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REGULAR ARTICLE

Inventory relocation for overlapping disaster settings in humanitarian operations

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Abstract The number and scale of humanitarian operations has significantly increased during the past decades due to the rising number of humanitarian emergencies and natural disasters worldwide. Therefore, the development of appropriate planning methods for optimization of the respective supply chains is constantly growing in importance. A specific problem in the context of humanitarian operations is the supply of relief items to the affected areas after the occurrence of a sudden change in demand or supply, for example, due to an epidemic or to unexpected shortages, during an ongoing humanitarian action. When such overlapping disasters occur, goods must be relocated to existing depots in a way which enables rapid supply to regions with new and urgent demand. At the same time, ongoing operations have to continue, i.e., the other regions should not suffer from shortages, and possible future emergencies must be taken into account. This is a planning situation under uncertainty as it is not known in advance if and where a disruption—and hence additional demand—will occur. In this paper, an optimization model for such situations is developed based on penalty costs for non-satisfied demand. A rolling horizon approach for solving the model is

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presented, and it is shown that taking into account the possibility of future disruptions can help to balance inventories and to reduce total non-served demand.

Keywords Humanitarian logistics · Overlapping disasters · Inventory relocation · Transshipment planning

1 Introduction

Each year, millions of people are affected by natural and man-made disasters which trigger humanitarian crises. Over the past decades the number of people who become victims of such incidents has increased tremendously (Burton 1997; Swiss Reinsurance Company 2010; Thomas and Kopczak 2005; EM-DAT 2009). Many humanitarian organizations work in a constant effort to help and support the affected communities, for example, by delivering nutrition, water, drugs and medical equipment, shelter, and non-food items (The Sphere Project 2004). As the humanitarian organizations mobilize and deploy a substantial amount of material, the major tasks that need to be carried out are logistical in nature (Van Wassenhove 2006): Relief items need to be procured domestically or internationally; in many cases they have to be stored locally and then must be transported to the affected regions. Furthermore, it has to be decided where to build central and regional depots (if any) and how to allocate goods to the depots and which amounts to store. Hence, a vast range of problems arises in humanitarian logistics. Some studies estimate the fraction of logistics and supply chain management at up to 80% of the total effort of these operations (Van Wassenhove 2006).

The disaster relief lifecycle can be partitioned into the phases of disaster preparation and disaster response (Kovács and Spens 2007; Tufinkgi 2006; Thomas and Kopczak 2007; Tomasini and Van Wassenhove 2009): The disaster preparation phase includes all activities which are carried out before a disaster strikes and which are not geared towards a specific disaster or a specific community. Disaster response comprises activities after the onset of a disaster that are aimed at directly supporting an affected community. Here, a short-term immediate response phase and a longer-term recovery and reconstruction phase are distinguished.

The transition between these two disaster response phases is gradual. A number of indicators can be used to observe the transition from the immediate response phase into the recovery and reconstruction phase: Basic needs of the affected community are covered, the crude mortality rate drops to below 1/10.000 people/day, morbidity equals comparative pre-disaster levels, health services are assured, the threat of an epidemic is reduced, and the humanitarian operations become more effectively coordinated (Médecins Sans Frontières 2009, internal presentation).

1.1 Planning situation: overlapping disasters

In this paper, a specific situation that may occur during the response phase or the recovery and reconstruction phase of a disaster is examined: In a given area, a humanitarian crisis has occurred and humanitarian operations are carried out in order to support the affected community. A number of regional depots have been erected, from which the relief items are distributed to the beneficiaries. These regional depots are served from a central depot within the area. The central depot, in turn, gets its supply periodically from a global depot.

During an ongoing humanitarian operation, the distribution of the relief items can be planned using the existing infrastructure and mostly reliable demand forecasts. These forecasts are commonly based on deterministic information regarding the relevant areas, the number of people affected, the seasonal pattern of certain diseases, etc. (Tomasini and Van Wassenhove 2009). Yet, different types of unplanned incidents can occur during an ongoing humanitarian action, which lead to uncertainties in operations planning.

On the supply side, a depot can be destroyed, for instance, by a fire, or goods can be stolen, leading to a shortage in supply. On the other side, demand for a specific item can suddenly increase, for instance, due to an outbreak of an epidemic. Humanitarian organizations may be able to estimate the probabilities of these incidents for different areas, but it still remains difficult for these organizations to prepare adequately for such situations.

When a sudden increase of demand occurs in one of the regions, i.e., at one of the depots, rapid delivery of the relief items to the newly affected region is required. As delivery from the central (or even the global) depot usually takes longer than delivery from neighboring regions, relocation of goods between neighboring depots according to the new demand data seems to be the best solution at first sight. However, such a re-distribution of goods might lead to future shortages at the supplying depots. Thus, current demand and possible future developments, i.e., the possibility of future demand increases in any of the regions, have to be taken into account in relocation planning. Therefore, if a sudden change of demand or supply occurs during an ongoing humanitarian operation, a complex planning problem results which includes decisions regarding the relocation of stocks and the transportation of relief items under uncertainty.

The respective situations can be termed *overlapping disasters*, as they result from a combination of different disastrous incidents. They have to lead to *embedded relief actions*, as short-term relief has to be carried out within an ongoing humanitarian operation.

Such a situation of overlapping disasters occurred, for example, in Haiti in 2010, where first an earthquake took place, and then hurricane Tomas struck during the ongoing humanitarian operations. The additional outbreak of cholera shortly afterwards exacerbated the situation even more and required additional relief activities, while the ongoing humanitarian operations had to be kept up. Hence, the sequence of incidents lead to a very complex planning situation and to an extraordinarily long response phase (Balaisyte et al. 2011).

Due to their complexity, such situations require specific solution approaches. Moreover, as in other humanitarian planning problems, conflicting objectives need to be balanced: The primary aim of the humanitarian organization conducting the humanitarian operation will be to support the affected communities as effectively as possible, i.e., the minimization of unsatisfied demand (Tomasini and Van Wassenhove 2009). Yet, as financial resources are scarce, effective control of costs also needs to be considered. This is exacerbated in the recovery and reconstruction phase of disaster relief, where it becomes increasingly hard for humanitarian organizations to fund their operations (Médecins Sans Frontières 2009b; Tomasini and Van Wassenhove 2009). In other words, while the cost-efficient distribution of the goods is required, this goal is in conflict with the humanitarian objective of helping a maximum number of people: There is a trade-off between the two, and the solution of the resulting multi-period, multi-objective planning problem under uncertainty is not straightforward.

1.2 Example situation

A specific example is used to describe the type of situations to which the model developed below applies. While the description of the following situation is taken from the annual report of a humanitarian organization and reflects an actual humanitarian crisis, the example case built upon this situation serves purely illustrative purposes.

The humanitarian organization Médecins Sans Frontières (MSF) has been working in Burundi since 1992 (Médecins Sans Frontières 2009a). In 2007, the organization supports a number of health centers and hospitals in rural parts of Burundi such as the Moso region. Furthermore, the organization runs health education, vaccination, nutrition, and outreach programs in order to survey emerging health needs of the communities which suffer from a long-lasting civil war that only recently came to an end (Médecins Sans Frontières 2008, 2009a).

MSF states in the international activity report for the year 2008: 'In April, two years after a peace deal was signed to end more than a decade of conflict in Burundi, rebels of the National Liberation Forces (FNL) launched an offensive against the capital, Bujumbura, prompting fears of a return to war. In June, the government and the rebels signed a ceasefire. However, the long years of war have weakened the country's health system. Therefore, MSF teams constantly monitor potential health emergencies, such as epidemics or nutritional crises' (Médecins Sans Frontières 2009a).

The situation in which MSF finds itself in the year 2008 is an example for the problem discussed in this work. The humanitarian organization runs various programs in the different regions of Burundi. These programs address the health needs of the communities which suffer from the armed conflict, from social violence, and health-care exclusion (Médecins Sans Frontières 2009a). As described earlier, although the immediate disaster response phase is over, humanitarian needs continue to exist. These needs include the treatment of malaria which occurs with a certain seasonality, as well as the prevention of possible epidemics such as the outbreak of meningitis.

Although the demand for the goods required to run the health programs can be predicted based on historical data, the overall situation in Burundi makes it likely that sudden changes in supply and/or demand can and will occur. A regional depot could be broken into, administrative obstacles due to corruption could prohibitively prolong lead times from a global warehouse to the central depot in Bujumbura, a disease could spread more quickly than expected, etc. These factors contribute to the uncertainty under which goods need to be distributed between and stored at the organization's domestic depots. Their occurrence would require additional relocation activities and would lead to an overlapping disaster situation as described above.

1.3 Research objective

While it is well known from the literature that Operations Research (OR) models and methods can be successfully applied to support different types of humanitarian operations (see Van Wassenhove and Pedraza Martinez (2010) and the literature review presented below), to the authors' knowledge, the situation in which sudden-event response has to be combined with preparedness for possible future incidents during an ongoing relief operation has not yet been analyzed in the OR literature.

The objective of the research presented here is therefore to study an inventory relocation problem which can occur in such overlapping disaster settings. This is motivated by cases like the situation in Haiti in 2010 or the example case of Burundi introduced above. These are complex planning situations in which humanitarian organizations have to relocate and distribute relief items quickly while their long-term operations have to continue.

Hence, the research questions to be answered are if a relocation model and a corresponding solution method can be applied in overlapping disaster situations,

(a) such that the amount of unsatisfied demand can be reduced and
(b) if this can be achieved while at the same time keeping costs under control.

Therefore, the aim of this study was to develop an appropriate quantitative model and a solution approach for planning and optimizing the supply of a specific relief item to a given number of regions, after the occurrence of a disruption or a sudden increase of demand at (at least) one of the regional depots during an ongoing humanitarian operation. In this model, also the possibility of further occurrences of sudden demand changes at the other depots which may result, for example, from the spread of an epidemic to other areas, is to be taken into account. As the model will be specifically aimed at supporting decisions regarding the relocation of relief items, it can be used to help humanitarian organizations in their operative planning. In this study, the approach will be examined by its application to an example case, using different scenarios to evaluate the results of the approach with respect to unsatisfied demand and total cost.

The remainder of this paper is organized as follows: First, the relevant literature from the humanitarian context as well as from the area of commercial supply chains is presented in a literature review in Sect. 2. Thereupon, a new linear multi-period MIP model which addresses the situation described above through the use of penalty costs for unsatisfied demand is presented in Sect. 3. Section 4 is dedicated to the rolling horizon solution approach which is developed for solving the model. Section 5 reports the findings of a number of simulation runs that were executed with different scenarios and data sets. Finally, in Sect. 6 some conclusions and an outlook are presented.

2 Literature review

2.1 Literature on humanitarian planning problems

Due to the importance of logistics in humanitarian operations (Kovács and Spens 2007; Van Wassenhove 2006), an increasing number of papers on humanitarian logistics have been published during the past decade, and some applications of OR methods to this area have been suggested. Studies in this field mostly focus on strategic and operative planning problems, for example, facility location planning, vehicle routing, delivery planning, and inventory planning. In order to solve the respective problems, for example maximum covering models, network flow or shortest path models are adapted for the situation at hand, and a wide range of (exact and heuristic) optimization methods have been developed.

To the authors' knowledge, none of the contributions in the field of humanitarian logistics using OR methods consider overlapping disasters. Most of them are dedicated to sudden-onset disasters (Adivar et al. 2010), and hence the respective approaches are not directly applicable to the situation which is to be examined here. Despite this fact, some of the work that has been done in the area is related to the approach presented below, and hence an overview on the most relevant contributions, especially from the field of inventory and distribution planning, is given here.

Inventory decisions, sometimes in combination with location decisions, are considered by different authors: Chang et al. (2007) formulate two stochastic models for locating warehouses for emergency response in the aftermath of a flood and for the allocation of inventories to warehouses. Also Balçik and Beamon (2008) develop a facility location and inventory planning model for sudden-onset disasters. Fiedrich et al. (2000) create an optimization model for resource allocation, and Beamon and Kotleba (2006) describe a long-term inventory model for disaster response. The latter calculate optimal reorder points and consider uncertainties in demand and therefore the possibility of shortages and emergency orders. Emergency orders are more expensive than regular orders but on the other hand, backorder costs are considered for shortages. Also Lodree and Taskin (2008) formulate a model which addresses inventory planning and considers shortage costs; they work within an insurance risk policy framework to find the optimal inventory for efficient disaster relief in the aftermath of a hurricane.

There is extensive literature on delivery planning in humanitarian operations, some of which relates to this work. Haghani and Oh (1996) formulate a deterministic large-scale MIP which is used to determine the cost-minimizing flows of multiple commodities from multiple supply sites to the beneficiaries. In order to ensure that demand does not remain unsatisfied for too long, they suggest the use of penalty costs (so-called carry-over costs) for late deliveries. Barbarosoğlu and Arda (2004) present a model for transportation planning in disaster response settings, considering uncertainties in route capacities, demand, and supply. Also these authors use penalty costs (shortage costs) to avoid unsatisfied demand. Other authors using a penalty cost approach in the field of delivery planning in humanitarian operations are Lin et al. (2009) who apply penalty costs in a multi-objective vehicle-routing model for disaster relief. In all cases, penalty costs are integrated in the objective function to minimize unsatisfied demand, and this approach is also taken in this work.

Özdamar et al. (2004) design a multi-period multi-commodity network flow model. They assume that current demand is known, but future changes in demand or supply can require a rebuilding of the transportation plan. Yi and Özdamar (2007) present an integer multi-commodity network flow model which is used to determine the distribution of the relief items including personnel. They distinguish temporary and permanent emergency units which both have to be served. Yi and Kumar (2007) develop a heuristic that first determines a vehicle routing plan and then assigns several relief commodities to the vehicles. The goal of the heuristic is to minimize delays of the required services. Sheu (2007) develops a model for relief logistics planning in the immediate response phase, and Tzeng et al. (2007) build a multi-objective model which is aimed at the optimal distribution of relief items. In their approach, the first objective is the minimization of costs, the second is the minimization of travel time, and as a third objective the maximization of satisfied demand is considered.

A special problem within pre-disaster planning for humanitarian logistics which is related to this work is the prepositioning of relief items, i.e., the decision where to place supplies in preparation for a disaster, and how much of them to allocate to the respective locations. The problem has been studied recently by Rawls and Turnquist (2010) who make use of a penalty cost approach, by Campbell and Jones (2011), and by Salmerón and Apte (2010) who also consider penalty costs for commodity shortages in their model. In contrast to the problem considered here, no ongoing humanitarian operations are considered, but the respective prepositioning problems relate exclusively to disaster preparation.

Hence, most of the applications discussed above address the preparation phase or the response phase of the disaster relief lifecycle, while the recovery phase is studied less often. However, some contributions discuss this phase as well, for instance, the work by Nolz et al. (2007) who formulate a model for water supply in the aftermath of a disaster, and the aforementioned work by Beamon and Kotleba (2006) who address complex emergencies in a longer timeframe. Moreover, the latter also consider stock-outs, i.e., disruptions in supply, within an ongoing operation. Other contributions in which a long-term perspective is taken are those by De Treville et al. (2006) on a tuberculosis control program, by Pedraza Martinez and Van Wassenhove (2009) on vehicle replacement, and by Pedraza Martinez et al. (2010) on fleet management in humanitarian operations. While they focus on long-term relief operations, none of these contributions considers the case of overlapping disasters which is studied in this work.

Partly due to decreasing media attention, donations decline in the later phase of the disaster relief lifecycle which is studied here, and therefore cost-aspects gain in importance (Stapleton et al. 2009; Tomasini and Van Wassenhove 2009; Médecins Sans Frontières 2009b). Therefore, standard inventory models, i.e., models addressing commercial supply chains, as, for instance, presented by Minner (2000) and by Graves and Willems (2000), are related to this kind of humanitarian problems; however, there are important differences with respect to the demand distribution structure and the degree of uncertainty involved, which impede their direct transfer. This is discussed in more detail below.

2.2 Literature on commercial supply chain management

Beyond the work which has been published in the area of humanitarian logistics, publications from other areas such as retail management or production and supply chain management also cover problems that are of a similar structure as the problem considered in this work. The main objective in these approaches is mostly profit maximization and hence minimization of costs. Herer et al. (2006), for instance, study a multi-location transshipment problem for retailers and develop cost-optimal coordinated replenishment and transshipment strategies for the different locations. Archibald (2007) and Archibald et al. (2010) also consider a network of retail outlets which receive periodic replenishments and have to serve randomly occurring demand. If one of the outlets cannot serve its demand due to a shortage in stock, goods can be transshipped to this outlet from another one (for a similar approach, see Minner et al. 2003). Alternatively, they can be delivered from a central depot. While these "emergency deliveries" have the disadvantage of being much more expensive than the transshipments, every outlet is in danger of running out of stock if too much of its inventory is relocated to another location; hence, a compromise between customer service and cost needs to be found. Due to the different background, however, the assumptions regarding the occurrence of demand differ largely from those made in this work.

Hua et al. (2009) consider a spare-part inventory system with non-stationary stochastic demand. Using a rolling horizon approach and the expected value concept, they derive policies for cost-optimal spare-part management. A production supply chain optimization problem under uncertainty is studied by Escudero et al. (1999) who apply a scenario analysis based approach. Sodhi and Tang (2011) study the sales-and-operations planning process in a supply chain under uncertain demand, but select a different approach: They consider different risks—the risk of unmet demand and the risk of excessive inventory among them—in a trade-off model which is based on the conditional value-at-risk concept. Also in these cases, the assumptions regarding the demand are different from the situation in a humanitarian context as considered here.

Risk management and especially demand uncertainty in commercial supply chains have been studied extensively in the respective literature (Rao and Goldsby 2009; Manuj and Mentzer 2008), but usually probability distributions for demand are assumed to be given, and high-variance demand is only rarely considered (Beamon and Balçik 2008). An exception is Nagar and Jain (2008) who use a scenario-based stochastic programming approach for supply chain planning when no probability distribution function for the demand is given. However, their approach which is based on expected values would not lead to sensible results if extreme demands occurred; as stated by Rawls and Turnquist (2010, p. 534), in this case "computing expected costs may tend to hide underlying issues rather than illuminate them". For this reason, a different solution approach is chosen here.

In contrast to demand uncertainty, disruptions in supply are less often considered in the literature on commercial supply chains. Tomlin and Snyder (2007) and Schmitt (2008) are two contributions which are dedicated to this issue. In the former work, the fact that the risk of disruptions changes over time is recognized and a "threat-dependent model" for inventory holding is formulated. Here, the risk is mainly mitigated by safety stocks. Also by Schmitt (2008), strategies for mitigating supply risk, especially by diversification and decentralization, are discussed. Similar strategies are applied in the humanitarian context, when prepositioning of supplies at different locations takes place (see, e.g., Rawls and Turnquist 2010; Campbell and Jones 2011). Other strategies which are useful in commercial supply chains as, for example, the postponement strategy, are more difficult to transfer to humanitarian operations, but still they offer new perspectives also in this field (Van Wassenhove and Pedraza Martinez 2010).

To summarize, there are some major differences between optimization of commercial supply chains and supply chain optimization in a humanitarian context: First, serving people in the affected area, and not profit maximization, is the central objective in humanitarian action. Second, uncertainty regarding demand in the humanitarian context differs largely from uncertainty in commercial supply chains; while the former "is generated from random events that are unpredictable in terms of timing, location, type, and size" (Beamon and Balçik 2008, p. 11), demand in commercial settings is "comparatively stable". Hence, with respect to sales, uncertain demand can usually be described by a (continuous) probability distribution, as it is the case in most of the publications mentioned earlier; however, this is hardly possible in the humanitarian context, especially in the setting of overlapping disasters.

Moreover, there are further aspects which differ significantly from supply chain planning in business logistics: While commercial supply chains mainly address the customer, as he is the source of revenue, humanitarian action is dependent on funding from the donors and hence has to address them by making its activities "visible" (Oloruntoba and Gray 2006); usually many stakeholders are involved in humanitarian activities, there is a higher pressure of time and often a lack of local infrastructure (Van Wassenhove 2006).

Thus, approaches from commercial supply chains are not directly applicable, but nevertheless some concepts can be transferred to the humanitarian context (Van Wassenhove and Pedraza Martinez 2010). However, the situation of overlapping disruptions is hardly discussed in the literature on commercial or humanitarian supply chains, even if different sources of risk are considered. Therefore, a novel transshipment model with penalty costs building up on ideas from Herer et al. (2006) and Haghani and Oh (1996) is developed in the following. This model addresses inventory relocation in an overlapping disaster situation where a sudden supply lack occurs during an ongoing humanitarian operation.

3 Inventory relocation model

3.1 General description

In the following, a model for inventory relocation in an overlapping disaster setting is developed. The focus of the model is on one specific product; for example, a specific medicine needed for the treatment of an epidemic, or a vaccine. A humanitarian organization is assumed to be already engaged in a humanitarian operation in the respective area and to have established a number of regional depots in order to supply the affected regions. (Of course, there also might be different organizations cooperating, as is often the case in reality. However, the structure of the planning problem as such would not change under these circumstances. Therefore, in order to simplify the presentation it is assumed here that all depots belong to the same organization which carries out the humanitarian operation exclusively.)

Moreover, there is a central depot which is located in or near to a major city in the affected area and from which the regional depots are supplied. If a shortage occurs at any of the regional depots, it can be served either from another regional or from the central depot. Finally, a global depot exists from which larger amounts can be ordered by the central depot.

If a sudden increase of demand or a disruption occurs at one of the regional depots, as it is considered here, quick supply of goods to the respective region is required. Therefore, it has to be decided from which depots the affected region should be supplied, what amounts should be transshipped, and how much of the good should be reordered from the central or even from the global depot. All these decisions should be made such that costs for transportation and inventory holding are kept as low as possible and such that at the same time the amount of unsatisfied demand is minimized. Moreover, the possibility of future disrupting incidents should be taken into account in the planning process.

3.2 Assumptions

In the optimization model formulation developed below for this situation, the following assumptions are made:

- The current inventories of all the regional depots as well as the inventory of the central depot are limited and known.
- Inventory of the global depot is assumed to be infinite as in principle, restocking from other sources—i.e., buying the good from the producers—is possible. However, this part of the system which is connected to the "outer market" is not considered here.
- The demand for the considered relief item during the ongoing humanitarian operation is assumed to be known from experience and/or forecasts (certain demand d^1) (Tomasini and Van Wassenhove 2009).
- Due to the fact that future disruptions are possible, uncertain future demand (d^2) is taken into account. The amount of the demand is assumed to depend on the number of people living in the respective region (the more people live there, the more can be affected). The amount and the probability of its occurrence can be estimated by the humanitarian organization based on their experience (Tomasini and Van Wassenhove 2009).
- Demand can remain unsatisfied for one or more days if there is no sufficient supply. In such a case, unsatisfied demand is back-logged, i.e., it can be served later (no "lost sales").
- A planning horizon of 14 days' length is considered, as this is the timeframe within which a demand peak or a disruption usually can be handled; after that, the humanitarian operation proceeds as before.
- Delivery from the central depot to the regional ones is assumed to take 2 days by truck, while transportation between the different regional depots is assumed to take only one day.
- Delivery from the global depot to the central depot is done by plane and takes one day.
- Variable transportation costs increase linearly with the amount of the good transported, while fixed transportation costs depend on the number of transportation units (trucks, planes) used.

In the literature, it is a widely accepted assumption that relief for urgent demand should be provided within the first 72 h after a disaster, as the affected regions usually cannot cope longer than that (Salmerón and Apte 2010; Kovács and Spens 2007). Hence, in most cases a timeframe of 14 days can be expected to be sufficient to stabilize operations after an incident. However, in special cases as, for example, the Haiti earthquake, the related humanitarian operations took about a month to stabilize. In such a situation, the model suggested below can be run repeatedly to deal with the occurrence of further disruptions (in the case of Haiti earthquake, hurricane etc.). The assumptions regarding transportation times may of course be changed, without affecting the validity of the model.

In the optimization model, the minimization of non-satisfied demand after a disruption or a change of demand is achieved by the means of a penalty cost approach (for a similar approach, see, e.g., Haghani and Oh 1996): In each period, unsatisfied demand is determined and weighted with a penalty cost parameter. Penalty costs for unsatisfied certain demand are higher than those for unsatisfied uncertain demand, as the uncertain demand might not occur at all. Furthermore, these penalty cost parameters are defined such that higher risks are associated with higher costs to avoid shortages. Finally, penalty costs are higher for demand which has not been satisfied for a longer time, i.e., for more than one period, than they are for demand which only occurred in the current period. This models the fact that people in a region which is affected, for instance, by an epidemic, might cope without medicine or vaccination for a day or two; but if the shortage lasts longer, the situation will become dangerous as the illness starts spreading quickly and cannot be controlled anymore, leading to a large number of deaths.

While the other data are exogenously given, penalty cost parameters have to be defined subjectively. Hence, it has to be assumed for the approach to be applicable that appropriate values of these parameters can be determined. This can be done either from experience, i.e., by building up on former, similar applications of the model, or the users of the model have to carry out a sensitivity analysis in order to determine sensible parameter values.

In order to avoid unsatisfied demand whenever possible, usually penalty cost parameters are set to rather high values compared with the other cost parameters as, for example, transportation costs (e.g., Rawls and Turnquist 2010; Barbarosoğlu and Arda 2004). The exact choice is not much of an issue, as long as the parameter values are sufficiently large. However, in the approach suggested here, different penalty parameters are needed for certain and uncertain demand, as stated above. While also in this case the penalty costs for unsatisfied certain demand can be set to rather high values, for unsatisfied uncertain demand a thorough analysis of the parameter selection is required because their choice is most crucial for the successful application of the penalty cost approach. Therefore, in this work, the penalty cost parameters for uncertain demand are determined by a sensitivity analysis which is presented in Sect. 5.2.1.

3.3 Model formulation

The model which is developed here is based on a distribution network modeling approach and is a refinement of the model suggested by Blecken et al. (2010). The network structure for a subsystem with two regional depots i and j and one central depot CD is shown in Fig. 1. (In order to reduce complexity, the global depot is not shown in the network. Moreover, instead of days, the notion of "periods" is used to

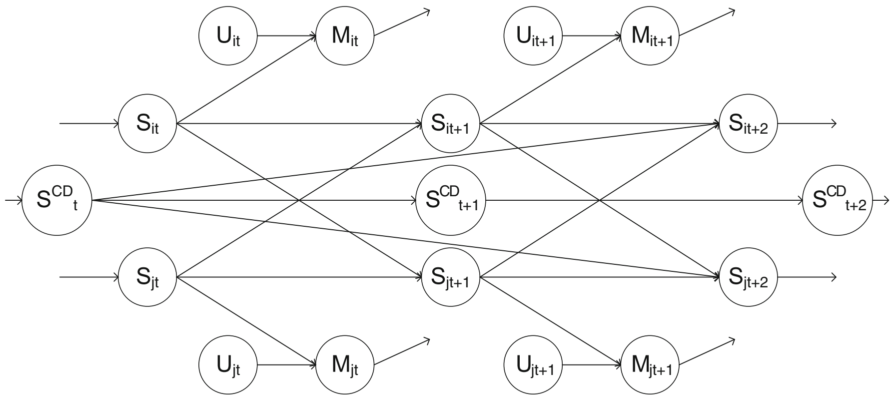

Fig. 1 Structure of the network for two periods

allow for a general formulation.) Nodes S_{it} represent the amount of the relief item which is in stock at depot i at the beginning of period t. Nodes U_{it} model the unsatisfied demand at depot i in period t, and nodes M_{it} stand for the total demand at i in period t. In the analytical model formulation below, flow variables F are used. A flow between two nodes can either be an amount which is transported (e.g., $F_{S_{it}S_{jt+1}}$ is the amount transported from depot i to j in period t) or an amount that stays in inventory ($F_{S_{it}S_{it+1}}$). Furthermore, there are flow variables describing satisfied ($F_{S_{it}M_{it}}$) and unsatisfied ($F_{U_{it}M_{it}}$) demands. All additional relevant notation (variables and parameters) is presented in Table 1.

The objective function (1) contains minimization of the sum of all costs: Fixed and variable transportation costs between all depots involved, replenishment costs for transportation from the global depot, inventory holding costs at regional and global depots, and penalty costs for unsatisfied demand at all depots are taken into account. (To simplify the presentation of the model, it is assumed that all variables with indices $t > T$ exist. While the transportation variables are set to zero, the inventory holding variables can also take positive values.)

$$
\begin{aligned}
\min & \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{t=1}^{T}(c_{ij} \cdot F_{S_{it}S_{jt+1}} + cFix_{ij} \cdot Y_{F_{ijt}}) \\
& + \sum_{i=1}^{N}\sum_{t=1}^{T}(h \cdot F_{S_{it}S_{it+1}} + c_{0i} \cdot F_{S^{CD}_{t}S_{it+2}} + cFix_{0i} \cdot Y_{F^{CD}_{it}}) \\
& + \sum_{t=1}^{T}(rFix \cdot Y_{F_{R_t S^{CD}_{t+1}}} + r \cdot F_{R_t S^{CD}_{t+1}} + h \cdot F_{S^{CD}_{t} S^{CD}_{t+1}}) \\
& + \sum_{i=1}^{N}\sum_{t=1}^{T}\left(p^1_i \cdot (F^{certPos}_{U_{it}M_{it}} - O^{1Pos}_{it}) + pMulti^1_i \cdot O^{1Pos}_{it}\right) \\
& + \sum_{i=1}^{N}\sum_{t=1}^{T}\left(p^2_i \cdot (F_{U_{it}M_{it}} - F^{certPos}_{U_{it}M_{it}} - O^{2Pos}_{it}) + pMulti^2_i \cdot O^{2Pos}_{it}\right) \qquad (1)
\end{aligned}
$$

Table 1 Variables, parameters and indices

	Definition
Indices	
i, j	Index for regional depots, $i, j \in DE$, and $DE := \{1, \ldots, N\}$
t, k	Index for periods, $t, k \in PE$, and $PE := \{1, \ldots, T\}$
Variables	
$F_{R_t S^{CD}_{t+1}}$	Flow from the global to the central depot (airfreight) between period t and $t+1$
$F_{S_{it} S_{it+1}}$	Goods stored at depot i between period t and $t+1$
$F_{S^{CD}_t S^{CD}_{t+1}}$	Goods stored at the central depot between period t and $t+1$
$F_{S_{it} M_{it}}$	Goods used for satisfying demand at depot i in period t
$F_{S_{it} S_{jt+1}}$	Flow from depot i to depot j between period t and $t+1$
$F_{S^{CD}_t S_{it+2}}$	Flow from the central depot to depot i between period t and $t+2$
$F_{U_{it} M_{it}}$	Unsatisfied demand in period t at depot i
$F^{cert}_{U_{it} M_{it}}$	Unsatisfied part of the certain demand
$F^{certPos}_{U_{it} M_{it}}$	$max(0, F^{cert}_{U_{it} M_{it}})$
O^1_{it}	Unsatisfied certain demand at depot i which occurred before period t
O^2_{it}	Unsatisfied uncertain demand at depot i which occurred before period t
O^{1Pos}_{it}	$max(0, O^1_{it})$
O^{2Pos}_{it}	$max(0, O^2_{it})$
$Y_{F_{ijt}}$	Number of trucks required for transportation between depot i and j in period t
$Y_{F^{CD}_{it}}$	Number of trucks required for transportation between the central depot and depot i in period t
$Y_{F_{R_t S^{CD}_{t+1}}}$	Number of airplanes required for transportation between the global and central depot in period t
Parameters	
c_{ij}	Variable transportation costs between depot i and j
c_{0i}	Variable transportation costs between the central depot and depot i
$cFix_{ij}$	Fixed transportation costs between depot i and j
$cFix_{0i}$	Fixed transportation costs between the central depot and depot i
d^1_{it}	Certain, forecasted demand at depot i in period t
d^2_{it}	Uncertain demand at depot i in period t
h	Inventory holding costs per unit and period
$maxAir$	Maximum capacity of an airplane
$maxRoad$	Maximum capacity of a truck
p^1_i	Penalty costs for unsatisfied certain demand which occurred in the current period at depot i
p^2_i	Penalty costs for unsatisfied uncertain demand which occurred in the current period at depot i
$pMulti^1_i$	Penalty costs for unsatisfied certain demand which occurred in a previous period at depot i
$pMulti^2_i$	Penalty costs for unsatisfied uncertain demand which occurred in a previous period at depot i
r	Variable transportation costs when using airfreight
$rFix$	Fixed transportation costs when using airfreight
s_{i1}	Initial inventory at depot i
s_{01}	Initial inventory at the central depot

In the following, the constraints of the model are explained. Due to the fact that the formulation is based on a network flow model, most of the constraints are continuity constraints of different kinds:

Constraint set 2 models the continuity of inventory at regional depot i: The amount that is in stock in period t either was there already in the previous period (period $t-1$), or it has been delivered from the central depot (in $t-2$) or from another regional depot (in $t-1$). (Note that the variable $F_{S_0^{CD} S_{i2}}$ is assumed to be zero, because period $t=0$ is not part of the planning horizon.) Moreover, it can either be consumed in that period, it can be transported to another depot (where it arrives in period $t+1$) or it can stay in stock. Note that for the first period, the left-hand side of constraints 2 must be replaced by the initial stock, s_{i1}, which leads to constraint 3.

$$F_{S_{it-1} S_{it}} + F_{S_{t-2}^{CD} S_{it}} + \sum_{j=1, j \neq i}^{N} F_{S_{jt-1} S_{it}}$$

$$= F_{S_{it} M_{it}} + \sum_{j=1, j \neq i}^{N} F_{S_{it} S_{jt+1}} + F_{S_{it} S_{it+1}} \quad \forall i \in DE, \; t = 2, \ldots, T \tag{2}$$

$$s_{i1} = F_{S_{i1} M_{i1}} + \sum_{j=1, j \neq i}^{N} F_{S_{i1} S_{j2}} + F_{S_{i1} S_{i2}} \quad \forall i \in DE \tag{3}$$

Constraint set 4 models continuity of inventory at the central depot. This depot can be supplied from the global depot by air which takes one time period; delivery to regional depots from the central depot takes two periods. For the first period, initial stock replaces the left-hand side (constraint 5).

$$F_{S_{t-1}^{CD} S_t^{CD}} + F_{R_{t-1} S_t^{CD}} = \sum_{i=1}^{N} F_{S_t^{CD} S_{it+2}} + F_{S_t^{CD} S_{t+1}^{CD}} \quad t = 2, \ldots, T \tag{4}$$

$$s_{01} = \sum_{i=1}^{N} F_{S_1^{CD} S_{i3}} + F_{S_1^{CD} S_2^{CD}} \tag{5}$$

Constraints 6 and 7 model the continuity of demand at depot i in period t: Total period demand consists of satisfied and unsatisfied demand, as expressed on the right hand-side. At the same time, total demand in period t can be split into a certain (d^1) and an uncertain part (d^2). Furthermore, for $t > 1$ the unsatisfied demand from the previous period is added, as unsatisfied demand persists in later periods.

$$d_{it}^1 + d_{it}^2 + F_{U_{it-1} M_{it-1}} = F_{S_{it} M_{it}} + F_{U_{it} M_{it}} \qquad \forall i \in N, t = 2, \ldots, T \tag{6}$$

$$d_{i1}^1 + d_{i1}^2 = F_{S_{i1} M_{i1}} + F_{U_{i1} M_{i1}} \qquad \forall i \in N \tag{7}$$

Constraint 8 is an "over all" continuity constraint. It ensures that the total amount required and the amounts which are still in stock at the end of the planning horizon (left-hand side of the equation) are either from the initial stock or become available through replenishment orders from the global depot during the planning horizon. Finally, there is the possibility that demand remains unsatisfied.

$$\sum_{t=1}^{T}\sum_{i=1}^{N}(d_{it}^{1}+d_{it}^{2})+\sum_{i=1}^{N}F_{S_{iT}S_{iT+1}}+F_{S_T^{CD}S_{T+1}^{CD}}$$
$$=\sum_{i=1}^{N}(F_{U_{iT}M_{iT}}+s_{i1})+s_{01}+\sum_{t=1}^{T}F_{R_tS_{t+1}^{CD}} \tag{8}$$

Constraint sets 9 to 11 make sure that the number of transportation units (trucks and planes) used in each period and on each connection is sufficient for transporting the required amounts of the good.

$$F_{S_{it}S_{jt+1}} \le maxRoad \cdot Y_{F_{ijt}} \qquad \forall i, j \in DE, \forall t \in PE \tag{9}$$
$$F_{S_t^{CD}S_{it+2}} \le maxRoad \cdot Y_{F_{it}^{CD}} \qquad \forall i \in DE, \forall t \in PE \tag{10}$$
$$F_{R_tS_{t+1}^{CD}} \le maxAir \cdot Y_{F_{R_tS_{t+1}^{CD}}} \qquad \forall t \in PE \tag{11}$$

In constraint set 12, the unsatisfied part of the certain demand is determined: It consists of the certain demand of period t and the unsatisfied certain demand from the previous period (if this is positive), from which the satisfied demand is subtracted. In the first period no backlogged demand exists; hence this variable is missing in constraints 13.

$$F_{U_{it}M_{it}}^{cert} = d_{it}^{1} + F_{U_{it-1}M_{it-1}}^{certPos} - F_{S_{it}M_{it}} \qquad \forall i \in DE,\ t = 2, \ldots, T \tag{12}$$
$$F_{U_{i1}M_{i1}}^{cert} = d_{i1}^{1} - F_{S_{i1}M_{i1}} \qquad \forall i \in DE \tag{13}$$

The last two sets of constraints, 14 and 15, enable the calculation of the part of demand which has been unsatisfied for more than one period and hence incurs higher penalty costs. This part of demand needs to be calculated explicitly, as it is incorporated in the objective function. Constraint 14 achieves this calculation for the certain demand by subtracting the certain demand of the current period from the unsatisfied certain demand; constraint 15 does the same for the uncertain demand. The values derived in these constraints are used in the objective function if they are positive; if not, they are set to zero.

$$O_{it}^{1} = F_{U_{it}M_{it}}^{certPos} - d_{it}^{1} \qquad \forall i \in DE, \forall t \in PE \tag{14}$$
$$O_{it}^{2} = F_{U_{it}M_{it}} - F_{U_{it}M_{it}}^{certPos} - d_{it}^{2} \qquad \forall i \in DE, \forall t \in PE \tag{15}$$

Constraints 16 to 18 define the non-negativity and integrality constraints for the different variables.

$$F_{S_{it}S_{it+1}}, F_{S_{it}S_{jt+1}}, F_{U_{it}M_{it}}, F_{S_t^{CD}S_{t+1}^{CD}}, F_{S_t^{CD}S_{it+2}}, F_{S_{it}M_{it}},$$
$$F_{R_tS_{t+1}^{CD}}, F_{U_{it}M_{it}}^{certPos}, O_{it}^{2Pos}, O_{it}^{1Pos} \ge 0 \quad \forall i, j \in DE, \forall t \in PE \tag{16}$$

$$Y_{F_{ijt}}, Y_{F_{it}^{CD}}, Y_{F_{R_t S_{t+1}^{CD}}} \in \mathbb{N} \quad \forall i, j \in DE, \forall t \in PE \tag{17}$$

$$F_{U_{it} M_{it}}^{cert}, O_{it}^1, O_{it}^2 \in \mathbb{R} \quad \forall i \in DE, \forall t \in PE \tag{18}$$

4 Rolling horizon solution approach

As already described in the introduction, the situation under consideration involves uncertainty (in terms of uncertain demand) and multiple objectives in a multi-period setting. The model described in the previous section treats uncertain demand d_{it}^2 in the same way as certain demand, except for the possibility to define different penalty costs for the different demand types: By setting the penalty costs for uncertain demand to a significantly lower level than those for the certain demand, it can be assured that certain demand is fulfilled first and that uncertain demand—which may, but does not have to occur in the future—is fulfilled only with lower priority.

Moreover, the assignment of values to the parameters d_{it}^2 is an important issue: If d_{it}^2 takes the value of the estimated possible future demand increase for each period t, although in fact usually it will be zero most of the time, future demand will be overestimated. Hence, this approach is only valid in specific situations as, for instance, in the example situation of a vaccination program described below (see Sect. 5). Another possibility is to assume a positive amount d_{it}^2 for some subsequent, but not all periods (days) in the near future. This leads to lower estimates and especially makes sense, for example, when studying the possibility of an occurrence of a heat wave or other weather-dependent uncertainties; but as neither the first period nor the duration of the incident is known, also this approach can be problematic.

If the model was solved as it is, the solution would give the amounts of the goods to be transported between the different depots and the amounts that should be stored in the depots for all planning periods within the planning horizon. But as some of the demand is uncertain and may never have to be satisfied, the model does not lead to an optimal—and may not even lead to a good—solution if the problem is solved in its closed form at the beginning of the planning horizon "once and for all".

In order to better handle the uncertainty involved, a stepwise "rolling horizon" solution approach is suggested here (see, e.g., Baker and Peterson 1979): In the first period, the model is solved for all future periods, which means that uncertain demand is treated similarly to certain demand. In all subsequent periods, the model is solved again for the remaining periods, taking new information regarding demand (for instance, a demand increase in one or more of the areas that occurred in the previous period), as well as transportation and order decisions made in the previous period(s) into account, updating the data accordingly (as suggested, e.g., by Özdamar et al. 2004). An update of the data also means to integrate uncertain demand into certain demand if it actually occurred in the respective period.

Hence, the model is solved $T - 1$ times, each time using a different initial state resulting from the previous period (see Fig. 2). Each optimization run leads to a transportation plan for the respective period which is actually carried out, and to a "forecast plan" for the following periods used to calculate the objective function value (costs plus penalty costs). The costs caused by actual transportation taking place in the respective

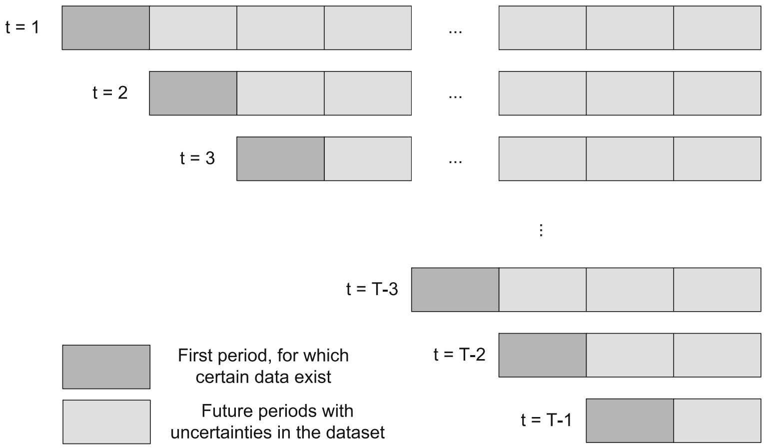

Fig. 2 Rolling horizon approach

period are stored and added up with the costs from former periods. Hence, at the end of the procedure, the total costs of all transportation and inventory holding activities are known and furthermore, detailed information about all unsatisfied demand at each depot and during each period is available.

5 Evaluation

5.1 Data of the example situation

The model developed in Sect. 3 is applicable to different long-term humanitarian operations and overlapping disasters. In the following, the example introduced in Sect. 1.2 is considered in more detail and is used to illustrate the solution concepts presented above. Note that the example situation is not a real situation, but it is based on realistic assumptions with respect to setting and choice of data.

Several humanitarian operations, as for example, health care or nutrition programs have been established in Burundi. In this work, a vaccination program in east Burundi, a rural area, is considered. The purpose of this program is to confine the spread of a meningitis epidemic. In order to achieve this aim, approximately 70% of the 300,000 people living in the considered area have to be vaccinated. Only inhabitants aged between 2 and 30 years are addressed by the program, since many people older than 30 years have been infected before and are immune, and for many children under the age of 2 years the available vaccine is ineffective (Médecins Sans Frontières 2010). The health care program is planned to last four weeks to ensure that all inhabitants in the relevant age group can be vaccinated; therefore, approximately 50,000 people have to be vaccinated each week. Health care centers with regional stocks have already been erected in Ruyigi, Kinyinya, Kabanga, Cankuzo, and Kangozi, splitting the area into five regions (see also Fig. 3).

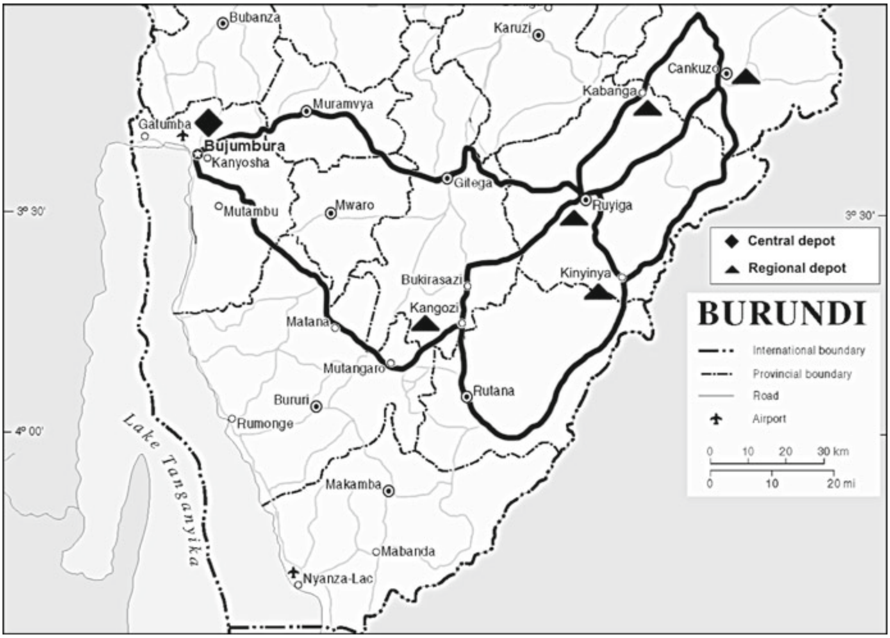

Fig. 3 Positions of the central and regional depots (United Nations Cartographic Section 2010, with own modifications)

A central depot has been erected in Bujumbura, the capital of Burundi. Transportation between the central depot and the regional depots takes 2 days. Transshipment between the regional depots is possible and takes one day despite the short distances because of bad road conditions and missing infrastructure. Under normal conditions, however, no transshipments are necessary to carry out the vaccination program as planned, and transportation between the central and a regional depot is only necessary to refill the inventories. It is assumed that at the end of the planning horizon a replenishment of all depots takes place to enable the continuation of the vaccination program.

Transportation costs consist of fixed and variable costs. The fixed part includes costs for labor and vehicles, while variable costs are incurred for each unit of vaccine. They include handling costs and costs which are related to the weight of the truckload. Moreover, the vaccine requires a cold chain which has to be taken into account when calculating the transportation costs. This requirement also has an impact on the inventory holding costs (which are set to 1.5 per unit). The fixed transportation costs are set to values of approx. 120 for transshipments between regional depots and of approx. 200 for transportation between the central and a regional depot (the values vary slightly, depending on the time required for transportation). The variable costs for transshipments are set to 1 per unit and the costs for transportation from the central to a regional depot to 2 per unit. Furthermore, the replenishment costs are set to 9000 (fixed costs) and 5 (variable costs) per unit. The penalty costs for unsatisfied certain demand are set to 100 per unit (and to 150 for unsatisfied demand which occurred in

Table 2 Initial situation

Depot	Risk of demand increase	Inventory (in units of vaccine)
RD 1	Higher risk	0
RD 2	Higher risk	21,500
RD 3	Lower risk	19,000
RD 4	Lower risk	20,000
RD 5	Higher risk	21,000
CD	No risk	30,000

a previous period), so that it will be avoided whenever possible. In comparison, the penalty costs for unsatisfied uncertain demand are much lower, because this demand might not occur; however, it is known that there is a certain risk of its occurrence which is estimated by humanitarian experts. The values of the penalty costs in the transshipment model are defined such that they reflect the relation of risks, i.e., the higher the risk, the higher the penalty costs. The determination of these penalty cost parameters is discussed in more detail in Sect. 5.2.

At the end of the first week of the humanitarian operation, a disruption occurs at the regional depot in Ruyigi (RD 1) caused by rebels who have broken into the depot and have destroyed all vaccines stored at the depot. This disruption leads to the necessity of replanning and hence to the application of the inventory relocation model at the beginning of the second week. Detailed information about the initial situation at the depots is shown in Table 2.

Further disruptions can occur within the timeframe of the program, as the threat of further rebel activities exists. Furthermore, the extent of the humanitarian operation can be subject to changes: If it becomes clear that the epidemic cannot be confined by the vaccination program described above, a wider population group has to be vaccinated. MSF states that in extreme cases the vaccination of people older than 30 and younger than 2 can be required to fight the spread of the epidemic (Médecins Sans Frontières 2010). The latter type of a sudden change in demand is considered in this work. Because of the heterogeneous population structure, the occurrence of such a situation is not equally likely in the different regions; hence, different probabilities of additional demand for vaccinations are considered (see Table 2). It is not known if and in which period additional demand will occur; however, if it occurs, replanning is necessary to proceed with the vaccination program.

The solution approach is tested below using scenarios in which additional demand occurs at different depots and at different points in time. First, a scenario in which no additional vaccinations are necessary is solved. Second, solutions for scenarios with additional demand for vaccinations at one regional depot are calculated, and third, scenarios in which the demand at two different depots increases during the planning horizon are considered (see Table 3).

5.2 Results

In this section, results from the application of the rolling horizon solution approach to the planning problem described above are presented with respect to total costs incurred and demand remaining unsatisfied. The solutions are derived with varying penalty cost

Table 3 Scenarios

#	Information on demand increase
1	No demand increase occurs
2a	One demand increase occurs at depot 2 in period 3
2b	One demand increase occurs at depot 4 in period 5
2c	One demand increase occurs at depot 5 in period 8
3a	Two demand increases occur at depot 2 in period 4 and at depot 4 in period 6
3b	Two demand increases occur at depot 3 in period 5 and at depot 5 in period 8

values for unsatisfied uncertain demand, in order to test the sensitivity of the solutions with respect to the choice of these (not exogenously given) parameters. Furthermore, the results of the rolling horizon approach are compared with the results found with the transshipment model presented in Sect. 3.3 when uncertain parts of demand are ignored; the latter thus serves as a reference model (benchmark).

The MIP models were solved using ILOG CPLEX 12.1 and the solution methods were implemented building a C# application in a. NET framework 3.5.

5.2.1 Impact of penalty costs

In order to analyze the effects of different parameter choices for the penalty costs, they were set to different values to carry out a sensitivity analysis for the rolling horizon approach. Total costs incurred (excluding penalty costs) and unsatisfied demand were calculated for the six scenarios at ten different levels of penalty costs; the results for one scenario are shown below in relation to the benchmark values achieved with the reference model which are normalized to one (see Fig. 4). The penalty cost values given in the figure are the lowest values of the respective data setting (i.e., the costs for unsatisfied uncertain demand with a low probability of occurrence). As stated earlier, penalty costs for unsatisfied demand which occurred in previous periods are higher, and they also depend on the risk of occurrences of future demand increases (see Table 2).

The scenario shown in Fig. 4 represents a situation where in the future additional vaccinations in two regions are required (see Table 3). In the figure, a trend is clearly apparent: Overall, costs of operations increase with growing penalty costs, and at the same time, unsatisfied demand decreases.

However, there are several exceptions, i.e., neither costs nor unsatisfied demand show a completely steady development. For example, for small values of the penalty cost parameter, total costs remain nearly constant until the penalty costs reach a certain value (here: 20) and only above this value they constantly increase. Unsatisfied demand is only slightly reduced in the lower parameter area in this scenario. However, if medium-sized parameter values are used, unsatisfied demand can be decreased significantly using the rolling horizon approach, while at the same time costs can be kept under control. For these parameter values, unsatisfied demand shows an obvious downwards trend. Once a certain threshold is reached for the penalty costs, unsatisfied demand takes its minimum possible value. (The minimum value is the amount of unsatisfied demand occurring in the first period, which cannot be avoided because

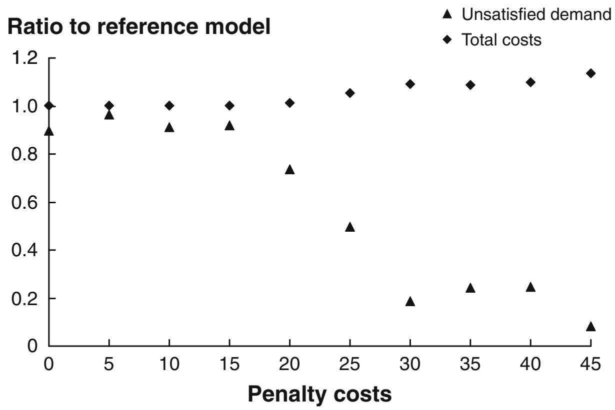

Fig. 4 Unsatisfied demand and total costs of scenario 3a for various penalty cost values

of the stock-out at the regional depot in Ruyigi). A further increase of penalty costs is therefore not studied, since it would only lead to a further increase in total costs without beneficial effects on the unsatisfied demand; hence, the maximum values of penalty costs are found when the minimum possible value of unsatisfied demand is reached. Overall, it can be observed that changes regarding the total costs are comparatively small (a maximum increase of less than 10%), while unsatisfied demand can be decreased significantly in relation to the reference model.

The results of the five other scenarios are similar to those presented in Fig. 4, although the trend is more obvious in cases where the demand situation is more complicated, since in these scenarios the rolling horizon approach can achieve larger effects. In all scenarios, with growing penalty costs for unsatisfied uncertain demand, transportation and inventory holding costs also increase, while at the same time the unsatisfied demand decreases.

It can be concluded that the penalty cost parameters may neither be chosen too small, as in that case the approach may not have any positive effect on unsatisfied demand and costs, nor should they be chosen too large, as in that case, no additional positive effect with respect to demand occurs, while total costs still increase. Hence, decision makers have to determine the relevant range of the cost parameters in order to be able to take advantage of the penalty cost approach.

Therefore, it may be necessary to solve the problem with different parameter values in order to determine a satisfactory solution and to find an acceptable compromise between serving the beneficiaries and minimizing the costs of the operations. Depending on the budget and the size of the organization, using lower penalty values (for cost minimization) or higher penalty values (for minimization of unsatisfied demand) within the relevant range can be the best strategy.

5.2.2 Evaluation of the rolling horizon solution approach

In this section, the solutions of the rolling horizon approach with different penalty cost values are compared with those of the reference model regarding total costs incurred and regarding unsatisfied demand. The six different scenarios introduced above are solved to compare the methods' performance with respect to the different objectives and in different situations.

Figure 5 shows that the rolling horizon approach with rather small penalty costs (value 10) leads to moderate (e.g., Scenario 2a) or even significant (e.g., Scenario 2b) decreases in unsatisfied demand compared to the benchmark situation (reference model) in which future uncertain demand is not considered at all. In contrast to that, the use of a higher (medium-sized) penalty cost parameter (value 30) results in a significant reduction of unsatisfied demand in all cases.

In terms of costs, the reference model almost always leads to the lowest values (see Fig. 6), as it does not take any future transportation activities for uncertain demand into account, while with respect to unsatisfied demand, the solutions of this approach are always poor (see Fig. 5). This is not surprising, as here no possibility of future disruptions or of sudden demand increases is considered, and it is well known that ignoring future uncertainties in demand usually leads to worse solutions with respect to fulfillment than if these uncertainties are taken into account. However, the comparison of the results illustrates that uncertainty can be incorporated successfully into a solution approach for redistributing inventory in a setting of overlapping disasters.

The rolling horizon approach with higher penalty costs incurs the highest cost values (see Fig. 6). This again illustrates the trade-off between unsatisfied demand—which is rather low for high penalty cost parameters—and total costs.

It should be noted that, even when the budget is constrained, the consideration of uncertainty can be beneficial: The results of the rolling horizon approach with low penalty costs show that unsatisfied demand can be reduced while the total costs do not increase considerably. The results of Scenario 3b even show a slight decrease in total costs (in comparison to the reference model), caused by bundling effects in transportation. In scenario 1, where no further demand increase occurs, total costs are higher than in the other scenarios because of the rather large amounts in stock and because inventory holding costs have to be incurred for each item in stock in every period.

The results show that the consideration of future uncertainty is beneficial for humanitarian operations in the situation of overlapping disasters, as it turns out that without increasing total costs significantly, unsatisfied demand can be reduced by the approach suggested in this work.

To analyze the effect of the penalty cost approach in more detail, the development of unsatisfied demand and total costs were observed over time (see Figs. 7 and 8 which represent the information for all periods and a selected scenario). As can be seen from Fig. 7, independent of the approach which is taken, unsatisfied demand occurs in period 1, as the shortage resulting from the disruption at depot 1 cannot be balanced instantaneously. Afterwards, there are no shortages until period 9, which is due to the fact that the increases in demand occurring in periods 5 and 8 in this scenario are only moderate and can be balanced for a while using existing inventories. However, these incidents lead to shortages in the later periods of the planning horizon, when not enough units of the vaccine are available at the respective regional depots anymore.

As higher penalty costs for unsatisfied uncertain demand enforce earlier relocation of relief items, or even additional replenishments, shortages occur later than with the reference model, and their amounts are significantly reduced. The penalty cost

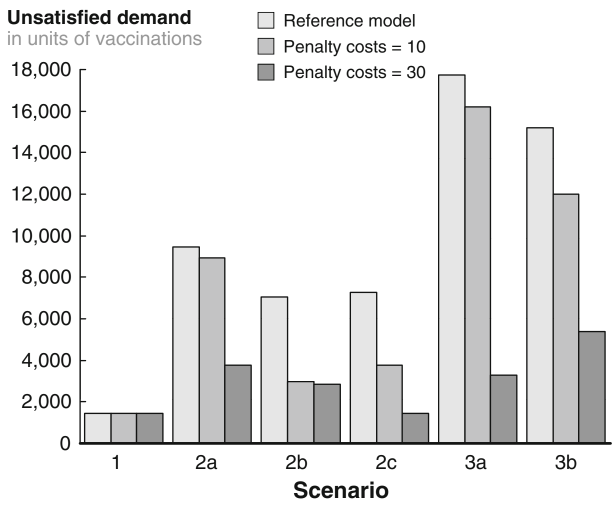

Fig. 5 Unsatisfied demand for all scenarios

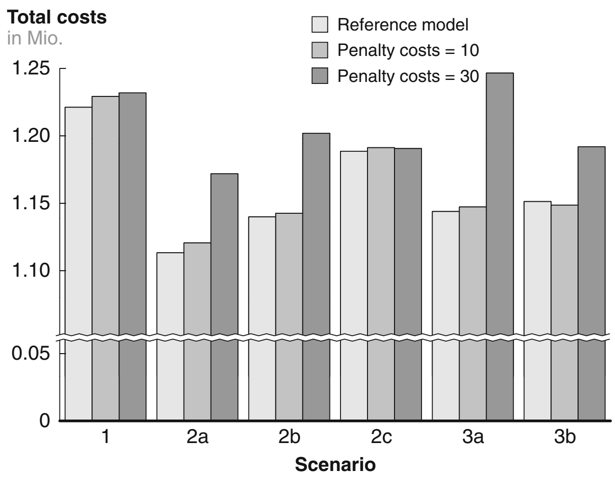

Fig. 6 Total costs for all scenarios

approach with a higher parameter value also avoids the sharp increase in unsatisfied demand which occurs in the last period with the other approaches. These shortages last only for one period, as after the end of the planning horizon new deliveries of vaccines to all regions take place. Hence, when there are only small penalties, the penalty costs for these shortages are traded-off in the model against the substantial re-ordering and transportation costs.

From Fig. 8, it is obvious that for all approaches, costs decrease over time due to the decreasing inventory levels at all depots. (Note that in Fig. 8, the inventory holding costs for the first period are included to improve the comparability of costs in the different periods, while they are not included in the numbers presented in Fig. 6 because

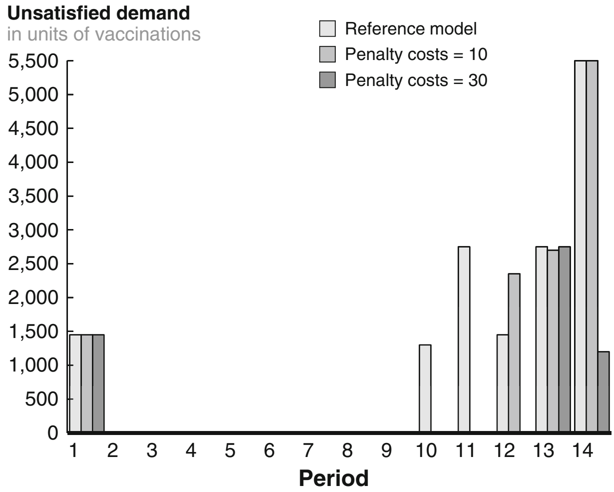

Fig. 7 Unsatisfied demand per period for scenario 3b

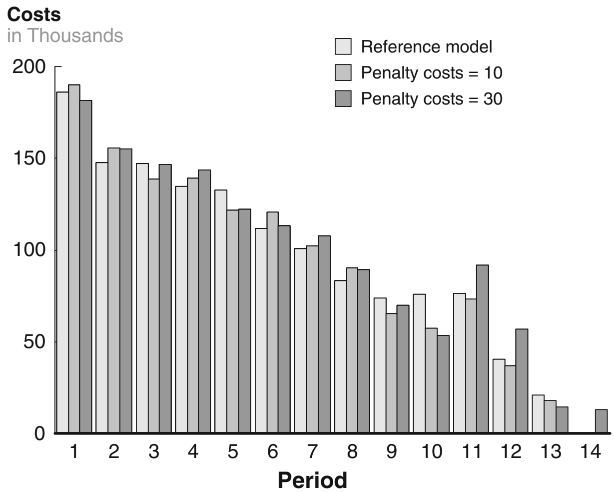

Fig. 8 Total costs per period for scenario 3b

they are identical for all solution approaches.) For the reference model, the additional increases in demand in later periods have a moderate effect on costs in periods 10 and 11, which is due to deliveries to the regional depots and a replenishment. In contrast, for the model with higher penalty costs (value 30), costs increase sharply in period 11; here, in period 10 the local safety stocks are still sufficient. The cost increase corresponds to the smaller amounts of unsatisfied demand which this model generates in the later periods; the improved service is achieved by a larger replenishment order (made in period 11), resulting in more transportation activity and higher safety stocks which, in turn, lead to higher costs. Moreover, application of this approach results in positive inventories at the end of the planning horizon, while inventories are reduced to zero by the reference approach. However, not all the amounts in stock are placed at the regions where they are required; therefore, some demand also remains unsatisfied in the last period under the penalty cost approach. When penalty costs are increased further, this issue is resolved, as can be seen in the sensitivity analysis: For larger penalty parameter values, the amount of unsatisfied demand finally reaches the minimum level, i.e., the unavoidable shortage occurring in the first period.

The analysis illustrates that the budget required per period differs only slightly, depending on the solution approach that is used. In particular, application of the model with higher penalty costs does not lead to considerably earlier occurrence of transportation and inventory holding costs, as might be expected. However, it should be kept in mind that the use of higher penalty costs usually leads to an increase in transshipment activity and to more orders, and therefore, a somewhat higher total budget is needed when this approach is to be used.

5.2.3 An alternative solution approach

As the treatment of uncertain demand as "certain demand with lower penalty cost" may lead to more transportation activities than actually necessary, a second approach for handling future uncertain demand was tested for the different scenarios. This alternative approach is a simple decision tree heuristic which is based on the fact that—on the one hand—each of the regional depots can serve as a supplier for other regions in case of a sudden increase of demand for the product under consideration, and that—on the other hand—each regional depot has to assure keeping sufficient supply for serving the region itself in case of a future incident. So each depot can decide how much of its inventory can be transshipped in case of an emergency at another depot, and how much of it needs to be reserved as safety stock. This decision is made for each regional depot based on the estimated probability of a future local increase of demand.

In the procedure, the decision alternative which minimizes expected unsatisfied demand is determined for each regional depot using a decision tree. The best alternatives define the amount of stock available for relocation at each depot after the current disruption and the amount of stock which is to be kept as safety stock for possible future incidents at the respective depot. Afterwards, the transshipment model presented in Sect. 3.3 is solved using the former amounts as initial inventory, but without considering the uncertain part of demand, as uncertainty is already taken into account by the safety stocks. These steps are repeated every time a disruption of the ongoing relief operation occurs at one of the regional depots, as each disruption leads to a new decision problem.

Unfortunately, this alternative solution method did not turn out to be very successful in most of the test runs. Although unsatisfied demand could be decreased compared with the reference model in situations with a large degree of uncertainty, costs increased considerably because of holding costs for unutilized inventory (safety stock) and due to the necessity of replenishing stock in order to satisfy demand. Moreover, in none of the cases that were studied the decision tree method was superior to the rolling horizon approach. Therefore, it was concluded that taking into account uncertainty by building regional safety stocks in this way is not a promising approach for most planning situations resulting from overlapping disasters and that the rolling horizon solution approach should be preferred.

6 Conclusions

The major aim of this work was to develop an OR model and an appropriate solution method that can be successfully applied for planning relocation activities in humanitarian operations for overlapping disaster situations. In particular, it was the purpose of this research to examine if the amount of unsatisfied demand resulting from inventory holding and relocation problems in such situations can be reduced, while keeping operational costs under control. To the authors' knowledge, this type of problem has not been studied in the literature before.

A mathematical model to support relocation decisions in an overlapping disaster situation was developed. This model, which is based on penalty costs for unsatisfied demand and incorporates future uncertainties, can be solved with the rolling horizon solution approach suggested in this work. To evaluate the performance of this method, several scenarios were solved and the results regarding unsatisfied demand and total costs were presented. It turned out that unsatisfied demand can be decreased significantly by taking uncertainty into account using the suggested penalty cost approach. Moreover, it could be shown that costs increase only moderately when the penalty cost values are chosen appropriately.

As the choice of the penalty cost parameters is an important issue, a sensitivity analysis was carried out in order to determine the effects of different parameter selections. It could be shown that the rolling horizon approach always has a positive effect on the unsatisfied demand, but the selection of appropriate penalty costs is crucial for achieving results which also lead to an acceptable cost level. Hence, it is recommended that calculations with different parameter values and various possible scenarios be carried out when using the model in real planning situations.

This is also the major limitation of the approach suggested here: The penalty parameters have to be determined specifically for the situation at hand. Hence, in real planning situations it may be required to carry out an extensive sensitivity analysis before the approach can be applied, and difficulties in determining the penalty costs may limit its applicability. Therefore, it will be an important avenue of future research to examine the adequate determination of these parameters also in empirical studies.

The model presented here is flexible and can be applied to different types of overlapping disasters and disruptions. Nevertheless, in some situations it can be a challenge to define the probabilities of future demand and to find good estimates for the amounts of the relief item that might be required in the different regions in the future. Again, further empirical research in cooperation with humanitarian organizations is required to gain more knowledge and experience regarding an appropriate determination of these data.

To enable the modeling of a wide range of situations, additional features can be implemented. For example, it is possible to integrate penalty costs for unsatisfied uncertain demand which change during the planning horizon, in order to simulate situations in which the risk of further disruptions increases (or decreases), and these "warnings" are to be taken into account in the planning process. Until now, no comprehensive calculations have been done with this feature, but first test runs have shown good results.

Moreover, periodically increasing penalty costs for unsatisfied demand can be integrated into the model. This enables an even better representation of many humanitarian operations, as increasing penalty costs can model the fact that a region can substitute for a specific item for a certain time, but with every period in which the demand remains unsatisfied the situation becomes more dangerous. Preliminary results for this adapted model formulation are encouraging. Hence, there are many possibilities of extending the approach suggested here which open new avenues for future research in the area of humanitarian logistics.

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