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A coordinated approach to the facility location problem in disaster relief management

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Abstract

When disaster strikes, the affected population needs food, water, shelter and sanitary and medical supplies and the government often requires the assistance of humanitarian organizations. One of the first decisions the government must make is where to locate the humanitarian aid facilities. Meanwhile, they must balance the different objectives of the organizations involved: location preferences and donor accountability requirements. A coordinated approach among the humanitarian organizations is necessary to avoid wasted response time and resources, while reaching as many people as possible. However, current research on facility location problems in a disaster context focuses on optimizing the global network without incorporating these individual objectives. This study aims to propose a planning tool for the placement of facilities from organizations with different objectives in disaster relief management. First, the facility location problem is examined for organizations that optimize their operations independently. Then, a multicriteria optimization model is used to identify opportunities for coordination. A comparison of both approaches shows that the uncoordinated approach may be suboptimal compared to the coordinated one. The model also helps to determine how an organization can be incentivized to coordinate if needed. An illustrative example evaluates the applicability of the model in the event of an earthquake. This allows to formulate recommendations to optimally use the budget raised after a donation campaign and to increase the total number of people that receive aid from the facilities.

Table of Contents

1 Introduction

1.1 Motivation and research question

Disasters are increasingly occurring and when they do, they often result in the death and injury of thousands of people, significant infrastructural damage and large economic impact. The Centre for Research on the Epidemiology of Disasters (CRED) defines disasters as "*situations or events which overwhelm local capacity, necessitating a request for external assistance at the national or international level.*" (CRED, n.d., para. 2). Similarly, the International Federation of Red Cross and Red Crescent Societies (IFRC, n.d., para. 1) defines disasters as "*serious disruptions to the functioning of a community that exceed its capacity to cope using its own resources.*" They can be characterized as being either natural or man-made and being either sudden onset or slow onset (Van Wassenhove, 2006). This study focuses on earthquakes, which are sudden onset natural disasters. For example, the Emergency Events Database (EM-DAT)[1] developed by CRED indicates that the 7.0-magnitude earthquake in Port-Au-Prince, Haiti, in 2010 killed about 222,570 people and affected 3.7 million people in total. More recently, the 7.8-magnitude earthquake in Turkey and Syria in 2023 affected 13.4 million people of whom 55,283 died and 115,904 were injured. This disaster required an estimated reconstruction cost of 114.8 billion dollars (CRED, n.d.).

Disasters can thus have such a devastating impact that dealing with the aftermath surpasses the emergency response capacity of the country in distress. This is especially true for countries where the population is vulnerable and the strength of the government and society is limited (Holguin-Veras et al., 2012). In these cases, they must rely on the help of international relief organizations to save lives and to alleviate the suffering of their people. These organizations provide medical care and distribute necessary resources such as medical equipment, blankets, water, nutrition and sanitary products from temporary humanitarian aid distribution centers located in or near the disaster-struck area. The government thus faces the decision on where to locate these facilities to service the population in the best way. This is called the facility location problem, which is situated within the field of operations research.

[1] The database contains disasters from the year 1900 onwards and an event is classified as a disaster in the database if it has at least one of the following effects: 10 fatalities, 100 affected people, a declaration of a state of emergency or a call for international assistance.

Coordination between the different organizations is of crucial importance to place the centers to reach as many people as possible. However, a humanitarian setting is different from a commercial setting and cooperation in disaster relief management is not an easy feat. First of all, the distribution network is established amidst destabilized infrastructure and only needs to be maintained for a short period of time as opposed to the long-term commitment in commercial supply chains (Salam & Khan, 2020). Furthermore, the humanitarian organizations involved often have their own strategic objectives and must meet donor expectations. They need to prove to them that they have reached the affected people with their relief efforts and that they have made an impact. Donors can even "*enforce actions they regard as required through the threat of withdrawing their support*." (Burkart et al., 2016, p.33).

In general, the large number and diversity of actors involved in disaster relief management, donor expectations, competition for funding, resource scarcity and unpredictability regarding timing, location and severity of the disaster and infrastructural damage are all elements that limit the coordination between aid providers (Balcik et al., 2010). This lack of coordination can in turn result in network congestion, and wasted resources and response time, which are undesirable effects in any scenario, but especially if there are lives at stake. Every aid effort counts, so coordination losses should be avoided. The government thus aims for a coordinated relief response of the different organizations and can therefore even request the help of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) to "*coordinate the flurry of response efforts to ensure they reach the people most in need*." (OCHA, n.d., para. 1). OCHA uses a cluster approach, that groups the organizations per functional area, as a coordination mechanism. Nevertheless, Ruesch et al. (2021) state that coordination in the field still poses challenges and failed in the aftermath of past disasters despite this approach.

Therefore, this study seeks to provide a coordinated approach to the facility location problem in disaster relief management. In recent years, there has been an increasing trend of using operations research methods to solve emergency humanitarian logistics problems (Boonmee et al., 2017; Kovacs & Moshtari, 2019). However, previous studies that develop optimization models for the facility location problem in a disaster context mostly take the perspective of one central planner, who tries to minimize travel distance or costs for example, without taking into account the heterogeneity of the players involved. The rationale behind such approach could be that all players work towards the common goal of alleviating the suffering, but their

specific mandates and competition for funding and other scarce resources often limit an efficient and effective response (Tatham et al., 2017) and this could result in coordination losses. This leads to the following research question:

How can operations research models be used as a planning tool to improve coordination between organizations for the facility location problem after a disaster in order to increase the total number of people served and which factors influence this coordination?

1.2 Limitations

It should be noted that the operations research models developed in this study face certain limitations. It is assumed that the government knows the objectives of the humanitarian organizations, but they may not always be willing to reveal their strategic objectives. This may cause an information problem for the government, who relies on the optimization of these objectives to identify coordination opportunities. Moreover, the models are pure facility location models, which means that the allocation of supplies to the facilities and the distribution of supplies to the population are not considered. The models are also all deterministic models. Hence, the state of the disaster-struck region and population is known, kept constant and given as input to the model, but in practice disasters are often characterized by uncertainties.

1.3 Outline

The remainder of this study is organized as follows: Chapter 2 consists of a literature review on disaster relief management, deterministic facility location problems and donor accountability. Chapter 3 discusses the mathematical optimization models. First, the objectives of the humanitarian organizations are optimized separately. Afterwards, a coordinated approach is put in place through multicriteria optimization. Then follows chapter 4 with an overview of the data used in this study. Chapter 5 covers the analysis of the model application. We compare the uncoordinated and coordinated approach. The results indicate that it is beneficial to work together in a number of situations, but that organizations do not always do this voluntarily and need an incentive. Afterwards, chapter 6 includes concluding remarks, limitations of this research and directions for future research. In short, the aim is to provide a tool that helps the government in its capacity as a coordinator to analyze coordination opportunities for humanitarian organizations with different goals, so that overall efficiency in the disaster-struck area can be improved.

2 Literature review

This chapter first reviews the specific context before and during a disaster. Then follows a literature review on deterministic facility location problems and a review on how donations can influence the operations of humanitarian organizations.

2.1 Large-scale disaster context

Altay and Green (2006) performed a literature review about disaster operations and stated that the disaster management cycle can be sectioned into four phases: mitigation, preparedness, response and recovery. The first two phases take place pre-disaster, the last two post-disaster. Mitigation concerns the prevention and reduction of long-term risk of disastrous events, while preparedness aims to organize operations before the disaster hits so that an efficient response can be ensured. In the response phase, that takes place shortly after the disaster when the population needs immediate support, emergency services are deployed to reduce suffering and prevent additional losses. Finally, the recovery deals with the reconstruction of the affected area both in the short and the long term to return to normalcy. This sectioning is commonly accepted and used in literature.

One of the activities in the preparedness phase is maintaining emergency supplies (Altay & Green, 2006). To this end, the United Nations Humanitarian Response Depot (UNHRD) network operates five hubs (in Panama, Accra, Brindisi, Dubai and Kuala Lumpur) that are close to regions with a high disaster probability and where humanitarian organizations can store emergency supplies freely as authorized users (UNHRD, 2024). The depots also store a so-called white stock or suppliers' stock that is not marked with any logo yet and that can be offered to users if needed (Schulz & Blecken, 2010). In this way, they can ensure a fast response within 24-48 hours after a disaster has struck, hereby entering the response phase. The transport of goods towards the region is organized through coordinated shipments, which reduces transportation costs (Balcik et al., 2010). Furthermore, some humanitarian organizations maintain their own warehouse network. Figure 1 (Emergency Supply Prepositioning Strategy (ESUPS), 2021) shows a map of the main humanitarian global and regional depots of pre-positioned relief items.

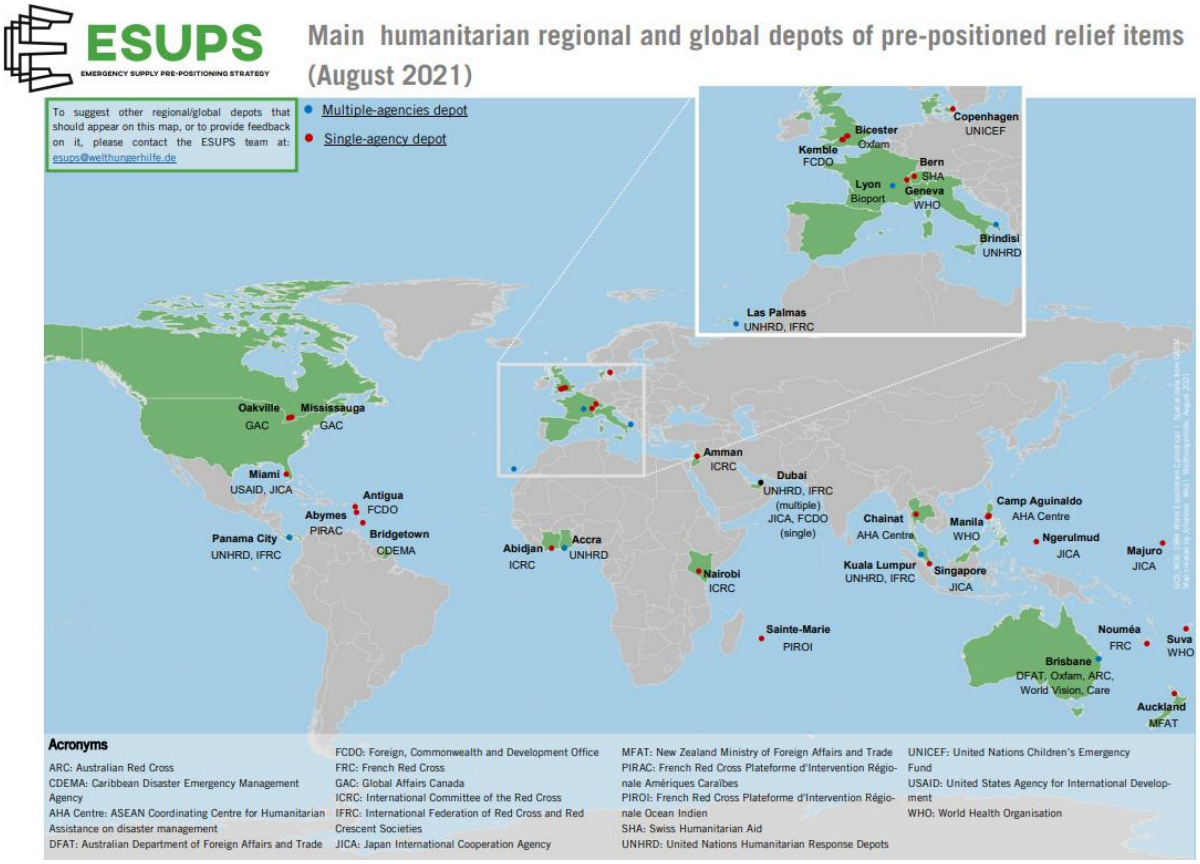

Figure 1: Map of depots with pre-positioned relief supplies as of August 2021.

Then, the emergency supplies need to reach the affected population. Temporary humanitarian aid distribution centers should be selected to service the affected area. This is the facility location problem. The set of candidate locations is usually already identified during the preparedness phase (Anaya-Arenas et al., 2014; Jia et al., 2007b). On the one hand, medical centers and supplies are needed to tend to the injured and food, water, blankets and clothes need to be distributed. On the other hand, adequate water, sanitation and hygiene (WASH) infrastructure and supplies are vital to prevent the transmission of infectious diseases that could arise in the aftermath of a disaster (Hosseinpourtehrani et al., 2022). Also, some organizations specialize in removing debris and waste from the disaster area, which should then be collected at sites not too close to the affected area in order to avoid health risks (Boonmee et al., 2017).

It is important to coordinate these disaster response activities as efficiently as possible to reach as many people as possible, while also avoiding wasted resources and response time. Schulz and Blecken (2010) researched opportunities involved in horizontal (or inter-organizational)

cooperation in disaster relief logistics. They state that "*cooperation has the general objective of realizing cost, time and quality improvements through economies of scale and scope as well as process improvements possible through the consolidation of the logistics tasks of different humanitarian organizations.*" (Schulz & Blecken, 2010, p. 641). In practice, OCHA uses the cluster approach as a coordination mechanism: they divide these different organizations into clusters with cluster leads according to their functional area, like logistics, WASH, health or nutrition (OCHA, n.d.). Jahre and Jensen (2010) conducted a case study on the logistics cluster and found that inter-cluster coordination remains a challenge. Ruesch et al. (2021) took a closer look at this system by means of qualitative research and agent-based simulation. The authors state that despite the cluster approach, coordination in the field still poses challenges and has often failed in the aftermath of past disasters. They found that the cluster lead agency should take on a purely facilitating role and should separate its own agenda from cluster activities to focus its efforts solely on resource-sharing among partners.

2.2 The facility location problem

Boonmee et al. (2017) conducted a literature review on the facility location problem in the context of emergency humanitarian logistics. They identified four problem types: deterministic, stochastic, dynamic and robust facility location problems and found that most research was done on deterministic problems where all parameters are known. Typical objectives of a deterministic problem in which p facilities need to be located are p-median (or minisum), p-center (or minimax) and maximal coverage. This means respectively minimizing the total distance between demand points and facilities, minimizing the maximum distance between demand points and facilities and maximizing the demand for which the maximum distance or travel time to the facility is within a certain threshold. These problems are all known to be NP-hard. The authors also reviewed the set covering problem where the objective is to minimize the number of facilities while covering all demand points within a threshold. For instance, Rekik et al. (2013) developed a decision support system for humanitarian network design where they started from a set covering problem to determine the minimum number of humanitarian aid centers that should be opened. Consecutively, they take decisions on where to open the centers, how to allocate resources and finally on the distribution planning. However, this approach does not take funding and resource restrictions into account, and it might not be feasible to open all required facilities in a disaster context.

Jia et al. (2007a) investigated the facility location problem of medical services for large-scale emergencies and take different levels of service quality into account, by focusing on the p-median, p-center and maximal coverage objectives. In a second paper, they propose three solutions and conclude that the location-allocation algorithm is best in terms of computing time. It also outperforms the proposed genetic algorithm and matches the Langrangian relaxation heuristic solution for large instances (Jia et al., 2007b). Covering models are most often used in emergency situations, but a decreasing average distance to a facility means an increasing effectiveness and accessibility of the facility, justifying a p-median approach. P-center models, on the other hand, promote equity since they minimize the worst performance (Jia et al., 2007a). The objective might also be phase dependent. For example, in the early response phase maximizing delivery speed and quantity of goods is relatively more important than equity, which can be considered in the recovery phase when there is more time for decision making (Kovacs & Moshtari, 2019).

Gralla et al. (2014) recognize that it is hard to determine an appropriate objective function in operational decision-making since trade-offs must be made between effectiveness (maximizing service, i.e. demand satisfied), efficiency (minimizing costs or transport time) and equity amongst others. To support the planning of transportation they develop a piecewise linear utility function for humanitarian aid delivery based on trade-offs made by humanitarian logistics experts. They found that effectiveness (delivering more cargo) is relatively more important than cost efficiency, which is generally true in the response phase when levels of funding are high. However, the authors only focused on the objective function in general and not on a specific optimization problem.

Murali et al. (2012) proposed a facility location model for medical supplies considering that persons at a relatively large distance from their assigned facility might be unwilling to travel there. Furthermore, they consider uncertainties in demand. Li et al. (2018) argued that it is likely that a demand point is covered by multiple facilities and developed a cooperative maximal covering model. Smadi et al. (2018) proposed a maximal coverage model for water distribution in a refugee camp that simultaneously determines the number of facilities to open. Maharjan et al. (2020) introduced a maximal coverage model to determine the location of logistics hubs for disaster response in Nepal. They explicitly included three qualitative variables in their model: the development index, the transportation accessibility and the

disaster vulnerability of a demand point. Nevertheless, none of these papers take into account the different objectives of humanitarian organizations.

Three studies do rely upon multi-criteria optimization for the deterministic facility location problem. Because of this trade-off between objectives, they come up with a set of alternative solutions instead of one optimal solution, hereby constructing a Pareto frontier (section 3.4). In this way, the decision-maker can choose an alternative according to his preferences. Doerner et al. (2009) investigate the placement of public facilities such as schools in tsunami-prone coastal areas. They trade off the minimization of tsunami risk with cost minimization and an equally weighted objective of the minisum and maximal coverage criterion. Nolz et al. (2010) work together with the Austrian Red Cross to focus on water distribution in disaster relief. They also use a combination of the minisum and maximal coverage criterion, but they trade it off with a minimization of transportation time. Abounacer et al. (2014) develop a model for locating distribution centers and distributing supplies for disaster response. The authors want to minimize (1) transportation time, (2) the number of people needed to operate the centers and (3) the amount of uncovered demand in the affected area. Nevertheless, the different objectives considered in these studies are not the objectives of different organizations that work together in the disaster region.

2.3 Funding and donor accountability

Humanitarian organizations depend on funding from donors to be able to respond when disaster strikes, which is a source of uncertainty. Moreover, they often have to compete with other organizations to obtain this limited funding. In this regard, media attention is a critical factor in attracting donors and it heavily influences the level of funding obtained (Aflaki & Pedraza-Martinez, 2016; Balcik et al., 2010). Typically, donations are high right after a major disaster, but they tamp down after the initial crisis, which is referred to as ‘donor fatigue’ (Brown & Minty, 2008; Jayaraman et al., 2023). The media also serve to signal that the money is spent wisely and to demonstrate effectiveness so that the organizations can secure future donations (Muggy & Heier Stamm, 2014; Werker & Ahmed, 2008).

A distinction can be made between in-kind donations and monetary donations. In-kind donations concern relief goods, but unsolicited goods may cause congestion in the relief chain (Balcik et al., 2010; Burkart et al., 2016). The monetary donations can either be earmarked – allocated to a specific purpose – or non-earmarked. The former creates constraints in resource

allocation and limits aid effectiveness, while the latter allows for more flexibility and better operational performance (Aflaki & Pedraza-Martinez, 2016). In general, there has been an increasing trend towards earmarked funding. However, the International Committee of the Red Cross (ICRC, n.d., para. 7) explicitly says that they "*will not accept donations that are very tightly earmarked and that would breach the principles of independence and impartiality*" and that they can rapidly mobilize resources in the first phase of response "*by using special funds that are not earmarked, […] thus giving us maximum flexibility in how we use them*."

Ríos Romero et al. (2023) conducted a literature review on the effect donor accountability on the activities of non-governmental organizations (NGOs). They propose to use accountability as a quality measure for attracting and retaining donors. The dimensions of accountability are threefold: to whom, for what and how. Firstly, such organizations are accountable to multiple actors: themselves, other NGOs, donors, volunteers, beneficiaries and society. Upwards accountability to donors is often prioritized to justify donations, but this may also divert the attention from long-term projects that could be more valuable for beneficiaries or more efficient in terms of operations. Secondly, NGOs are evaluated both on the use of financial resources and the performance with regard to their goals. Thirdly, mechanisms to evaluate NGOs are mostly variations of mechanisms used in a commercial context, where there is a focus on financial results and reports. For example, the International Committee of the Red Cross (ICRC, n.d., para. 1) recognizes that "*contributions [of donors] remain voluntary and there is no guarantee that such contributions will last into the long-term*." To show that these contributions are properly used, they therefore "*have set up a system of internal and external audits whereby all key financial figures and procedures are checked*."

Werker and Ahmed (2008) even argue that the donors can be regarded as customers of the humanitarian organization instead of the aid beneficiaries themselves. Indeed, in a commercial context, customers have the choice not to purchase a certain product from an organization, whereas aid beneficiaries have no choice in which aid they receive and from whom. Donors, on the other hand, can choose to withdraw their support. Therefore, they state that "*donations are the only 'market force' in NGO-sector industry*" (Werker & Ahmed, 2008, p. 78).

3 Model formulation

By now it is clear that a disaster context complicates coordination. When disaster strikes, humanitarian organizations enter the scene, but the papers that study the facility location problem do not consider the heterogeneity of the organizations and the fact that they do pursue their own goals because of donor accountability, hereby using their own resources. To address this, a multicriteria model is proposed to coordinate the facility location decision so that the resources are optimally used to aid the population. In this chapter, we begin by identifying the uncoordinated approach: we optimize the facility location problem for a medical organization by means of a maximal coverage model and for an organization providing clean drinking water and WASH supplies by solving a minisum model. Then, we look at what the ideal scenario would be in terms of facility locations through the set covering model. Afterwards, the multicriteria optimization model, that incorporates the possibility of realizing economies of scale, is developed as a tool for the government to identify coordination opportunities and to investigate how organizations can be incentivized to agree to such a coordinated facility placement if needed. Finally, we investigate a dynamic multicriteria model.

The following simplifying assumptions apply to all models:

- candidate locations to place facilities are identified during the preparedness phase;
- facilities prepositioned during the preparedness face are severely damaged (or even destroyed) such that repairment costs are as high as the costs for installing a new facility;
- the demand points are aggregated demand points;
- facilities cannot be relocated since relocation is inconvenient in emergency situations.

Furthermore, an organization that is funded by donors needs to show that they used the funds efficiently, often through financial reports. Therefore, a volume indicator can be used as a measure of financial efficiency. Indeed, the more people they are able to help with the allocated funds, the higher the efficiency and the higher the chances that they will receive repeat funding for the future so that they can continue their operations.

3.1 Maximal coverage for medical organizations

An organization that comes to the rescue with emergency medical teams and supplies needs a medical facility to treat the injured after the earthquake took place. They also want to save

as many lives as possible given the budget at their disposal. Furthermore, injured people are not often able to travel a long distance themselves and they may not even be in a condition to be transported over a long distance. For instance, Medecins Sans Frontieres (MSF) explains that they want to place the field hospitals as close to the population as possible since most people come by foot (MSF, 2018). Therefore, a maximal coverage objective, which maximizes the population covered within a threshold distance, is appropriate to decide on where to place the medical facilities. The equivalent of maximizing the covered population is minimizing the uncovered population, which is the approach that we will use here.

Let I be the set of demand points and J be the set of candidate facility locations. The parameters used in this problem and the decision variables to be optimized are described in Table 1 and Table 2, respectively.

Table 1: Parameters of the maximal coverage model

Notation	Description
$\boldsymbol{d_{ij}}$	The distance between demand point i and candidate facility location j
$\boldsymbol{D^*}$	The maximum distance between demand point i and facility location j for which the demand point is considered as covered
$\boldsymbol{F_j}$	The cost for placing a facility at location j
$\boldsymbol{B_{med}}$	The available budget for placing facilities, which consists of donations
$\boldsymbol{\varepsilon_i}$	The disaster impact parameter for medical care demand point i, $\varepsilon_i \in [0,1]$
$\boldsymbol{P_i}$	The population at demand point i

Table 2: Decision variables of the maximal coverage model

Notation	Description
$\boldsymbol{x_j}$	= 1 if a facility is placed at location $j \in J$ = 0 otherwise
$\boldsymbol{w_i}$	= 1 if demand point $i \in I$ is covered by at least one facility within threshold D^* = 0 otherwise

We can formulate the maximal coverage model as follows:

$$\min \sum_{i \epsilon I} \varepsilon_i P_i (1 - w_i) \quad (1)$$

$$s.t. \sum_{j \in J} F_j x_j \leq B_{med} \quad (2)$$

$$\sum_{j \in J : d_{ij} \leq D^*} x_j \geq w_i \quad \forall i \in I \quad (3)$$

$$x_j \in \{0,1\} \quad \forall j \in J \quad (4)$$

$$w_i \in \{0,1\} \quad \forall i \in I \quad (5)$$

The objective (1) states that we want to minimize the share of the population impacted by the disaster that is not covered by at least one facility, which is equivalent to maximizing the covered population. Constraint (2) imposes that the cost of placing the facilities should be within the budget that is available to the organization through donations. Constraint (3) says that a demand point is covered if there is at least one facility placed within the threshold distance D^*. Finally, constraints (4) and (5) are binary constraints that force the facilities to be either opened or not and the demand points to be either fully covered or not.

3.2 Minisum for drinking water

As is explained by Hosseinpourtehrani et al. (2022) and Nolz et al. (2010), providing WASH services is indispensable to prevent both dehydration and the spread of diseases. Therefore, the humanitarian organization in charge of distributing clean water and sanitary products would like to reach the whole population. At the same time, they operate with a limited budget of donations, which should be used in the most effective way. Therefore, it is appropriate to implement the minisum objective since this maximizes accessibility while taking the whole population into account. Furthermore, water and sanitary products can be transported by truck, so trucks can depart from these facilities to reach more scarcely populated areas. The parameters used in this problem and the decision variables to be optimized are described in Table 3 and Table 4, respectively.

Table 3: Parameters of the minisum model

Notation	Description
$\boldsymbol{d_{ij}}$	The distance between demand point i and candidate facility location j
$\boldsymbol{F_j}$	The cost for placing a facility at location j
$\boldsymbol{B_{wash}}$	The available budget for placing facilities, which consists of donations
$\boldsymbol{\delta_i}$	The disaster impact parameter for water for demand point i, $\delta_i \in [0,1]$
$\boldsymbol{P_i}$	The population at demand point i

Table 4: Decision variables of the minisum model

Notation	Description
$\boldsymbol{x_j}$	= 1 if a facility is placed at location $j \in J$ = 0 otherwise
$\boldsymbol{u_{ij}}$	= 1 if demand point $i \in I$ is served by facility $j \in J$ = 0 otherwise

We can formulate the minisum model as follows:

$$min \sum_{i \in I} \sum_{j \in J} \delta_i P_i d_{ij} u_{ij} \quad (6)$$

$$s.t. \sum_{j \in J} F_j x_j \leq B_{wash} \quad (7)$$

$$\sum_{j \in J} u_{ij} = 1 \quad \forall i \in I \quad (8)$$

$$u_{ij} \leq x_j \quad \forall i \in I, \forall j \in J \quad (9)$$

$$x_j \in \{0,1\} \quad \forall j \in J \quad (10)$$

$$u_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in J \quad (11)$$

The objective (6) states that we want to minimize the total distance between demand points and facilities weighted by the population at the demand points. Constraint (7) is the same as constraint (2). Constraint (8) says that each demand point should be allocated to a facility. This allocation to a specific facility is only possible if that facility is opened, which is expressed by constraint (9). Finally, constraints (10) and (11) are once again binary constraints that force the facilities to be either opened or not and the demand points to be either assigned to a facility at location j or not.

Another organization might want to focus specifically on the rural areas when providing drinking water, so that the communities there can keep on tending to their crops. It helps the country in the medium to long term if food production in the countryside is maintained as best as possible, which is important for the recovery phase. This organization is also dependent on donations and wants to maximize results, so they want to minimize the total weighted distance to rural areas. To this end, define I' as the set of demand points i with a population $P_i \leq 15{,}000$. The minisum model can then be run for the sets I' and J.

3.3 Set covering as ideal situation

Ideally, disaster relief services are provided for the whole population and in close proximity. To determine the minimum number of multifunctional humanitarian aid facilities $\underline{z}$ that would be required to serve everyone, they can use a set covering problem as proposed by Rekik et al. (2013). The only decision variable figuring in this model is x_j: a binary variable that decides whether a facility is opened at location j or not. Also, the threshold distance D^* reappears here. The larger the threshold distance, the less facilities will be required to be opened.

$$\underline{z} = \min \sum_{j \in J} x_j \quad (12)$$

$$s.t. \sum_{j \in J : d_{ij} \leq D^*} x_j \geq 1 \quad \forall i \in I \quad (13)$$

$$x_j \in \{0,1\} \quad \forall j \in J \quad (14)$$

The objective (12) minimizes the number of facilities to open. Constraint (13) says that there needs to be at least one open facility within the threshold distance for each demand point and the last constraint (14) is the binary constraint. The government has only limited funds for disaster relief management (and often has limited experience) and thus they cannot place all the required facilities themselves. This is the very reason why humanitarian organizations come to the rescue and why trade-offs are necessary. As a result, the government should consider how they can use their budget to coordinate the organizations to open facilities in the best way possible. To this end, a multicriteria optimization model is proposed.

3.4 Multicriteria model

A trade-off must be made between the two criteria developed above. Therefore, it is possible to construct a set of alternative solutions: the Pareto frontier. The government can choose a certain solution that represents a set of facility locations from this frontier depending on their priorities and the situation at hand. In this way, the model can be used as a planning tool. The approach builds on the concepts of dominance and Pareto optimality (Nolz et al., 2009, p. 174; Winston & Geldhof, 2004, p. 695):

- Dominance: A feasible solution $\hat{x}$ dominates a feasible solution x' to a multiple-objective problem if $\hat{x}$ is at least as good as x' with respect to every objective and is strictly better than x' with respect to at least one objective.
  For $(f_1(x), f_2(x), \dots, f_n(x))$ to be minimized, $\hat{x}$ dominates x' if $f_i(\hat{x}) \leq f_i(x') \ \forall i \in \{1, \dots, n\}$ and $\exists i \in \{1, \dots, n\}$: $f_i(\hat{x}) < f_i(x')$.
- Pareto optimality: A solution x^* to a multiple-objective problem is Pareto optimal if no other feasible solution x' is at least as good as x^* with respect to every objective and is strictly better than x^* with respect to at least one objective.

Combining these two definitions, a solution is Pareto optimal if it is not dominated by another feasible solution. The set of Pareto optimal solutions is called the Pareto frontier. Two of the

most common methods to construct this frontier are the following (Nolz et al., 2009, p. 178; Ransikarbum & Mason, 2016, p. 53):

- Epsilon constraint method: First, we optimize the problem for objective 1, which gives an objective value z_1. Then, we calculate the objective value z_2 for objective 2 under the constraint that we cannot do worse for objective 1, i.e. $f_1(x) \leq z_1$ for a minimization problem. This process can be iterated to find Pareto optimal points by stating that we can do at most ε times worse than z_1 for objective 1 when optimizing objective 2, i.e. $f_1(x) \leq \varepsilon z_1$ with $\varepsilon > 1$ for a minimization problem.
- Weighted objective method: The different objectives are weighted with a factor α_i and $\sum_{i=1}^{n} \alpha_i = 1$. For two objectives, we have α and $(1-\alpha)$. Now, we obtain a single objective to optimize: $f(x) = \alpha f_1(x) + (1-\alpha) f_2(x)$. If the objective functions are expressed in different units, it is necessary to put them onto a common scale and then $f(x) = \alpha \frac{f_1(x) - f_1^{min}(x)}{f_1^{max}(x) - f_1^{min}(x)} + (1-\alpha) \frac{f_2(x) - f_2^{min}(x)}{f_2^{max}(x) - f_2^{min}(x)}$ for a minimization problem. The minimum and maximum objective function values can be found by optimizing the model for a single objective. By alternating the value of α, different points on the Pareto frontier can be identified. The extreme points can be found for $\alpha \in \{0,1\}$.

Thus, it is clear that the Pareto frontier represents solutions in which there is given relatively more or less importance to a certain objective. In a coordinated approach, it is possible to realize economies of scale through cost sharing, which is also recognized by Schulz and Blecken (2010) as a means to improve inter-organizational cooperation. For the facility location problem, it translates in the placement of joint facilities, which could result in more facilities placed overall for a given budget. So, even if the objective of the first organization is deemed more important by the government, the second organization could possibly still be satisfied with the solution in a coordinated approach thanks to the economies of scale. In this context, medical supplies and WASH-products can be stored together. Injured people treated at the facility immediately have access to clean water and vice versa. However, if the organizations do not coordinate, they miss out on the opportunity to save costs, which can result in a suboptimal solution. This leads to the following proposition:

Proposition 1: When two or more humanitarian organizations with private objectives are independently optimizing their operations after a disaster, the resulting solution can be suboptimal, i.e. the solution is not located on the Pareto frontier and is thus dominated.

Now, let $K = \{1,2,3\}$ be the set of types of facilities k. The organizations can install a joint facility (k=3) at location j for a cost that is less than the cost of setting up two separate specialized facilities: one distribution center for water and sanitary products (k=1) and one medical center (k=2). As a result, we transform the decision variable x_j into x_{jk} that now decides whether a facility of type k is placed at location j or not. Similarly, we transform parameter F_j into F_{jk}.

$$f_1 = min \sum_{i \in I} \varepsilon_i P_i (1 - w_i) \quad (15)$$

$$f_2 = min \sum_{i \in I} \sum_{j \in J} \delta_i P_i d_{ij} u_{ij} \quad (16)$$

$$s.t. \sum_{j \in J} \sum_{k \in K} F_{jk} x_{jk} \leq B \quad (17)$$

$$\sum_{j \in J} F_{j1} x_{j1} + \mu F_{j3} x_{j3} \leq B_{wash} \qquad (17a)$$

$$\sum_{j \in J} F_{j2} x_{j2} + (1 - \mu) F_{j3} x_{j3} \leq B_{med} \quad (17b)$$

$$\sum_{k \in K} x_{jk} \leq 1 \quad \forall j \in J \quad (18)$$

$$\sum_{j \in J} u_{ij} = 1 \quad \forall i \in I \quad (19)$$

$$u_{ij} \leq x_{j1} + x_{j3} \quad \forall i \in I, \forall j \in J \quad (20)$$

$$\sum_{j \in J : d_{ij} \leq D^*} x_{j2} + x_{j3} \geq w_i \quad \forall i \in I \quad (21)$$

$$w_i \in \{0,1\} \qquad \forall i \in I \qquad (22)$$

$$x_{jk} \in \{0,1\} \quad \forall j \in J, \forall k \in K \quad (23)$$

$$u_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in J \quad (24)$$

The objectives (15) and (16) did not change as compared to the models for one organization only. Now, the total costs of all the facilities that are opened must be within the total budget

as is explained by constraint (17). This constraint divides the constraining resource over the different facilities that are opened. Here, the constraining resource is the money raised after the earthquake. Since the organizations compete to obtain this money, they will not share their budget to finance a facility that only benefits the other organization. Therefore, constraints (17a) and (17b) are used instead of constraint (17). Each organization can spend their own budget on the construction of their own specialized facilities and/or joint facilities. μ represents the share of costs of the WASH organization when setting up a joint facility. Constraint (18) says that there can be at most one type of facility opened at location j. In other words, we can either place a distribution center (k=1) or a medical center (k=2) or a joint facility (k=3) there. Constraint (19) is the same as constraint (8). Constraint (20) states that a demand point is only assigned to a certain facility if water is distributed from a distribution center or joint facility that is opened there. Similarly, constraint (21) imposes that a demand point is covered if there is a medical center or a joint facility opened within the threshold distance. The last three constraints (22), (23), (24) are the binary constraints we have seen before.

It is possible to come up with other types of resource constraints that are applicable in this context and that make use of constraints (17a) and (17b). For instance, the organizations can also dispose of their own aid workers or vehicles that need to be divided over the different facilities. If the constraining resource is not proprietary to the organizations, constraint (17) can be used to model this. For example, B can represent the total time available for unloading a ship. We know that shipments are sent from a UNHRD in a coordinated way so that they contain goods of multiple organizations. It then takes a specific amount of time to unload a set of goods that makes the facility operational e.g. generator, beds, refrigerators, construction materials… When setting up a joint facility, it might be possible to save time because, for example, they will need one slightly bigger generator, instead of two for two separate facilities.

3.5 Dynamic multicriteria model

It is possible to consider the fact that funding becomes available gradually. This means that the organizations can gradually open more facilities if more funds are available. The decision variables x_j, w_i, u_{ij} now become x_{jt}, w_{it}, u_{ijt} because a decision must be made for each period $t \in T$. This time dependency can be modelled as follows:

$$f_1 = min \sum_{i \in I} \sum_{t \in T \setminus \{0\}} \varepsilon_i P_i (1 - w_{it}) \quad (25)$$

$$f_2 = min \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} \delta_i P_i d_{ij} u_{ijt} \quad (26)$$

$$s.t. \sum_{j\in J}\sum_{k\in K}\sum_{r=1}^{t} F_{jk}(x_{jk,r} - x_{jk,r-1}) \leq \sum_{r=1}^{t} B_r \quad \forall t \in T\backslash\{0\} \quad (27)$$

$$\sum_{j\in J}\sum_{r=1}^{t} F_{j1}(x_{j1,r} - x_{j1,r-1}) + \mu F_{j3}(x_{j3,r} - x_{j3,r-1}) \leq \sum_{r=1}^{t} B_{wash} \quad \forall t \in T\backslash\{0\} \quad (27a)$$

$$\sum_{j\in J}\sum_{r=1}^{t} F_{j2}(x_{j2,r} - x_{j2,r-1}) + (1-\mu) F_{j3}(x_{j3,r} - x_{j3,r-1}) \leq \sum_{r=1}^{t} B_{med} \quad \forall t \in T\backslash\{0\} \quad (27b)$$

$$x_{jk,t-1} \leq x_{jk,t} \quad \forall j \in J, \forall k \in K, \forall t \in T\backslash\{0\} \quad (28)$$

$$\sum_{k\in K} x_{jkt} \leq 1 \qquad \forall j \in J, \forall t \in T \qquad (29)$$

$$\sum_{j\in J} u_{ijt} = 1 \quad \forall i \in I, \forall t \in T\backslash\{0\} \quad (30)$$

$$u_{ijt} \leq x_{j1t} + x_{j3t} \quad \forall i \in I, \forall j \in J, \forall t \in T \quad (31)$$

$$\sum_{j\in J: d_{ij} \leq D^*} x_{j2t} + x_{j3t} \geq w_{it} \quad \forall i \in I, \forall t \in T \quad (32)$$

$$w_{it} \in \{0,1\} \quad \forall i \in I, \forall t \in T \quad (33)$$

$$x_{jk0} = 0 \quad \forall j \in J, \forall k \in K \quad (34)$$

$$x_{jkt} \in \{0,1\} \quad \forall j \in J, \forall k \in K, \forall t \in T\backslash\{0\} \quad (35)$$

$$u_{ijt} \in \{0,1\} \quad \forall i \in I, \forall j \in J, \forall t \in T \qquad (36)$$

The objectives (25), (26) and constraints (29), (30), (31), (32), (33), (35) and (36) are simply updated with regard to the time period so that they now must hold for each time period. Constraint (27) imposes that the costs for installing facilities up to time t can never be larger than the budget available up to time t. This also allows for the transfer of any leftover budget in period $t-1$ to period t. We use once again constraints (27a) and (27b) in this case instead of the more general constraint (27). The formulation of these three constraints relies on constraint (28) that says that if a facility of a certain type is opened in a certain period, it should still be open in the next periods, which is an assumption we made at the beginning of this chapter. To implement this correctly, constraint (35) says that there are no facilities available at time zero, which is another assumption we made at the beginning.

4 Data

To illustrate the model, we will simulate an earthquake using population data from Belgium. In Belgium, the National Crisis Center conducted a large-scale risk assessment for the period 2018 until 2023 (National Crisis Center, n.d.-a). For each risk scenario they calculated a probability and impact score. The latter is based on human, social, environmental and financial factors. For the earthquake scenario they determined that the probability is likely, whereas the impact will be low. After all, infrastructure in Belgium is subject to Eurocode 8 (National Crisis Center, n.d.-b), which is a standard that prescribes rules for construction aimed at withstanding earthquakes so that "*human lives are protected, damage is limited, [and] structures important for civil protection remain operational*." (European Commission, n.d., para. 1). However, developing countries often have poorly constructed infrastructure. They either have no proper construction codes in place or these codes are not properly enforced (Miyamoto et al., 2024). This implies that if an earthquake of the same magnitude as in Belgium strikes in one of these countries, the infrastructural damage because of building collapse, and therefore also the human suffering, will be larger, as is evidenced by the significant impact of the earthquakes in Haiti and Turkey (CRED, n.d.; Miyamoto et al., 2024). So, without loss of generality, assume that an earthquake hits a developing country that has the same population density as Belgium. This country can be considered as an island. It is therefore not possible that a facility is placed outside the border to cover demand of the disaster-struck country and all humanitarian aid arrives by ship or by plane.

4.1 Demand

The population data was retrieved from the site of StatBel, the Belgian statistical office (Statbel, 2023). They provide a dataset with the place of residence per inhabitant as of January 1st 2023, called municipalities. The center of each municipality is an aggregated demand point. There are 581 municipalities in total, uniquely identified through their 'niscode' – a five-digit code for geographical areas developed by StatBel. The system of niscodes also defines regions within Belgium, e.g. municipalities with the number 1 as first digit are located in the province of Antwerp. It is practical to select only a subset of municipalities for illustration of the model as this limits the size of the instance and therefore the computing time, while it still allows for representation of facility locations on a map. The instance used in this study contains Antwerp, Limburg excluding 'Voeren' and Flemish Brabant including Brussels (niscodes starting with 1;

7; 21, 23, 24 respectively). Table 5 displays an excerpt of the population data; the full list can be found in Appendix 1. 'Antwerpen' has the highest number of residents. In total, the instance represents 5,230,253 residents divided over 194 municipalities (the set I). 81 municipalities count less than 15,000 residents, while there are 26 with at least 40,000 residents. They are considered as rural (the set I') and urban areas, respectively.

Table 5: Excerpt of population data

CityID	Niscode	Municipality	Population
1	11001	Aartselaar	14 752
2	11002	Antwerpen	538 910
3	11004	Boechout	13 806
4	11005	Boom	19 062
5	11007	Borsbeek	11 309
6	11008	Brasschaat	38 575
7	11009	Brecht	30 387
8	11013	Edegem	22 761
9	11016	Essen	19 629

4.2 Distance matrix

The distance matrix for Belgium is calculated by the National Geographic Institute (Robberechts, 2022). It shows the distances between all Belgian municipality centers. Table 6 displays an excerpt from the distance matrix. The matrix is symmetric, which means that the transpose of the matrix is equal to the matrix itself. In other words, the same route can be taken to go from 'Aartselaar' to 'Boechout' and from 'Boechout' to 'Aartselaar' for example.

Table 6: Excerpt of distance matrix with distances expressed in kilometers

Municipalities		Aartselaar	Antwerpen	Boechout	Boom	Borsbeek	Brasschaat	Brecht	Edegem	Essen
	niscode	11001	11002	11004	11005	11007	11008	11009	11013	11016
Aartselaar	11001	0	11	11	6	13	22	34	7	48
Antwerpen	11002	11	0	14	16	12	12	25	12	39
Boechout	11004	11	14	0	18	4	20	32	4	46
Boom	11005	6	16	18	0	20	27	39	14	53
Borsbeek	11007	13	13	4	20	0	15	28	7	42
Brasschaat	11008	22	12	20	27	15	0	14	18	21
Brecht	11009	37	25	32	42	28	14	0	34	19
Edegem	11013	7	12	4	15	6	18	31	0	45
Essen	11016	48	36	46	53	41	21	19	44	0

It is important to note that an earthquake can bring significant damage to road infrastructure, leading to blocked roads or roads with decreased capacity and to increased travel distance. In practice, data about the state of the road network after the disaster can be obtained through satellite images. Sakuraba et al. (2016) addressed the road network accessibility problem that determines the shortest unblocked path from origin to destination along with the fastest

repairable paths. Here, we assume that any detours necessary due to damaged roads are already incorporated into the distance matrix. It would also be possible to work with travel times as a measure of distance. The time needed to travel from one zone to another might thus increase as compared to the situation before. Hence, the distance matrix then indicates the shortest travel time needed to travel from one zone to another.

4.3 Impact parameters

δ_i represents the impact of the earthquake on water and sanitary requirements of the population. Since this is indispensable to life, we assume that δ_i = 1 for all locations.

ε_i represents the proportion of the population that is in need of medical supplies and attention after the earthquake has struck. We assume that the whole contiguous region is hit. In densely populated urban areas, the concentration of people and infrastructure increases the likelihood of injuries because of collapsing buildings and falling debris, especially in developing countries with poorly constructed infrastructure. Rural areas suffer more from landslides. Therefore, the proportion of injured people is higher in urban areas and ε_i is defined in Table 7 as follows:

Table 7: Parameter values of ε_i

Condition	Parameter value
$\boldsymbol{P_i \leq 15,000}$	$\varepsilon_i = 0{,}15$
$\boldsymbol{15,000 \leq P_i \leq 40,000}$	$\varepsilon_i = 0{,}30$
$\boldsymbol{40,000 \leq P_i}$	$\varepsilon_i = 0{,}50$

Consequently, there are 1,907,320 people in total who have been injured. Part of the impacted population only has minor injuries that can be tended to quickly, while a small part is severely injured. In this study, we make abstraction of the level of injury and illness.
In a dynamic model, the impact parameters may change too over time. For example, an aftershock can cause more damage and people treated in a certain period may not need medical care or supplies anymore in the following periods. For simplicity, the impact parameters are kept constant over time here.

4.4 Fixed costs

Since it proved to be difficult to find numbers about the costs of installing facilities, I based myself on numbers that are used in Li et al. (2018). The cost of a medical facility is set to 250,000 and the cost of a WASH facility to 200,000 for every location.

5 Results

In this section, the models developed in Chapter 3 are run while using the data explained in Chapter 4. We begin by discussing the results in case the humanitarian organizations independently optimize their facility location decision and then we move on to the analysis of the multicriteria model where the government takes on the role of coordinator.

All computations are performed on an HP Pavilion x360 convertible laptop with Intel Core i5-7200U CPU and 12 GB RAM. The models are programmed using JuMP, which is a modeling language for mathematical optimization integrated within the Julia programming environment. Furthermore, Gurobi 11.0.2 is used as a solver for the programmed problems.

5.1 Maximal coverage for medical organizations

We first consider the model for a medical organization that focuses on reaching as many people in need of medical attention and/or supplies as possible within close proximity, or equivalently on minimizing the number of patients not treated. The threshold distance is set at 5 kilometers to start with and then gradually increases by 5 kilometers each time. We look into different budgets that are raised after the earthquake struck. In every municipality there is a candidate facility location identified, so the set of demand points I is equal to the set of candidate facility locations J, which is true for all applications in Chapter 5. The results can be found in Table 8.

We observe that if the threshold distance increases, the uncovered and thus unserved population decreases. We also remark that the medical facilities are located in the city periphery. This can be explained by the fact that in order to maximize coverage they are placed to cover both the city and smaller municipalities around the city. Nevertheless, a larger threshold might not be desirable in emergency situations. If people travel by foot and the threshold is set at 25 km, some of them would need at least five hours to reach the facility. If they are injured, this trajectory probably takes even more time. Therefore, we set the maximum distance equal to 10 km. Besides, if the organization has a larger budget available, the added value of a larger threshold becomes lower in terms of population covered (Figure 2), although some municipalities are then covered by multiple facilities.

As for the budget, a higher level of funding translates in a lower part of the affected population that is uncovered and thus more people receiving medical care and supplies. It is important to

remark that if the budget increases, the population covered does not increase proportionally (Figure 2) because the biggest cities with the most injured people are already covered at the beginning.

Table 8: Results minimal uncovered model for medical organization

Budget ('000 €)	Threshold (km)	Population uncovered	Percentage uncovered	Facilities
1000	5	988 839	51,84%	Antwerpen, Anderlecht, Sint-Lambrechts-Woluwe, Leuven 2, 70, 87, 142
	10	790 809	41,46%	Schoten, Duffel, Brussel, Diepenbeek 22, 34, 73, 156
	15	591 002	30,99%	Kontich, Dilbeek, Kortenberg, Hasselt 14, 92, 140, 160
	20	369 563	19,38%	Kontich, Sint-Joost-ten-Node, Aarschot, Hasselt 14, 83, 124, 160
	25	240 534	12,61%	Zandhoven, Brussel, Aarschot, Diepenbeek 27, 73, 124, 156
2000	5	829 191	43,47%	Antwerpen, Mechelen, Anderlecht, Sint-Lambrechts-Woluwe, Grimbergen, Leuven, Genk, Hasselt 2, 37, 70, 87, 95, 142, 157, 160
	10	534 640	28,03%	Schoten, Duffel, Meerhout, Schaarbeek, Sint-Pieters-Leeuw, Herent, Diepenbeek, Heusden-Zolder 22, 34, 57, 84, 109, 134, 156, 170
	15	283 771	14,88%	Brasschaat, Lier, Lille, Sint-Gillis, Meise, Bertem, Hasselt, Tessenderlo 6, 36, 56, 82, 104, 127, 160, 166
	20	85 560	4,49%	Schoten, Turnhout, Elsene, Kapelle-op-den-Bos, Aarschot, As, Leopoldsburg, Sint-Truiden 22, 65, 78, 100, 124, 154, 162, 165
	25	3 376	0,18%	Brecht, Rumst, Kasterlee, Brussel, Rotselaar, Sint-Truiden, Hechtel-Eksel, Maasmechelen 7, 19, 55, 73, 145, 165, 178, 194
3000	5	722 049	37,86%	Antwerpen, Mortsel, Mechelen, Vosselaar, Anderlecht, Sint-Lambrechts-Woluwe, Grimbergen, Leuven, Beringen, Genk, Hasselt, Houthalen-Helchteren 2, 16, 37, 67, 70, 87, 95, 142, 155, 157, 160, 179
	10	359 097	18,83%	Schoten, Duffel, Willebroek, Herenthout, Meerhout, Oud-Turnhout, Evere, Sint-Pieters-Leeuw, Wemmel, Herent, Diepenbeek, Heusden-Zolder 22, 34, 41, 51, 57, 61, 75, 109, 120, 134, 156, 170
	15	106 926	5,61%	Brasschaat, Lier, Lille, Etterbeek, Gooik, Londerzeel, Rotselaar, Linter, Tessenderlo, Hechtel-Eksel, Dilsen-Stokkem, Bilzen 6, 36, 56, 74, 94, 102, 145, 150, 166, 178, 180, 184
	20	2 691	0,14%	Aartselaar, Wuustwezel, Lier, Turnhout, Laakdal, Ganshoren, Kraainem, Holsbeek, Zoutleeuw, Peer, Dilsen-Stokkem, Bilzen 1, 26, 36, 65, 69, 77, 117, 136, 149, 176, 180, 184
	25	0	0,00%	Aartselaar, Brecht, Herentals, Retie, Vorselaar, Overijse, Pepingen, Affligem, Rotselaar, Sint-Truiden, Peer, Maasmechelen 1, 7, 50, 63, 66, 107, 108, 123, 145, 165, 176, 194

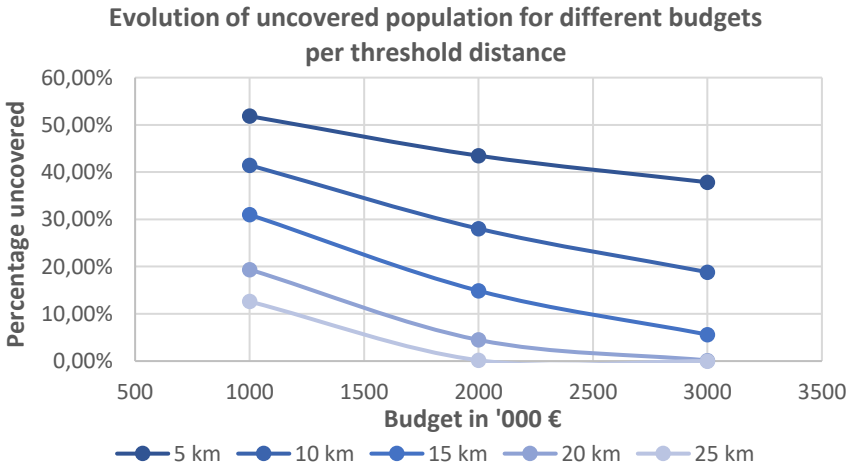

Figure 2: Evolution of uncovered population for different budgets per threshold distance

5.2 Minisum for drinking water

The organization that focuses on supplying water and sanitary products across the whole country minimizes the average distance to facilities. The results for different budgets are shown in Table 9. We also computed the total weighted distance to rural areas when facilities are placed taking the whole population into account. Facilities are mostly located in urban areas, since their high population numbers make them more important in the objective function. It is important to remark that for a budget of 2.5 million for example, the organization has 100,000 left that cannot be used. This suggests that if organizations coordinate, the total budget could potentially be spent in a better way, that is serving more people in closer proximity to the facilities.

Table 9: Results for minisum model for WASH organization that focuses on whole population

Budget ('000 €)	Total distance (km)	Average distance (km)	Total distance to rural areas (km)	Average distance to rural areas (km)	Facilities
625	90 864 014	17,37	21 174 581	25,49	Mortsel, Sint-Joost-ten-Node, Hasselt 16, 83, 160
800	75 826 667	14,50	18 460 328	22,22	Antwerpen, Herentals, Sint-Joost-ten-Node, Hasselt 2, 50, 83, 160
1000	68 145 968	13,03	16 094 844	19,38	Antwerpen, Herentals, Sint-Joost-ten-Node, Herent, Hasselt 2, 50, 83, 134, 160
1500	57 356 328	10,97	14 509 977	17,47	Antwerpen, Mechelen, Lille, Sint-Joost-ten-Node, Leuven, Hasselt, Leopoldsburg 2, 37, 56, 83, 142, 160, 162
1600	53 565 480	10,24	13 662 115	16,45	Antwerpen, Malle, Mechelen, Geel, Sint-Joost-ten-Node, Leuven, Hasselt, Bree 2, 30, 37, 48, 83, 142, 160, 172
2000	48 264 408	9,23	12 305 474	14,81	Antwerpen, Malle, Mechelen, Herselt, Mol, Brussel, Ukkel, Leuven, Hasselt, Bree 2, 30, 37, 52, 59, 73, 85, 142, 160, 172
2500	43 915 768	8,40	12 008 455	14,46	Antwerpen, Zoersel, Mechelen, Turnhout, Westerlo, Brussel, Ukkel, Machelen (Halle-Vilvoorde), Leuven, Hasselt, Hechtel-Eksel, Maasmechelen 2, 28, 37, 65, 68, 73, 85, 103, 142, 160, 178, 194
3000	38 222 537	7,31	10 411 368	12,53	Antwerpen, Brecht, Mechelen, Nijlen, Mol, Turnhout, Brussel, Ukkel, Machelen (Halle-Vilvoorde), Leuven, Scherpenheuvel-Zichem, Hasselt, Sint-Truiden, Peer, Maasmechelen 2, 7, 37, 38, 59, 65, 73, 85, 103, 142, 151, 160, 165, 176, 194

When comparing these results to the results of an organization that only provides water to rural areas (Table 10), we see that the total distances to rural areas are significantly lower and that the facilities themselves migrate from big city centers towards the more rural areas. These areas represent a population of 830,687 residents. Thus, when the first organization disposes of a budget of 3.0 million, the average distance from a rural area to a facility is 12.53 km (Table 9), whereas the average distance is 7.35 km (Table 10) when the second organization disposes of such budget. This change in priority considerably increases accessibility to water and sanitary products for rural areas.

Table 10: Results for minisum model for WASH organization that focuses on rural areas only

Budget ('000 €)	Total distance to rural areas (km)	Average distance to rural areas (km)	Facilities
625	20 100 823	24,20	Zandhoven, Steenokkerzeel, Hasselt 27, 110, 160
800	16 579 834	19,96	Zandhoven, Roosdaal, Herent, Hasselt 27, 115, 134, 160
1000	14 142 204	17,02	Boechout, Oud-Turnhout, Roosdaal, Herent, Hasselt 3, 61, 115, 134, 160
1500	10 823 978	13,03	Kontich, Herenthout, Oud-Turnhout, Roosdaal, Bertem, Sint-Truiden, Bree 14, 51, 61, 115, 127, 165, 172
1600	9 832 171	11,84	Kontich, Herenthout, Oud-Turnhout, Roosdaal, Kortenberg, Lubbeek, Bocholt, Alken 14, 51, 61, 115, 140, 143, 171, 183
2000	8 422 123	10,14	Boechout, Schelle, Olen, Oud-Turnhout, Steenokkerzeel, Roosdaal, Bierbeek, Kortenaken, Bocholt, Wellen 3, 20, 60, 61, 110, 115, 128, 139, 171, 193
2500	7 316 299	8,81	Boechout, Schelle, Herenthout, Oud-Turnhout, Kampenhout, Roosdaal, Wezembeek-Oppem, Geetbets, Lubbeek, Ham, Bocholt, Wellen 3, 20, 51, 61, 99, 115, 121, 132, 143, 169, 171, 193
3000	6 105 892	7,35	Boechout, Schelle, Grobbendonk, Hulshout, Merksplas, Retie, Gooik, Kampenhout, Wezembeek-Oppem, Affligem, Geetbets, Lubbeek, Ham, Bocholt, Wellen 3, 20, 49, 54, 58, 63, 94, 99, 121, 123, 132, 143, 169, 171, 193

In Figure 3, Figure 4 and Figure 5 (provincies.incijfers.be, n.d.) we look at where the facilities are placed in the three situations explained above when the organizations received funding to place respectively 4, 8 and 12 facilities (indicated in Tables 8, 9, 10). We indeed see that distribution centers delivering water to the whole country (blue dots) are mostly located at city centers, whereas medical facilities (red dots) are placed in the city periphery. If a WASH organization prioritizes rural areas, then their facilities (green dots) are located further away from big city centers.

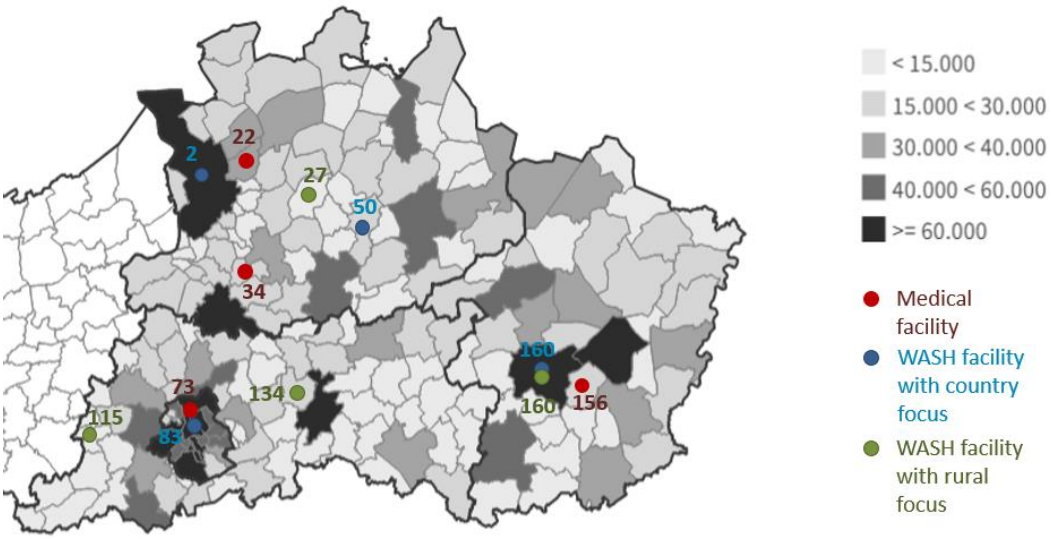

Figure 3: Map of Antwerp, Flemish Brabant, Limburg with 4 independent facilities for each organization

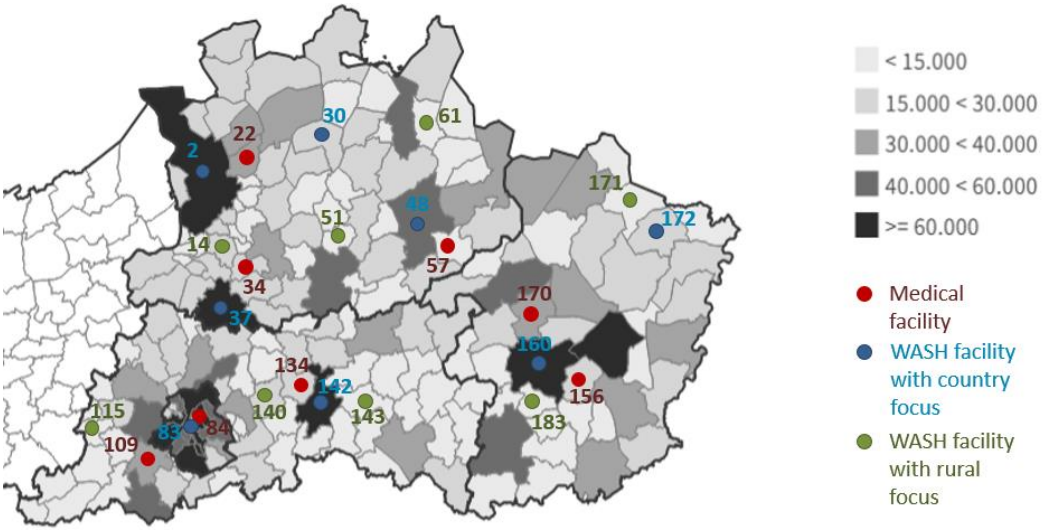

Figure 4: Map of Antwerp, Flemish Brabant, Limburg with 8 independent facilities for each organization

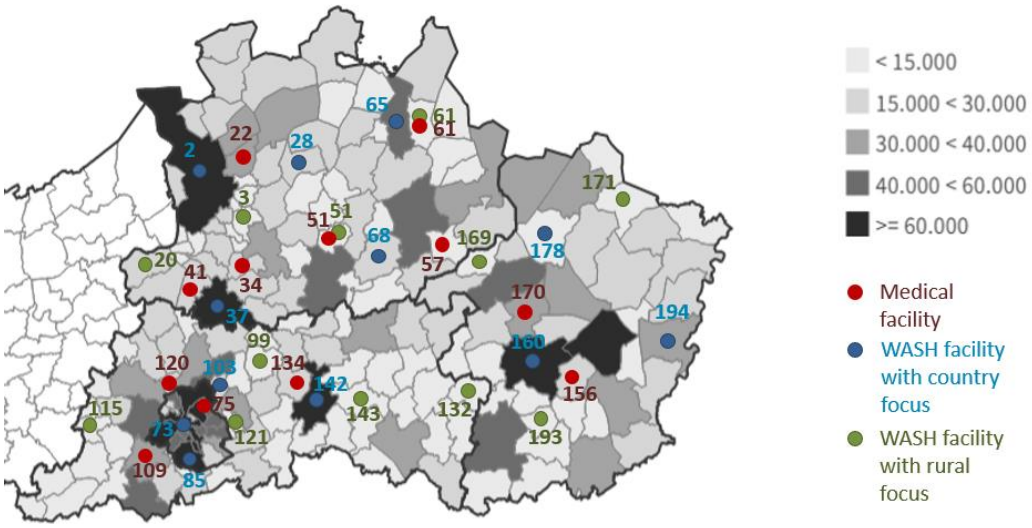

Figure 5: Map of Antwerp, Flemish Brabant, Limburg with 12 independent facilities for each organization

Globally, the red and blue facilities lie closer together than red and green facilities, suggesting that coordination opportunities could be higher in the first case. After all, both the medical organization and the WASH organization focus on maximizing volume across the whole affected area. That is not to say that there are no opportunities for cooperation between a medical organization and a WASH organization focusing on rural areas. On the contrary, in Figure 5 there are even two locations (51, 61) where both organizations want to place a facility.

5.3 Set covering as ideal situation

When setting the threshold distance to 10 km, which is considered here as the maximum distance to receive qualitative aid of all types, there should be 39 multifunctional facilities placed. In Figure 6 (provincies.incijfers.be, n.d.), we see that they are more evenly spaced.

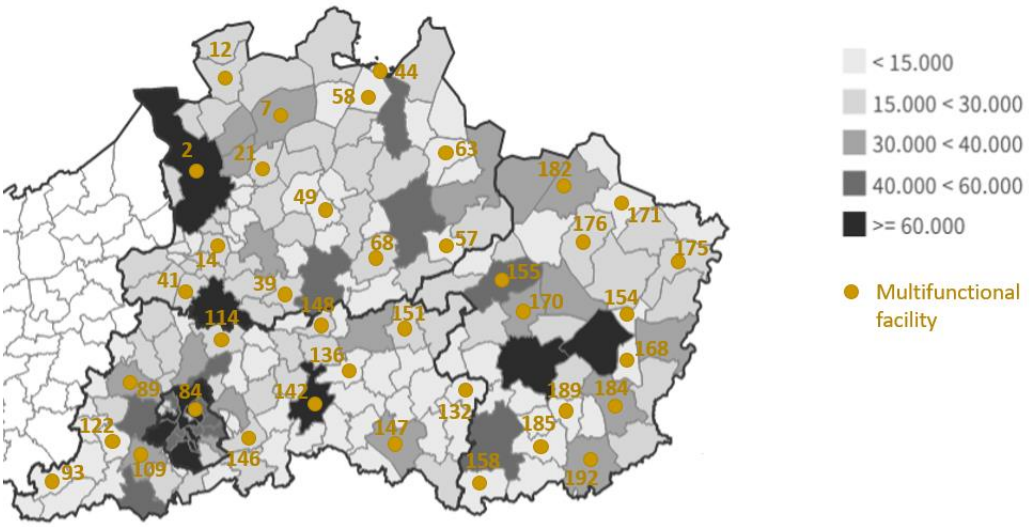

Figure 6: Map of Antwerp, Flemish Brabant, Limburg with 39 multifunctional facilities according to set covering model

From the results above, we know that rural areas are less likely to be served in a qualitative way when focusing on the population overall. Indeed, facilities are located close to densely populated areas since organizations want to reach high volumes given their financial situation. The budget that is at the government's disposal can then be used to focus on rural areas, for example, by procuring and installing water pumps there so that they can provide in clean water themselves or by dispatching mobile medical units that visit distant rural areas. In this way the total number of facilities increases and the total number of people receiving aid too.

If the humanitarian organizations work together, it may be possible to realize economies of scale when placing facilities, which will also lead to a higher number of facilities. For the government acting as a coordinator, it is then necessary to think about which locations should be selected for which facilities, a decision that can be supported by the multicriteria model.

5.4 Multicriteria optimization

The multicriteria model can allow for a coordinated approach in facility placement because the organizations can benefit from cost savings when placing joint facilities. Since two different objectives need to be optimized, a Pareto frontier of alternate solutions can be established. The government acts as the coordinator and can settle on a certain solution on the frontier that it proposes to the organizations.

Acceptance principle: An organization i with a private objective can accept a proposal for coordinated facility placement if they can get at least as much benefit from this configuration as from installing facilities independently for a given budget. This is also known as the

individual rationality constraint: $f_{i,coordinated}(x) \leq f_{i,uncoordinated}(x)$ for a minimization problem.

The existence of such an acceptable proposal is consistent with proposition 1: when optimizing independently, the result could be suboptimal. If both organizations can improve their objective functions by coordinating, they will do this voluntarily. However, the Pareto frontier also contains solutions that improve the situation for only one organization. Should the government prefer this solution, they should incentivize the organization whose objective value initially deteriorates in this case and they could use the multicriteria model to do this. Here, we focus on monetary incentives given by the government, but they can also give other incentives e.g. priority access to the (air)port…

We can now identify three cases which indicate whether coordination is possible or not:

1. Both organizations could possibly set up more facilities by joining forces:

$$\left\lfloor \frac{B_{wash}}{\mu F_3} \right\rfloor > \left\lfloor \frac{B_{wash}}{F_1} \right\rfloor \text{ and } \left\lfloor \frac{B_{med}}{(1-\mu)F_3} \right\rfloor > \left\lfloor \frac{B_{med}}{F_2} \right\rfloor$$

   The maximum number of joint facilities possible is given by $\min\{\left\lfloor \frac{B_{wash}}{\mu F_3} \right\rfloor, \left\lfloor \frac{B_{med}}{(1-\mu)F_3} \right\rfloor\}$.

   Both organizations can potentially benefit and there are coordination opportunities.

2. Only one organization could benefit from coordination (here the medical organization):

$$y = \left\lfloor \frac{B_{wash}}{\mu * F_3} \right\rfloor \leq \left\lfloor \frac{B_{wash}}{F_1} \right\rfloor \text{ and at least one of the following conditions is satisfied for}$$

$$k \in \{1, \dots, y\}: k + \left\lfloor \frac{B_{med} - k*(1-\mu)*F_3}{F_2} \right\rfloor > \left\lfloor \frac{B_{med}}{F_2} \right\rfloor .$$

   To capitalize on the benefits of coordination, the other organization needs an incentive.

3. Neither organization can place more facilities by coordinating:

$$\left\lfloor \frac{B_{wash}}{\mu * F_3} \right\rfloor \leq \left\lfloor \frac{B_{wash}}{F_1} \right\rfloor \text{ and } \left\lfloor \frac{B_{med}}{(1-\mu)F_3} \right\rfloor \leq \left\lfloor \frac{B_{med}}{F_2} \right\rfloor$$

   There is no opportunity to potentially improve their objective function values. Coordination is not necessary.

The extent of coordination opportunities depends on the objective functions. Here, all objectives take a utilitarian point of view because all organizations have to justify their funding. However, when the location preferences are similar enough, organizations could potentially benefit more than when they have a preference for more different facility locations.

In case 3, the organizations optimize their facility location decision independently as they do in sections 5.1 and 5.2. We will look at examples of case 1 in sections 5.4.1-2 and at examples of case 2 in section 5.4.3. To solve the examples, the epsilon constraint method is used. Moreover, we assume that the costs for a joint facility are split in an egalitarian way: $\mu = \frac{F_1}{F_1+F_2}$ and $(1-\mu) = \frac{F_2}{F_1+F_2}$. This gives the organizations an equal percentagewise cost advantage.

5.4.1 Coordination for separate budgets and joint area

Suppose both organizations have raised the same budget of 2.0 million after the earthquake has struck and that the cost for a joint facility is 360,000 (20% cost reduction compared to placing two separate facilities at the same location). Thus, $\left\lfloor \frac{B_{wash}}{\mu F_3} \right\rfloor = 12 > \left\lfloor \frac{B_{wash}}{F_1} \right\rfloor = 10$ and $\left\lfloor \frac{B_{med}}{(1-\mu)F_3} \right\rfloor = 10 > \left\lfloor \frac{B_{med}}{F_2} \right\rfloor = 8$ and both organizations could potentially benefit. Furthermore, the maximum number of joint facilities is 10. We have two objectives in the multicriteria model, so we can analyze this situation by constructing the Pareto frontier (Figure 7).

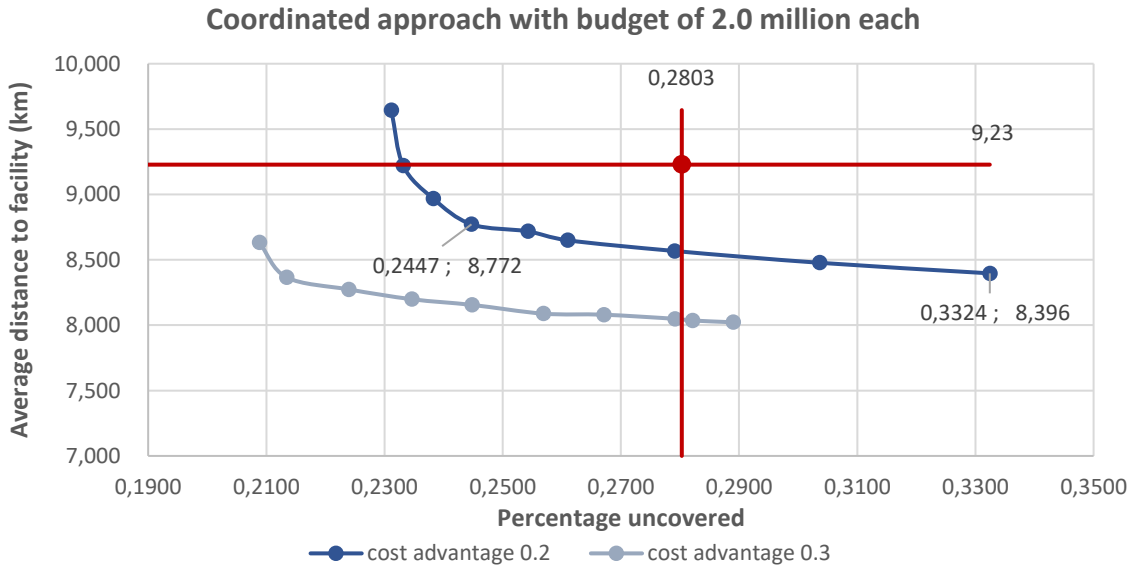

Figure 7: Pareto frontier for multicriteria model with a budget of 2.0 million for each organization

When planning the facility locations with the multicriteria model, coordination can be reached when a set of facilities is chosen in such a way that the resulting objective values are located in the bottom left quadrant. The red lines indicate the minimum objective values needed (see section 5.1 and 5.2) for each organization to accept the proposal. For instance, the point indicated on the dark blue curve results in 24.47% of the injured uncovered with an average distance to water and sanitary products of 8.77 km. This is a better result than when the

organizations would operate independently (red dot) because then 28.03% of the injured people would be uncovered and the average distance would be 9.23 km to get access to water, which is an illustration of proposition 1.

If the government decides to place more emphasis on lowering the distance to WASH distribution points, this can lead to a point on the Pareto frontier past the maximum acceptable limit for medical care, for example the point on the far right. In this case, the medical organization needs an incentive to accept. To this end, the government could transfer part of its budget to the medical organization so that they can set up additional facilities (Table 11), but they would need to give at least 0.5 million so that less than 28.03% of the population is uncovered. The government could also opt to provide the WASH organization with a slightly larger budget. Although this may seem counterintuitive, it allows for a different configuration of facilities that benefits both organizations as is evidenced by comparing rows 1 and 5. The second option thus induces a higher incentive for the medical organization for a lower budget offered by the government and is in short more effective in generating a coordinated approach.

Table 11: Incentives given by government to get medical organization to enter the coordination agreement

scenario	budget medical ('000 €)	budget WASH ('000 €)	min uncovered objective	min uncovered (people)	min uncovered percentage	min distance (km)	average distance (km)	medical facilities	WASH facilities	joint facilities
base case	2000	2000	optimize given min distance	634 061	0,3324	43 915 768	8,396	/	68, 178	2, 28, 37, 65, 73, 85, 103, 142, 160, 194
government sponsers medical organization	**2250**	2000	optimize given min distance	578 876	0,3035	43 915 768	8,396	31	68, 178	2, 28, 37, 65, 73, 85, 103, 142, 160, 194
	2500	2000	optimize given min distance	523 719	0,2746	43 915 768	8,396	31, 156	31, 178	2, 28, 37, 65, 68, 73, 85, 103, 142, 194
	2750	2000	optimize given min distance	473 601	0,2483	43 915 768	8,396	31, 156, 170	31, 178	2, 28, 37, 65, 68, 73, 85, 103, 142, 194
government sponsers WASH organization	2000	**2200**	optimize given min distance	455 471	0,2388	43 891 937	8,392	/	2, 132, 172	22, 34, 57, 65, 73, 104, 109, 134, 156, 170

In the example given above, the benefits of coordination are rather limited. If the cost advantage for placing a joint facility would be bigger, then the improvement in objective function values of both organizations will also be bigger and thus they will have a higher incentive to coordinate, as is illustrated in Figure 7 with a cost reduction of 30% (315,000 per joint facility). We see that in this case, the WASH organization will always benefit from working together with the medical organization since the light blue curve is completely below the line indicating their minimum objective value for entering the coordination agreement.

If we now also consider the case where both organizations managed to raise a higher budget, that is 3.0 million, we observe the same trend (Figure 8). For the 30% cost advantage (light

blue curve), it is possible to attain a 5.3% increase in injured people treated while simultaneously lowering the average distance by 1.3 kilometers. Another possibility would be to realize an even larger increase in injured people treated compared to the uncoordinated approach (8%), but this goes at the expense of accessibility to WASH products (now only 0.9 km less). In an emergency situation where only a limited budget is available there are always trade-offs to be made. It is up to the government (in consultation with humanitarian professionals) to decide on a point on the Pareto frontier depending on the situation at hand.

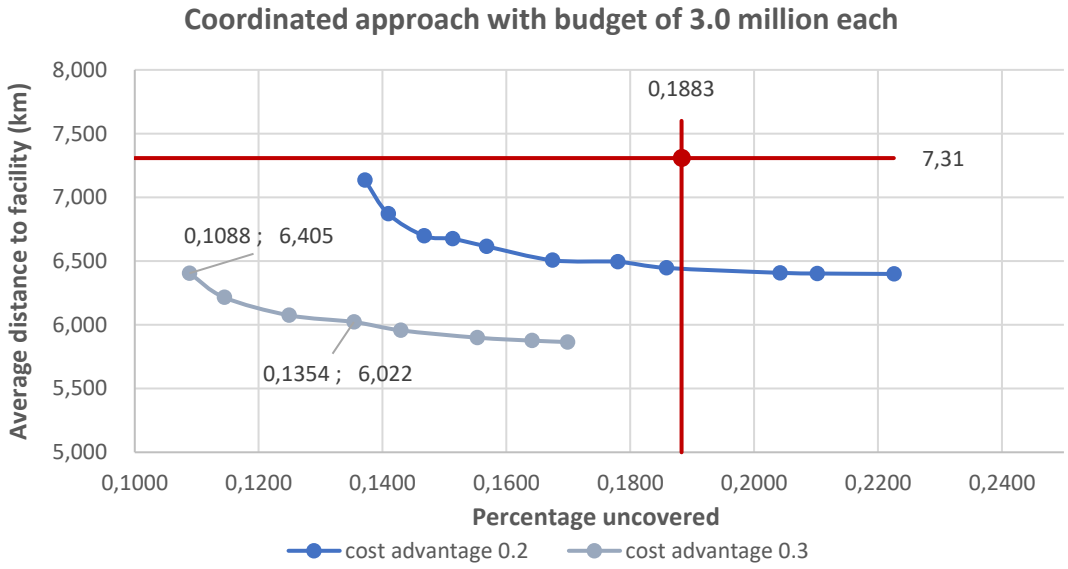

Figure 8: Pareto frontier for multicriteria model with a budget of 3.0 million for each organization

Since all humanitarian organizations compete for funding from donors, it is likely that the budgets at the disposal of these organizations will differ. The findings from above still hold. In general, significant improvements can be realized by coordinating the placement of facilities and the possibility of setting up joint facilities can be fully exploited. The location preferences resemble each other close enough so that joining forces effectively results in more people served by placing more facilities. Furthermore, higher budgets lead to more people that are served, but also the benefits of coordination are slightly higher. Since media attention influences the level of funding, the government should facilitate media coverage on the site of the disaster and ensure that media crews are protected when doing so.

5.4.2 Coordination for separate budgets and different area

Now we look at the situation where the objectives of the organizations on the scene differ more from each other. The objective of the medical organization is unchanged, that is they

want to maximize medical care within 10 km from the earthquake victims who are mostly located in urban areas. The objective of the other organization is to provide water to rural areas (the set I'). In Figure 9, the Pareto frontiers are once more constructed for economies of scale of 20% and 30% and for a budget of 2.0 million (dashed curves) and 3.0 million (full curves) for each organization.

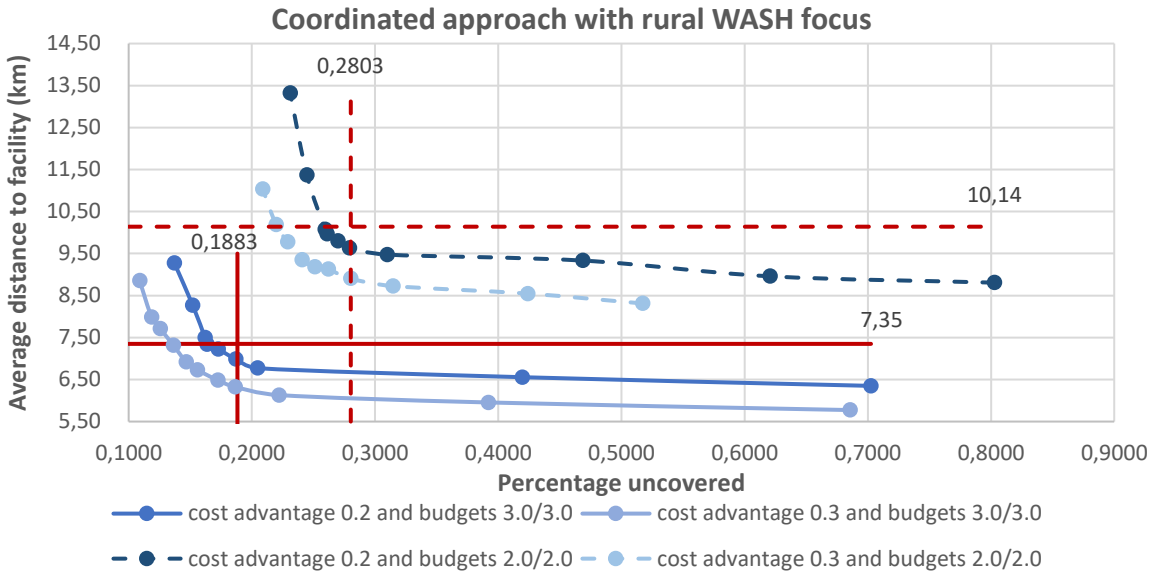

Figure 9: Pareto frontier for multicriteria model with separate budgets and different area focus

Giving full priority to either objective results in a large improvement for given objective at the expense of the other objective, as can be seen from the extreme points on the graph. The potential benefits are smaller than for the cases analyzed in section 5.4.1 where the WASH organization considers the whole population. Also, solutions in the bottom left quadrants contain only a limited number of joint facilities. Since the objectives are rather different, they cannot fully exploit the cost advantages from setting up a joint facility and each organization opts to install some specialized facilities too.

The government can once again give monetary incentives to the organizations if they prefer a solution outside the bottom left quadrant. However, there is another action the government could take. Up to now, we assumed that all facilities present before the disaster were destroyed. Of course, each country has operational hospitals before the onset of the earthquake. The government could therefore repair some of those hospitals, which could result in the medical organization focusing more on rural areas too, since the hospitals in the cities are already present then.

We assume that the government uses the objective of the medical organization to select the hospitals to repair and that the medical organization can still send medical supplies and personnel to those hospitals. In this case, it is in the organization's interest to reveal their objective truthfully because they can attain the best outcome by doing so. In practice, the government may have to deal with asymmetric information and this could potentially lead to a different outcome.

Let us consider the case where both organizations have a budget of 2.0 million and the cost for a joint facility is 360,000 since this is where there are the fewest possibilities for coordination without intervention of the government. From the list of Belgian hospitals (Wikipedia, n.d.), general purpose hospitals of at least 100 beds are considered to be repaired by the government. Let $G \subset J$ be the set of municipalities with such a hospital. Then we add the following constraint to the multicriteria model to impose that the government repairs M hospitals of the given set: $\sum_{g \in G} x_{g2} \leq M$. We adapt constraint (17b) as follows: $\sum_{j \in J} F_{j2} x_{j2} + (1-\mu) F_{j3} x_{j3} \leq B_{medical} + \sum_{g \in G} F_{g2} x_{g2}$. This is essentially the same as the government depositing funds to the medical organization, but the difference is now that the additional facilities must be placed within a set of predefined locations.

As can be seen in Figure 10, repairing more hospitals can reduce the number of untreated patients significantly, whereas the potential improvements for the WASH organization are limited because they still have a limited budget. The best possible objective value for the WASH organization is an average distance of 8.81 km no matter how many hospitals are repaired.

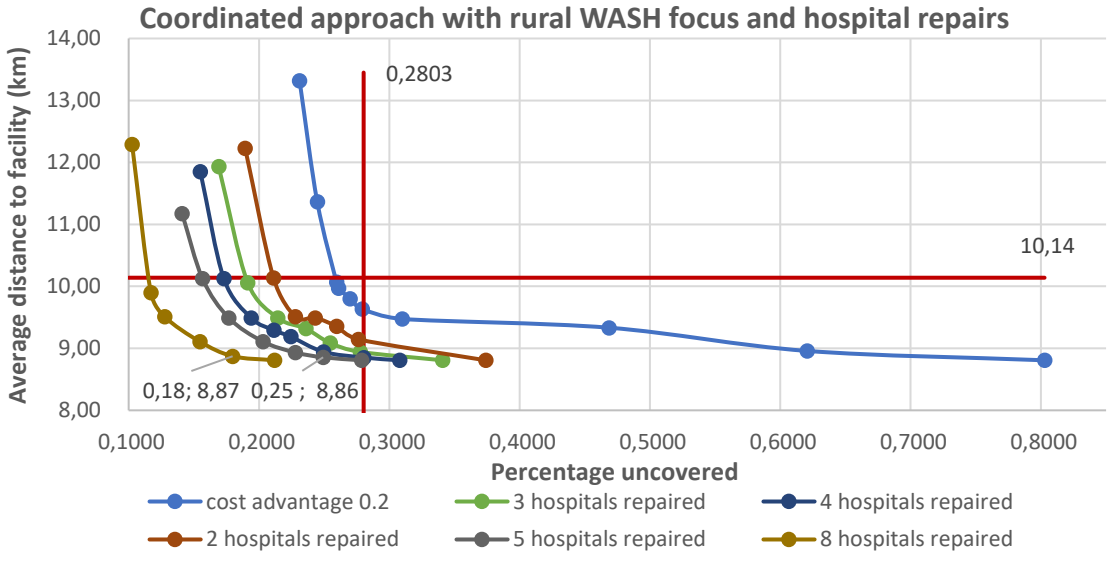

Figure 10: Pareto frontier for multicriteria model with a budget of 2.0 million for each organization and hospital repairs

We observe that with 4 repaired hospitals the limit of 8.81 km is already reached within the boundaries of the bottom left quadrant. Repairing more hospitals will therefore only benefit the objective of the medical organization. Thus, the curve moves to the left with every repairment but does not move downwards. For example, by repairing 5 hospitals it would be possible to attain a 3% decrease in uncovered population, while realizing an average distance of 8.86 km, which is almost optimal. With 8 repaired hospitals a decrease of 10% can be attained for approximately the same average distance.

Although these repairments are necessary in view of the recovery phase, it would be better to also give an amount of money to the WASH organization since this would shift the whole curve to the lower left and then better coordinated solutions could be reached with a lower total budget.

5.4.3 Coordination opportunities for one organization only

There exists a set of scenarios where coordination cannot readily be achieved. We look at the case where the WASH organization that considers the whole population has a lower budget then the medical organization, but similar results hold for the reversed situation.

For $B_{wash} = 0.625\,million$ and $F_3 = 360{,}000$, it holds that $\left\lfloor \frac{B_{wash}}{\mu * F_3} \right\rfloor = 3 \leq \left\lfloor \frac{B_{wash}}{F_1} \right\rfloor = 3.$

For $B_{med} = 1.4\,million$ and $k \in \{2,3\}$, it holds that $k + \left\lfloor \frac{B_{med} - k*(1-\mu)*F_3}{F_2} \right\rfloor = 6 > \left\lfloor \frac{B_{med}}{F_2} \right\rfloor = 5.$

So, the medical organization can potentially benefit from coordination, but the WASH organization has currently no incentive to do so. Either the government gives them enough money from their budget so that they too can open one more facility or, if it is not too tightly earmarked, the medical organization can contribute any leftover funds.

When the WASH organization optimizes its own operations without taking other organizations into account, they attain an average distance of 17.37 km (Table 12). When using the multicriteria model, their optimal objective is evidently still the same. However, if the objective of the medical organization is prioritized, the best attainable objective value for the WASH organization becomes 18.28 km on average. The WASH organization does not want to coordinate voluntarily, but the medical organization can realize a maximum decrease of uncovered population from 37.44% to 33.45%. In this case, the WASH organization needs to be incentivized. The minimum amount should be $\min_k F_1 - (B_{wash} - k\mu F_3 - (y-k)F_1)$,

which is what is still needed to install one more facility and equal to 55,000 in this situation (last row). Remark that if $B_{med} \in [1{,}455{,}000; 1{,}500{,}000[$, the budget needed to incentivize them could also come from the medical organization, who benefits from donating the money.

Table 12: Situation in which WASH organization cannot place more facilities by coordinating and needs to be incentivized

scenario	budget medical ('000 €)	budget WASH ('000 €)	min uncovered objective	min distance objective	min uncovered (people)	min uncovered percentage	min distance (km)	average distance (km)	medical facilities	WASH facilities	joint facilities
optimize independently	1 400	0	optimal	/	714 045	0,3744	/	/	22, 34, 84, 109, 156	/	/
	0	625	/	optimal	/	/	90 864 014	17,37	/	16, 83, 160	/
multicriteria model	1 400	625	optimal	optimize given min uncovered	638 029	0,3345	95 583 590	18,28	34, 84, 109, 134	83	22, 156
	1 400	625	optimize given min distance	optimal	701 089	0,3676	90 864 014	17,37	22, 114, 134, 156	160	16, 83
multicriteria model, WASH organization gets incentive	1 400	**680**	<= 638 029	optimize given constraint	638 029	0,3345	85 103 403	16,27	34, 109, 134	48	22, 84, 156

For the WASH organization with rural focus, we can perform the same analysis. We obtain similar results and can draw the same conclusions. This may seem counterintuitive because the objective functions are now more different from each other, which can lead one to think that they will not set up a joint facility. However, the budget of the WASH organization is limited and allows for the placement of three facilities at most. Since rural areas are spread around the urban centers as can be seen on Figure 3 and since the WASH organization is minimizing the total distance to all these rural areas, the joint facilities are placed somewhat in the middle and thus in the city periphery like the medical facilities. The larger the budget of the WASH organization, the more their facilities will move away from these urban centers (Figures 4, 5).

5.5 Dynamic multicriteria model

After the disaster, money becomes available gradually and funding levels are highest right after the disaster. In this context, the dynamic model serves to indicate which facilities should be built when. We take the example where $F_3 = 360{,}000$, the medical organization raises 2.5 million in total over three periods and the WASH organization 1.6 million. Moreover, we assume that the government gives priority to medical care and minimizes the uncovered injured population. The results are shown in Table 13.

If the money is raised according to the scheme in the first row (base case), the budget of the WASH organization is sufficiently large so that the medical organization can place the maximum number of joint facilities in each period. However, the WASH organization needs an incentive to accept this facility placement proposal since they can obtain an average distance

of 14.50 km when operating independently in period 1. This is shown in Figure 11 where the red dashed lines indicate the minimum objective function value per period based on the cumulative budget up to that period. Although the incentive of 0.2 million given in period 1 is big enough to satisfy the organization in the next periods, it is insufficient for the first period. Since response time is of the utmost importance in an emergency situation, the WASH organization will probably prefer a higher objective value compared to placing its facilities independently in period 1 over a situation that only promises a better objective value in the future. Indeed, the incentive of 0.4 million results in an acceptable proposal with 2 specialized facilities in period 1 (row 3) from which the benefits pass on to the next periods.

Table 13: Dynamic multicriteria model for three periods with budgets 1.3/0.8/0.4 and 0.8/0.5/0.3 million

scenario	budget medical ('000 €)	budget WASH ('000 €)	min uncovered objective	min distance objective	min uncovered (people)	min uncovered percentage	min distance (km)	average distance (km)	medical facilities	WASH facilities	joint facilities
base case	1300	800	optimal	optimize given min uncovered	640 156	0,3356	85 769 806	16,40	34	/	22, 75, 109, 134, 156
	800	500			440 879	0,2312	66 887 477	12,79	+ 170	/	+ 51, 57, 104
	400	300			359 447	0,1885	60 637 033	11,59	-	/	+ 61, 150
government gives incentive to WASH organization	1300	**1000**	optimal	optimize given min uncovered	640 156	0,3356	76 742 416	14,67	75	73	22, 34, 109, 134, 156
	800	500			440 879	0,2312	59 950 180	11,46	+ 51	-	+ 57, 104, 170
	400	300			359 447	0,1885	53 295 681	10,19	-	-	+ 61, 150
government gives incentive to WASH organization	1300	**1200**	optimal	optimize given min uncovered	640 156	0,3356	64 592 474	12,35	22	2, 59	34, 75, 109, 134, 156
	800	500			440 879	0,2312	56 089 824	10,72	+ 57	-	+ 51, 104, 170
	400	300			359 447	0,1885	50 210 236	9,60	-	-	+ 61, 150

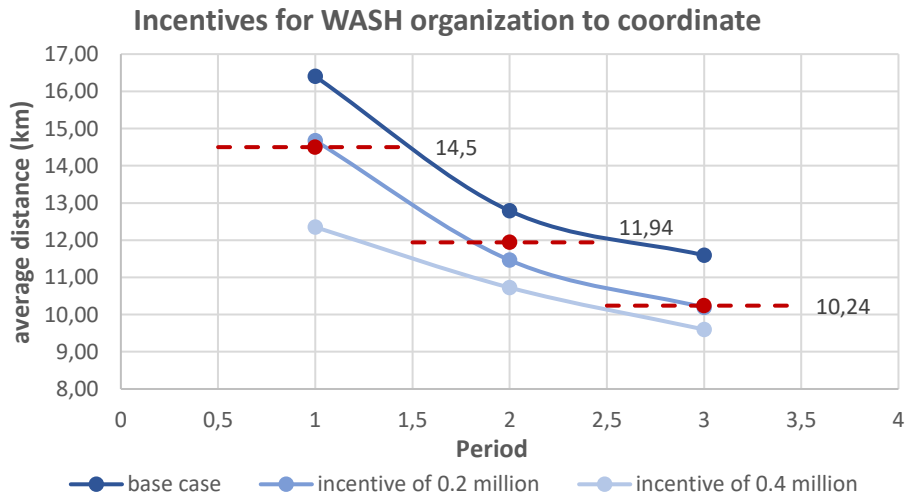

Figure 11: Dynamic multicriteria model with incentives for WASH organization to agree to coordinated approach

If the WASH organization would already start with a budget of 1.2 million, then we obtain the results in Table 14. From row 1 we can derive that the WASH organization contributes

$6 * \mu F_3 = 0.96$ million to the construction of the joint facilities in period 1, which means that part of the budget of the WASH organization is transferred to period 2 to set up enough joint facilities then. This is a result of the prioritization of the medical objective by the government. However, the WASH organization will never agree with this since they have the funds to set up an extra specialized facility in period 1 and in a disaster context quick response time is highly important. Row 2 considers the scenario in which the WASH organization does this. This can be enforced in the model by adding the constraint:

$$\sum_{r=1}^{t} B_{wash} - \sum_{j \in J} \sum_{r=1}^{t} F_1(x_{j1,r} - x_{j1,r-1}) + \mu F_3(x_{j3,r} - x_{j3,r-1}) < F_1 \quad \forall t \in T \backslash \{0\}$$

and a similar one for the medical organization. Now, the medical organization cannot reach the same objective value anymore at the end because they can place only 11 facilities overall instead of 12. The objective value of the WASH organization improves in the first period, but is slightly worse in the second and third period and they would still need an incentive. Indeed, Figure 11 shows that when a cumulative budget of 1.6 million is reached (in period 3), the minimum objective value is 10.24 km on average. The most effective solution in this case is to give the WASH-organization once again an incentive of 0.4 million in period 1 (row 3).

Table 14: Dynamic multicriteria model over three periods with budgets 1.3/0.8/0.4 and 1.2/0.4/0 million

scenario	budget medical ('000 €)	budget WASH ('000 €)	min uncovered objective	min distance objective	min uncovered (people)	min uncovered percentage	min distance (km)	average distance (km)	medical facilities	WASH facilities	joint facilities
base case	1300	1200	optimal	optimize given min uncovered	640 156	0,3356	79 959 641	15,29	/	/	22, 34, 75, 109, 134, 156
	800	400			440 879	0,2312	60 739 702	11,61	/	/	+ 51, 57, 104, 170
	400	0			359 447	0,1885	60 739 702	11,61	61, 150	/	-
WASH organization places 1 facility in period 1	1300	1200	optimal	optimize given min uncovered	640 156	0,3356	68 099 577	13,02	/	48	22, 34, 75, 109, 134, 156
	800	400			440 879	0,2312	61 915 359	11,84	51, 57	-	+ 104, 170
	400	0			398 291	0,2088	61 915 359	11,84	+ 61	-	-
WASH organization places 1 facility in period 1, government gives incentives	1300	**1600**	optimal	optimize given min uncovered	640 156	0,3356	57 306 587	10,96	/	2, 48, 70	22, 34, 75, 109, 134, 156
	800	400			440 879	0,2312	51 621 538	9,87	51, 57	-	+ 104, 170
	400	0			398 291	0,2088	51 621 538	9,87	+ 61	-	-

Of course, funding is uncertain and it is difficult to predict in period 1 what the budget for period 3 will be. The dynamic model thus mainly serves to set priorities for facility locations based on budgetary estimates. The government should be cautious when optimizing the model, because transferring money that could be used for facility placement now to a later period to get better results in that period does not reflect the reality of a disaster.

6 Conclusion

6.1 Scientific contributions

This study forms the basis of a planning tool for coordinating the facility placement process of humanitarian organizations that have their own private objectives after an earthquake. It is based on the multicriteria model that acknowledges that each organization uses its own resources to achieve its objectives because of donor accountability, while also considering that organizations could benefit from economies of scale through coordination. We establish that when the organizations do not coordinate, the result may be suboptimal. When coordination is considered as a possibility, the multiple objectives in the multicriteria model result in the construction of a Pareto frontier with alternate solutions to choose from. The government, in its capacity as coordinator, must make trade-offs between these objectives and must propose a facility configuration to the organizations, who will only accept this if it improves their objective function value. The multicriteria model helps the government in generating an acceptable proposal by identifying what the opportunities for coordination are through three separate cases: both organizations can potentially place more facilities, only one organization can do so, or neither organization can increase the number of facilities. Relying on the acceptance principle, the model also demonstrates how coordination could be reached should one of the organizations need to be incentivized. Finally, the dynamic multicriteria model helps the coordinator to establish priorities for the actions to be taken, i.e. which facilities should be built where and in what order.

Additionally, since the model and objectives are kept rather generic, this tool might also be useful in other disaster contexts. Also, the constraining resource can be something else than money. Furthermore, the limited number of constraints and variables makes the model understandable for practitioners too.

6.2 Managerial contributions

The multicriteria approach helps the government decide how to organize humanitarian organizations with different goals and how they should use their own budget to facilitate coordination and to help their population. This study focuses on a medical and a WASH organization, but the approach holds for other scenarios with goal conflicts as well. Coordination opportunities can be identified by means of the acceptance principle. The

government can analyze the impact of providing incentives for a certain organization on their objective function values, which comes down to the impact on accessibility of WASH facilities and on the number of people that can receive medical care in this study. Doing so allows the government to provide the incentives in the most effective way so that they have more budget left themselves to invest in other post disaster activities during the response and recovery phase. Similarly, they can evaluate the effect of repairing existing facilities on the placement of emergency facilities. Furthermore, the government can identify which areas are not covered by the facilities of the humanitarian organizations and they can take measures accordingly. For instance, they can use their budget to send medical teams to rural areas, if these areas are not yet served by humanitarian organizations. Finally, a larger budget can facilitate more coordination opportunities and can serve more people. Therefore, it is important that the government allows media crews access to the scene, since media coverage of the disaster impacts the funding level of donors.

As for the humanitarian organizations themselves, they are guided in placing their facilities and can as a result reach more people with the same budget. This is good from a societal point of view but also from a financial point of view, since this increase in objective function value increases their chances of receiving repeat funding from their donors at the same time.

6.3 Societal contributions

The nature of the application this study proposes, in itself, clearly shows its importance for society. By improving the facility location process through a coordinated approach, it is possible to reach more people in distress than without such an approach. It immediately serves the common goal of the government and the humanitarian organizations: alleviating the suffering of the people. In the long term, this will also have a positive effect on the recovery phase.

6.4 Limitations and further research

This study is subject to a few limitations that could be elevated by future research.

- The government may face an information problem when determining the objectives of the organizations. Each organization has its private and strategic objectives, which they do not always readily share with third parties. Because of this information asymmetry, the government can only infer the objectives from actions taken in previous disaster

emergencies. Those actions are observable to some extent as organizations communicate about their efforts through the media to satisfy donors.

- As for the scope of the facility location problem, we studied it here without allocating supplies to these facilities and without establishing a distribution plan. This could be added to the model to come to an integrated approach. Also, the capacity of the facilities might be considered.
- We assumed that the state of the population and the region in the aftermath of the earthquake is known and stays constant. Therefore, we made estimates about the parameters, but obtaining real life data after a disaster has struck might prove to be difficult and people can move in response to the construction of facilities, which can in turn impact the placement of the next facilities. The impact of the earthquake could be assessed by experienced professionals on the ground and this can be supplemented by satellite data and mobile phone data to get an overview of the situation and of the number of people migrating to another zone.
- Beforehand, there is uncertainty about where and when the disaster will strike, what the impact of the disaster will be and whether there will be aftershocks. This study adopted deterministic models, but it might be a good idea to transform them into stochastic models that take this uncertainty into account. For example, when accounting for the fact that the location of the disaster will be uncertain, one can use probabilities or scenarios and optimize the model to obtain the least bad outcome. Similarly, the health effects of the disaster could be randomly distributed throughout the affected region and could be taken into account with stochastic modelling.
- The computing power of the device used is rather limited. As a consequence, the size of the instances run is limited too. However, real life instances can be larger than the one tested here, so it might be beneficial to use a more performant device and to look for a good heuristic when computing time increases.
- It would also be interesting to run and investigate the model with real life disaster data instead of the data used here to simulate an earthquake. Furthermore, it can be valuable to consult certain humanitarian organizations about their objectives, which can open up discussion with the government about their objectives and trade-offs too.

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Appendices

Appendix 1: Population data

CityID	Niscode	Municipality	Population
1	11001	Aartselaar	14 752
2	11002	Antwerpen	538 910
3	11004	Boechout	13 806
4	11005	Boom	19 062
5	11007	Borsbeek	11 309
6	11008	Brasschaat	38 575
7	11009	Brecht	30 387
8	11013	Edegem	22 761
9	11016	Essen	19 629
10	11018	Hemiksem	12 105
11	11021	Hove (Antwerpen)	8 444
12	11022	Kalmthout	19 422
13	11023	Kapellen (Antwerpen)	27 743
14	11024	Kontich	21 624
15	11025	Lint	8 548
16	11029	Mortsel	26 391
17	11030	Niel	10 799
18	11035	Ranst	19 609
19	11037	Rumst	15 417
20	11038	Schelle	8 662
21	11039	Schilde	20 293
22	11040	Schoten	34 360
23	11044	Stabroek	18 837
24	11050	Wijnegem	10 432
25	11052	Wommelgem	13 230
26	11053	Wuustwezel	21 644
27	11054	Zandhoven	13 352
28	11055	Zoersel	22 427
29	11056	Zwijndrecht	19 547
30	11057	Malle	16 007
31	12002	Berlaar	11 949
32	12005	Bonheiden	15 458
33	12007	Bornem	21 982
34	12009	Duffel	17 982
35	12014	Heist-op-den-Berg	44 226
36	12021	Lier	37 909
37	12025	Mechelen	88 614
38	12026	Nijlen	23 409
39	12029	Putte	18 631
40	12035	Sint-Katelijne-Waver	21 595
41	12040	Willebroek	27 773
42	12041	Puurs-Sint-Amands	26 772

43	13001	Arendonk	13 344
44	13002	Baarle-Hertog	3 012
45	13003	Balen	23 308
46	13004	Beerse	18 416
47	13006	Dessel	9 805
48	13008	Geel	41 828
49	13010	Grobbendonk	11 519
50	13011	Herentals	28 575
51	13012	Herenthout	9 417
52	13013	Herselt	14 805
53	13014	Hoogstraten	22 245
54	13016	Hulshout	10 564
55	13017	Kasterlee	19 478
56	13019	Lille	16 871
57	13021	Meerhout	10 348
58	13023	Merksplas	8 799
59	13025	Mol	38 159
60	13029	Olen	12 689
61	13031	Oud-Turnhout	14 734
62	13035	Ravels	15 338
63	13036	Retie	11 841
64	13037	Rijkevorsel	12 531
65	13040	Turnhout	46 923
66	13044	Vorselaar	8 044
67	13046	Vosselaar	11 802
68	13049	Westerlo	25 466
69	13053	Laakdal	16 707
70	21001	Anderlecht	125 065
71	21002	Oudergem	35 346
72	21003	Sint-Agatha-Berchem	25 396
73	21004	Brussel	194 291
74	21005	Etterbeek	49 558
75	21006	Evere	44 255
76	21007	Vorst (Brussel-Hoofdstad)	57 724
77	21008	Ganshoren	25 548
78	21009	Elsene	88 521
79	21010	Jette	53 704
80	21011	Koekelberg	22 563
81	21012	Sint-Jans-Molenbeek	98 270
82	21013	Sint-Gillis	49 323
83	21014	Sint-Joost-ten-Node	27 068
84	21015	Schaarbeek	130 775
85	21016	Ukkel	86 101
86	21017	Watermaal-Bosvoorde	25 392
87	21018	Sint-Lambrechts-Woluwe	59 778
88	21019	Sint-Pieters-Woluwe	42 497
89	23002	Asse	35 191
90	23003	Beersel	26 474

91	23009	Bever	2 265
92	23016	Dilbeek	44 650
93	23023	Galmaarden	8 912
94	23024	Gooik	9 428
95	23025	Grimbergen	39 368
96	23027	Halle (Halle-Vilvoorde)	42 047
97	23032	Herne	6 763
98	23033	Hoeilaart	11 537
99	23038	Kampenhout	12 445
100	23039	Kapelle-op-den-Bos	9 659
101	23044	Liedekerke	13 877
102	23045	Londerzeel	19 288
103	23047	Machelen (Halle-Vilvoorde)	16 486
104	23050	Meise	20 239
105	23052	Merchtem	17 740
106	23060	Opwijk	14 890
107	23062	Overijse	25 978
108	23064	Pepingen	4 567
109	23077	Sint-Pieters-Leeuw	36 052
110	23081	Steenokkerzeel	12 614
111	23086	Ternat	16 488
112	23088	Vilvoorde	46 993
113	23094	Zaventem	36 408
114	23096	Zemst	23 357
115	23097	Roosdaal	11 866
116	23098	Drogenbos	5 851
117	23099	Kraainem	14 051
118	23100	Linkebeek	4 640
119	23101	Sint-Genesius-Rode	18 739
120	23102	Wemmel	17 743
121	23103	Wezembeek-Oppem	14 608
122	23104	Lennik	9 431
123	23105	Affligem	13 556
124	24001	Aarschot	30 854
125	24007	Begijnendijk	10 487
126	24008	Bekkevoort	6 672
127	24009	Bertem	10 276
128	24011	Bierbeek	10 469
129	24014	Boortmeerbeek	13 263
130	24016	Boutersem	8 527
131	24020	Diest	24 677
132	24028	Geetbets	6 263
133	24033	Haacht	15 425
134	24038	Herent	22 723
135	24041	Hoegaarden	6 797
136	24043	Holsbeek	10 158
137	24045	Huldenberg	10 080
138	24048	Keerbergen	13 196

139	24054	Kortenaken	7 970
140	24055	Kortenberg	20 920
141	24059	Landen	16 284
142	24062	Leuven	103 009
143	24066	Lubbeek	14 911
144	24086	Oud-Heverlee	11 545
145	24094	Rotselaar	17 499
146	24104	Tervuren	23 101
147	24107	Tienen	36 282
148	24109	Tremelo	15 338
149	24130	Zoutleeuw	8 668
150	24133	Linter	7 317
151	24134	Scherpenheuvel-Zichem	23 705
152	24135	Tielt-Winge	11 440
153	24137	Glabbeek	5 426
154	71002	As	8 214
155	71004	Beringen	47 895
156	71011	Diepenbeek	19 423
157	71016	Genk	67 573
158	71017	Gingelom	8 670
159	71020	Halen	9 557
160	71022	Hasselt	80 351
161	71024	Herk-de-Stad	12 817
162	71034	Leopoldsburg	16 407
163	71037	Lummen	15 366
164	71045	Nieuwerkerken (Hasselt)	7 190
165	71053	Sint-Truiden	41 353
166	71057	Tessenderlo	18 838
167	71066	Zonhoven	21 653
168	71067	Zutendaal	7 345
169	71069	Ham	11 337
170	71070	Heusden-Zolder	34 623
171	72003	Bocholt	13 743
172	72004	Bree	16 695
173	72018	Kinrooi	12 330
174	72020	Lommel	34 826
175	72021	Maaseik	25 737
176	72030	Peer	16 534
177	72037	Hamont-Achel	14 458
178	72038	Hechtel-Eksel	12 914
179	72039	Houthalen-Helchteren	30 960
180	72041	Dilsen-Stokkem	21 305
181	72042	Oudsbergen	23 791
182	72043	Pelt	34 100
183	73001	Alken	11 839
184	73006	Bilzen	32 644
185	73009	Borgloon	11 455
186	73022	Heers	7 554

187	73028	Herstappe	77
188	73032	Hoeselt	9 921
189	73040	Kortessem	8 726
190	73042	Lanaken	26 270
191	73066	Riemst	16 850
192	73083	Tongeren	31 915
193	73098	Wellen	7 473
194	73107	Maasmechelen	39 914
Total			**5 230 253**

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