegarao City airport Lagundi Street 7.7 km
Arc 15	Tuguegarao City airport Pallua Road 6.3 km

Arc 16	Tuguegarao City airport Caimito Street 2.7 km
Arc 17	Tuguegarao City airport Bartolome Street 1.4 km
Arc 18	Tuguegarao City airport Atulayan Road 4.7 km
Arc 19	Tuguegarao City airport Linao-Carig Road 3.1 km
Arc 20	Tuguegarao City airport Caritian Highway 3.5 km
Arc 21	University of St Louis San Gabriel 1.7 km
Arc 22	University of St Louis Bassig Street 0.6 km
Arc 23	University of St Louis Gonzaga Street 0.9 km
Arc 24	University of St Louis Lagundi Street 3.1 km
Arc 25	University of St Louis Pallua Road 3 km
Arc 26	University of St Louis Caimito Street 3 km
Arc 27	University of St Louis Bartolome Street 4 km

Arc 28	University of St Louis Atulayan Road 4.6 km
Arc 29	University of St Louis Linao-Carig Road 5.5 km
Arc 30	University of St Louis Caritian Highway 3.1 km
Arc 31	Cagayan State University San Gabriel 7.3 km
Arc 32	Cagayan State University Bassig Street 7.2 km
Arc 33	Cagayan State University Gonzaga Street 6 km
Arc 34	Cagayan State University Lagundi Street 9.7 km
Arc 35	Cagayan State University Pallua Road 7.8 km
Arc 36	Cagayan State University Caimito Street 4.5 km
Arc 37	Cagayan State University Bartolome Street 3.3 km
Arc 38	Cagayan State University Atulayan Road 4.5 km
Arc 39	Cagayan State University Linao-Carig Road 2.9 km

	Arc 40	Cagayan State University Caritian Highway 5.4 km
Supply facility	Stationary warehouse 1	10,000 emergency shelter kits
Aid workers	Working time	7 hours per day per person
	Number of aid workers at locations for a LDC	3 at Tuguegarao City sports complex 3 at Tuguegarao City airport 3 at University of St Louis 3 at Cagayan State University
Relief item	Time for distribution	2.5 minutes per distribution
Factors and bounds	Number of LDCs to be erected	1
	Upper distance limit per coverage level	2.99 km for coverage level “high” 4.99 km for coverage level “medium” 7 km for coverage level “low”
	Maximum percentage of demand at a settlement to be satisfied from LDCs that provide a certain coverage level	100% demand satisfaction with coverage level “high” 50% demand satisfaction with coverage level “medium” 10% demand satisfaction with coverage level “low”
	Duration of disaster response	5 days

```
/**********************************************
 * OPL 12.5.1.0 Data Set for the Philippines case study
 * Author: Henning Gösling
 * Creation Date: 16.01.2015 at 14:05:09
 **********************************************/
Settlements = {SG,BassigSt,GonzagaSt,LagundiSt,PalluaRd,CaimitoSt,
BartolomeSt,AtulayanRd,LinaoRd,CaritianHwy};
LocationsForLDCs = {SportsComplex,Airport,UniversityStLouis,
StateUniversity};
CoverageLevels = {high,medium,low};
Capacity = [2520,2520,2520,2520];
Distance = [[1.8,2,0.9,4.5,3.2,2.2,3.2,3.3,4.1,1.6],
                 [5.2,5.2,4,7.7,6.3,2.7,1.4,4.7,3.1,3.5],
                 [1.7,0.6,0.9,3.1,3,3,4,4.6,5.5,3.1],
                 [7.3,7.2,6,9.7,7.8,4.5,3.3,4.5,2.9,5.4]];
Demand = [200,600,400,300,100,100,100,100,300,200];
NumberLDCs = 1;
LowerDistanceLimit = [0,3,5];
UpperDistanceLimit = [2.99,4.99,7];
DemandShare = [1,0.5,0.1];
Supply = 10000;
```

Table A.4 Solution for the Philippines case study determined with the OR model of Murali et al. (2012)

Category	Elements	Properties
LDCs	Local distribution center 1	Sports Complex
		1,950 distributed emergency shelter kits
Transportation resource		1,950 transferred emergency shelter kits from SW1 to LDC1
Inputs	Distribution resources: number of LDCs	1
Outputs	Delivered relief item quantity: amount of allocated relief items	1,950 emergency shelter kits
	Distance to LDCs: amount of allocated relief items collected from LDCs that provide a certain coverage level for a settlement	Beneficiaries at San Gabriel collect 200 emergency shelter kits from LDC1 providing coverage level “high”
		Beneficiaries at Bassig Street collect 600 emergency shelter kits from LDC1 providing coverage level “high”
		Beneficiaries at Gonzaga Street collect 400 emergency shelter kits from LDC1 providing coverage level “high”
		Beneficiaries at Lagundi Street collect 150 emergency shelter kits from LDC1 providing coverage level “medium”
		Beneficiaries at Pallua Road collect 50 emergency shelter kits from LDC1 providing coverage level “medium”
		Beneficiaries at Caimito Street collect 100 emergency shelter kits from LDC1 providing coverage level “high”
		Beneficiaries at Bartolome Street collect 50 emergency shelter kits from LDC1 providing coverage level “medium”
		Beneficiaries at Atulayan Road collect 50 emergency shelter kits from LDC1 providing coverage level “medium”
		Beneficiaries at Linao Road collect 150 emergency shelter kits from LDC1 providing coverage level “medium”
		Beneficiaries at Caritian Highway collect 200 emergency shelter kits from LDC1 providing coverage level “high”

Objectives and requirements	Limiting number of distribution resources	Buffer 0
	Ensuring number of distribution resources	Buffer 0
	Maximizing delivered relief item quantity	Objective function value 1,950
	Limiting distance to LDCs	Buffer 0 for San Gabriel regarding LDCs with coverage level “high”
		Buffer 100 for San Gabriel regarding LDCs with coverage level “medium”
		Buffer 20 for San Gabriel regarding LDCs with coverage level “low”
		Buffer 0 for Bassig Street regarding LDCs with coverage level “high”
		Buffer 300 for Bassig Street regarding LDCs with coverage level “medium”
		Buffer 60 for Bassig Street regarding LDCs with coverage level “low”
		Buffer 0 for Gonzaga Street regarding LDCs with coverage level “high”
		Buffer 200 for Gonzaga Street regarding LDCs with coverage level “medium”
		Buffer 40 for Gonzaga Street regarding LDCs with coverage level “low”
		Buffer 300 for Lagundi Street regarding LDCs with coverage level “high”
		Buffer 0 for Lagundi Street regarding LDCs with coverage level “medium”
		Buffer 30 for Lagundi Street regarding LDCs with coverage level “low”
		Buffer 100 for Pallua Road regarding LDCs with coverage level “high”
		Buffer 0 for Pallua Road regarding LDCs with coverage level “medium”
		Buffer 10 for Pallua Road regarding LDCs with coverage level “low”
		Buffer 0 for Caimito Street regarding LDCs with coverage level “high”
		Buffer 50 for Caimito Street regarding LDCs with coverage level “medium”
		Buffer 10 for Caimito Street regarding LDCs with coverage level “low”
		Buffer 100 for Bartolome Street regarding LDCs with coverage level “high”

	Buffer 0 for Bartolome Street regarding LDCs with coverage level “medium”
	Buffer 10 for Bartolome Street regarding LDCs with coverage level “low”
	Buffer 100 for Atulayan Road regarding LDCs with coverage level “high”
	Buffer 0 for Atulayan Road regarding LDCs with coverage level “medium”
	Buffer 10 for Atulayan Road regarding LDCs with coverage level “low”
	Buffer 300 for Linao Road regarding LDCs with coverage level “high”
	Buffer 0 for Linao Road regarding LDCs with coverage level “medium”
	Buffer 30 for Linao Road regarding LDCs with coverage level “low”
	Buffer 0 for Caritian Highway regarding LDCs with coverage level “high”
	Buffer 100 for Caritian Highway regarding LDCs with coverage level “medium”
	Buffer 20 for Caritian Highway regarding LDCs with coverage level “low”

Table A.5 Data gathered for the application of the OR model of Balcik et al. (2008) to the Philippines case study

Category	Elements	Properties
Location for a supply facility	Subic Bay airport	14°47′39″N, 120°16′15″E
Locations for LDCs	Alaminos	16°09'18.9"N 119°58'48.0"E
		250 emergency shelter kits at the beginning of the time horizon
	Aurora	16°59'21.3"N 121°38'11.1"E
		500 emergency shelter kits at the beginning of the time horizon
	Bambang	16°22'52.9"N 121°06'25.1"E
		700 emergency shelter kits at the beginning of the time horizon
	Bongabon	15°37'42.2"N 121°08'50.8"E
		550 emergency shelter kits at the beginning of the time horizon
	Cabagan	17°25'42.7"N 121°46'15.8"E
		800 emergency shelter kits at the beginning of the time horizon
	Cabanatuan	15°28'37.3"N 120°57'32.5"E
		1,400 emergency shelter kits at the beginning of the time horizon
	Caiguran	16°12'34.3"N 122°02'33.9"E
		500 emergency shelter kits at the beginning of the time horizon
	Daguapan City	16°02'37.8"N 120°20'45.0"E
		1,400 emergency shelter kits at the beginning of the time horizon
	Dipaculao	15°59'11.8"N 121°38'59.3"E
		200 emergency shelter kits at the beginning of the time horizon
	Iba	15°19'36.9"N 119°58'08.8"E
		100 emergency shelter kits at the beginning of the time horizon
	Lamut	16°38'59.7"N 121°13'25.6"E
		100 emergency shelter kits at the beginning of the time horizon
	Maddela	16°20'41.7"N 121°40'56.3"E
		650 emergency shelter kits at the beginning of the time horizon

	Malolos City	14°50'21.9"N 120°48'50.0"E 3,100 emergency shelter kits at the beginning of the time horizon
	Maria Aurora	15°47'50.0"N 121°28'31.4"E 500 emergency shelter kits at the beginning of the time horizon
	Muñoz	15°42'51.2"N 120°54'35.8"E 200 emergency shelter kits at the beginning of the time horizon
	Roxas	11°35'06.1"N 122°45'06.9"E 800 emergency shelter kits at the beginning of the time horizon
	San Miguel	15°08'49.6"N 120°58'22.6"E 100 emergency shelter kits at the beginning of the time horizon
	Santa Cruz	15°45'45.8"N 119°54'38.2"E 200 emergency shelter kits at the beginning of the time horizon
	Santiago City	16°41'15.8"N 121°33'02.6"E 300 emergency shelter kits at the beginning of the time horizon
	Talavera	15°35'05.9"N 120°54'55.1"E 500 emergency shelter kits at the beginning of the time horizon
	Tarlac City	15°29'06.2"N 120°35'14.8"E 1,000 emergency shelter kits at the beginning of the time horizon
	Tuguegarao City	17°36'36.7"N 121°43'22.2"E 1,950 emergency shelter kits at the beginning of the time horizon
	Tumauini	17°16'45.0"N 121°48'31.1"E 100 emergency shelter kits at the beginning of the time horizon
Routes	Route 1	Subic Bay airport, Malolos City, San Miguel, Cabanatuan, Tarlac City, Daguapan City, Alaminos, Santa Cruz, Iba, Subic Bay airport 566 km 50 km/h
	Route 2	Subic Bay airport, Tarlac City, Bongabon, Maria Aurora, Dipaculao, Caiguran, Maddela, Lamut, Bambang, Munoz, Talavera, Subic Bay airport

		885 km
		50 km/h
	Route 3	Subic Bay airport, Tarlac City, Tuguegarao City, Cabagan, Tumauini, Roxas, Aurora, Santiago City, Subic Bay airport
		1,095 km
		50 km/h
Supply facility	Stationary warehouse 1	Subic Bay airport
		10,000 emergency shelter kits on day 1
		5,000 emergency shelter kits on day 3
		5,000 emergency shelter kits on day 4
		5,000 emergency shelter kits on day 5
LDCs	LDC 1	Alaminos
	LDC 2	Aurora
	LDC 3	Bambang
	LDC 4	Bongabon
	LDC 5	Cabagan
	LDC 6	Cabanatuan
	LDC 7	Caiguran
	LDC 8	Daguapan City
	LDC 9	Dipaculao
	LDC 10	Iba
	LDC 11	Lamut
	LDC 12	Maddela
	LDC 13	Malolos City
	LDC 14	Maria Aurora
	LDC 15	Munoz
	LDC 16	Roxas
	LDC 17	San Miguel
	LDC 18	Santa Cruz
	LDC 19	Santiago City
	LDC 20	Talavera
	LDC 21	Tarlac City
	LDC 22	Tuguegarao City
	LDC 23	Tumauini
Transportation vehicles	Transportation vehicle 1	65 m^3
		26 t
		90 km/h

	Transportation vehicle 2	65 m³
		26 t
		90 km/h
	Transportation vehicle 3	65 m³
		26 t
		90 km/h
	Transportation vehicle 4	65 m³
		26 t
		90 km/h
	Transportation vehicle 5	65 m³
		26 t
		90 km/h
Relief item types	Volume	0.0122 m³
	Weight	4.2 kg
Factors	Transportation costs for a transportation vehicle on a route	US$400 for each vehicle on route 1
		US$600 for each vehicle on route 2
		US$800 for each vehicle on route 3
	Costs per 1% of unsatisfied demand for a relief item type at a location	US$500 on day 1 at each location
		US$1,000 on day 2 at each location
		US$2,000 on day 3 at each location
		US$4,000 on day 4 at each location
		US$10,000 on day 5 at each location

```
/************************************************
 * OPL 12.5.1.0 Data Set for the Philippines case study
 * Author: Henning Gösling
 * Creation Date: 08.04.2015 at 12:21:12
 ************************************************/
TimePeriods = {1,2,3,4,5,6};
TransportationVehicles = {V1,V2,V3,V4,V5};
Routes = {R1,R2,R3};
LocationsForLDCs =
{Alaminos, Aurora, Bambang, Bongabon, Cabagan, Cabanatuan, Caiguran,
DaguapanCity, Dipaculao, Iba, Lamut, Maddela, MalolosCity, MariaAurora,
Munoz, Roxas, SanMiguel, SantaCruz,   SantiagoCity, Talavera, TarlacCity,
TuguegaraoCity, Tumauini};
LocationsOnRoutes =
[{MalolosCity,SanMiguel,Cabanatuan,TarlacCity,
DaguapanCity,Alaminos,SantaCruz,Iba},{TarlacCity,Bongabon,
MariaAurora,Dipaculao,Caiguran,Maddela,Lamut,Bambang,Munoz,
Talavera},{TarlacCity,TuguegaraoCity,Cabagan,Tumauini,Roxas,
Aurora,SantiagoCity}];
ReliefItems = {RI1};
ReliefItemsOfType = [{RI1},{}];
CostForDriving =
[[400,400,400,400,400],[600,600,600,600,600],[800,800,800,800,800]];
Capacity = [5327,5327,5327,5327,5327];
TransportationTime =
[[0.5,0.5,0.5,0.5,0.5],[0.75,0.75,0.75,0.75,0.75],[0.92,0.92,0.92,0.92,0.92]];
Demand  =
[[[250,0,0,0,0,0],[500,0,0,0,0,0],[700,0,0,0,0,0],[550,0,0,0,0,0],[800,0,0,0,0,
0],[1400,0,0,0,0,0],[500,0,0,0,0,0],[1400,0,0,0,0,0],[200,0,0,0,0,0],[100,0,0,
0,0,0],[100,0,0,0,0,0],[650,0,0,0,0,0],[3100,0,0,0,0,0],[500,0,0,0,0,0],[200,0,
0,0,0,0],[800,0,0,0,0,0],[100,0,0,0,0,0],[200,0,0,0,0,0],[300,0,0,0,0,0],[500,0
,0,0,0,0],[1000,0,0,0,0,0],[1950,0,0,0,0,0],[100,0,0,0,0,0]]];
CostForShortage =
[[500,1000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2
000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,4000,10
000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1
000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,40
00,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[
500,1000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,20
00,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,4000,100
00,0],[500,1000,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,10
00,2000,4000,10000,0],[500,1000,2000,4000,10000,0],[500,1000,2000,400
0,10000,0],[500,1000,2000,4000,10000,0]]];
Supply = [[10000,0,5000,5000,5000,0]];
```

Table A.6 Solution for the Philippines case study determined with the OR model of Balcik et al. (2008)

Category	Elements	Properties
Supply facility	Stationary warehouse 1	3 Transportation vehicle processed in period 1
		1 Transportation vehicle processed in period 3
		1 Transportation vehicle processed in period 4
LDCs	LDC 1	1 Transportation vehicle processed in period 1
		54 relief items distributed in period 1
		1 Transportation vehicle processed in period 3
		165 relief items distributed in period 3
		1 Transportation vehicle processed in period 4
		31 relief items distributed in period 4
	LDC 2	1 Transportation vehicle processed in period 1
		500 relief items distributed in period 1
	LDC 3	1 Transportation vehicle processed in period 1
		700 relief items distributed in period 1
	LDC 4	1 Transportation vehicle processed in period 1
		550 relief items distributed in period 1
	LDC 5	1 Transportation vehicle processed in period 1
		800 relief items distributed in period 1
	LDC 6	1 Transportation vehicle processed in period 1
		305 relief items distributed in period 1
		1 Transportation vehicle processed in period 3
		927 relief items distributed in period 3
		1 Transportation vehicle processed in period 4
		168 relief items distributed in period 4
	LDC 7	1 Transportation vehicle processed in period 1
		500 relief items distributed in period 1
	LDC 8	1 Transportation vehicle processed in period 1
		305 relief items distributed in period 1
		1 Transportation vehicle processed in period 3
		927 relief items distributed in period 3
		1 Transportation vehicle processed in period 4
		168 relief items distributed in period 4
	LDC 9	1 Transportation vehicle processed in period 1
		200 relief items distributed in period 1
	LDC 10	1 Transportation vehicle processed in period 1
		21 relief items distributed in period 1

	1 Transportation vehicle processed in period 3
	66 relief items distributed in period 3
	1 Transportation vehicle processed in period 4
	13 relief items distributed in period 4
LDC 11	1 Transportation vehicle processed in period 1
	100 relief items distributed in period 1
LDC 12	1 Transportation vehicle processed in period 1
	650 relief items distributed in period 1
LDC 13	1 Transportation vehicle processed in period 1
	677 relief items distributed in period 1
	1 Transportation vehicle processed in period 3
	2052 relief items distributed in period 3
	1 Transportation vehicle processed in period 4
	371 relief items distributed in period 4
LDC 14	1 Transportation vehicle processed in period 1
	500 relief items distributed in period 1
LDC 15	1 Transportation vehicle processed in period 1
	200 relief items distributed in period 1
LDC 16	1 Transportation vehicle processed in period 1
	800 relief items distributed in period 1
LDC 17	1 Transportation vehicle processed in period 1
	21 relief items distributed in period 1
	1 Transportation vehicle processed in period 3
	66 relief items distributed in period 3
	1 Transportation vehicle processed in period 4
	13 relief items distributed in period 4
LDC 18	1 Transportation vehicle processed in period 1
	44 relief items distributed in period 1
	1 Transportation vehicle processed in period 3
	132 relief items distributed in period 3
	1 Transportation vehicle processed in period 4
	25 relief items distributed in period 4
LDC 19	1 Transportation vehicle processed in period 1
	300 relief items distributed in period 1
LDC 20	1 Transportation vehicle processed in period 1
	500 relief items distributed in period 1

	LDC 21	1 Transportation vehicle processed in period 1
		218 relief items distributed in period 1
		1 Transportation vehicle processed in period 3
		662 relief items distributed in period 3
		1 Transportation vehicle processed in period 4
		120 relief items distributed in period 4
	LDC 22	1 Transportation vehicle processed in period 1
		1950 relief items distributed in period 1
	LDC 23	1 Transportation vehicle processed in period 1
		100 relief items distributed in period 1
Transportation vehicles	Transportation vehicle 1	Route 1 in period 1
		1,650 transferred emergency shelter kits
	Transportation vehicle 3	Route 1 in period 4
		900 transferred emergency shelter kits
	Transportation vehicle 4	Route 2 in period 1
		3,900 transferred emergency shelter kits
	Transportation vehicle 5	Route 3 in period 1
		4,450 transferred emergency shelter kits
		Route 1 in period 3
		5,000 transferred emergency shelter kits
Input	Transportation resource: transportation costs	US$2,600
Output	Delivered relief item quantity:	
	- Maximum relief item shortage costs	US$391 in period 1
		US$781 in period 2
		US$238 in period 3
		US$0 in period 4
		US$0 in period 5
	- Transferred relief items	10,000 in period 1
		5,000 in period 3
		900 in period 4
	Delivery time: Maximum relief item shortage costs	US$391 in period 1
		US$781 in period 2
		US$ 238 in period 3
		US$0 in period 4
		US$0 in period 5

Objectives and requirements	Minimizing input	Objective function value 4,010,59
	Maximizing minimum delivered relief item quantity	Objective function value 4,010,59
	Minimizing maximum delivery time	Objective function value 4,010,59
	Ensuring delivered relief item quantity	Buffer 196 at LDC 1 in period 1
		Buffer 196 at LDC 1 in period 2
		Buffer 30 at LDC 1 in period 3
		Buffer 0 at LDC 1 in period 4
		Buffer 0 at LDC 1 in period 5
		Buffer 0 at LDC 2 in period 1
		Buffer 0 at LDC 2 in period 2
		Buffer 0 at LDC 2 in period 3
		Buffer 0 at LDC 2 in period 4
		Buffer 0 at LDC 2 in period 5
		Buffer 0 at LDC 3 in period 1
		Buffer 0 at LDC 3 in period 2
		Buffer 0 at LDC 3 in period 3
		Buffer 0 at LDC 3 in period 4
		Buffer 0 at LDC 3 in period 5
		Buffer 0 at LDC 4 in period 1
		Buffer 0 at LDC 4 in period 2
		Buffer 0 at LDC 4 in period 3
		Buffer 0 at LDC 4 in period 4
		Buffer 0 at LDC 4 in period 5
		Buffer 0 at LDC 5 in period 1
		Buffer 0 at LDC 5 in period 2
		Buffer 0 at LDC 5 in period 3
		Buffer 0 at LDC 5 in period 4
		Buffer 0 at LDC 5 in period 5
		Buffer 1095 at LDC 6 in period 1
		Buffer 1095 at LDC 6 in period 2
		Buffer 167 at LDC 6 in period 3
		Buffer 0 at LDC 6 in period 4
		Buffer 0 at LDC 6 in period 5
		Buffer 0 at LDC 7 in period 1
		Buffer 0 at LDC 7 in period 2

Buffer 0 at LDC 7 in period 3
Buffer 0 at LDC 7 in period 4
Buffer 0 at LDC 7 in period 5
Buffer 1095 at LDC 8 in period 1
Buffer 1095 at LDC 8 in period 2
Buffer 167 at LDC 8 in period 3
Buffer 0 at LDC 8 in period 4
Buffer 0 at LDC 8 in period 5
Buffer 0 at LDC 9 in period 1
Buffer 0 at LDC 9 in period 2
Buffer 0 at LDC 9 in period 3
Buffer 0 at LDC 9 in period 4
Buffer 0 at LDC 9 in period 5
Buffer 79 at LDC 10 in period 1
Buffer 79 at LDC 10 in period 2
Buffer 12 at LDC 10 in period 3
Buffer 0 at LDC 10 in period 4
Buffer 0 at LDC 10 in period 5
Buffer 0 at LDC 11 in period 1
Buffer 0 at LDC 11 in period 2
Buffer 0 at LDC 11 in period 3
Buffer 0 at LDC 11 in period 4
Buffer 0 at LDC 11 in period 5
Buffer 0 at LDC 12 in period 1
Buffer 0 at LDC 12 in period 2
Buffer 0 at LDC 12 in period 3
Buffer 0 at LDC 12 in period 4
Buffer 0 at LDC 12 in period 5
Buffer 2423 at LDC 13 in period 1
Buffer 2423 at LDC 13 in period 2
Buffer 370 at LDC 13 in period 3
Buffer 0 at LDC 13 in period 4
Buffer 0 at LDC 13 in period 5
Buffer 0 at LDC 14 in period 1
Buffer 0 at LDC 14 in period 2
Buffer 0 at LDC 14 in period 3
Buffer 0 at LDC 14 in period 4
Buffer 0 at LDC 14 in period 5

Buffer 0 at LDC 15 in period 1
Buffer 0 at LDC 15 in period 2
Buffer 0 at LDC 15 in period 3
Buffer 0 at LDC 15 in period 4
Buffer 0 at LDC 15 in period 5
Buffer 0 at LDC 16 in period 1
Buffer 0 at LDC 16 in period 2
Buffer 0 at LDC 16 in period 3
Buffer 0 at LDC 16 in period 4
Buffer 0 at LDC 16 in period 5
Buffer 79 at LDC 17 in period 1
Buffer 79 at LDC 17 in period 2
Buffer 12 at LDC 17 in period 3
Buffer 0 at LDC 17 in period 4
Buffer 0 at LDC 17 in period 5
Buffer 157 at LDC 18 in period 1
Buffer 157 at LDC 18 in period 2
Buffer 24 at LDC 18 in period 3
Buffer 0 at LDC 18 in period 4
Buffer 0 at LDC 18 in period 5
Buffer 0 at LDC 19 in period 1
Buffer 0 at LDC 19 in period 2
Buffer 0 at LDC 19 in period 3
Buffer 0 at LDC 19 in period 4
Buffer 0 at LDC 19 in period 5
Buffer 0 at LDC 20 in period 1
Buffer 0 at LDC 20 in period 2
Buffer 0 at LDC 20 in period 3
Buffer 0 at LDC 20 in period 4
Buffer 0 at LDC 20 in period 5
Buffer 782 at LDC 21 in period 1
Buffer 782 at LDC 21 in period 2
Buffer 120 at LDC 21 in period 3
Buffer 0 at LDC 21 in period 4
Buffer 0 at LDC 21 in period 5
Buffer 0 at LDC 22 in period 1
Buffer 0 at LDC 22 in period 2
Buffer 0 at LDC 22 in period 3

	Buffer 0 at LDC 22 in period 4
	Buffer 0 at LDC 22 in period 5
	Buffer 0 at LDC 23 in period 1
	Buffer 0 at LDC 23 in period 2
	Buffer 0 at LDC 23 in period 3
	Buffer 0 at LDC 23 in period 4
	Buffer 0 at LDC 23 in period 5