Master's degree thesis

LOG950 Logistics

Evaluation of the humanitarian logistics model for disaster relief operations

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PREFACE

I would like to start with sharing why I am so inspired by conducting this master's thesis. Molde University College is a great place for study, since everything here intends to support students in achieving their educational goals. Many interesting people and specialists in their field work and teach at Høgskolen i Molde. I would like to thank every person I met on this two-year-long journey, who put a piece of their knowledge into me and allowed me to be where I am now, namely, writing my final assignment – the master's thesis.

In particular, I would like to personally thank my supervisor Professor Arild Hoff for his help and support, as well as for maintaining a positive frame of mind, despite the difficult situation with quarantine due to coronavirus. Thanks to The Eurasia Programme and personally Professor Irina Gribkovskaya, coordinator of the Norwegian-Belarusian study program in Logistics Analytics, for the opportunity to study on Master of Science in Logistics in beautiful Norway. Many thanks to Gregorio Tirado for the consultation and fresh ideas on this specific and very important topic of humanitarian logistics.

My interest in this topic was born a year ago, when one of our esteemed professors invited his colleague, researcher and professor Gregorio Tirado, to a guest lecture. Gregorio is a member of the research group “Decision Aid Models for Logistics and Disaster Management (Humanitarian Logistics)” of the Complutense University of Madrid (UCM-HUMLOG Research Group 2016). Despite the fact that our university covers a wide range of logistics areas, humanitarian logistics is not taught at Molde University College.

I held my bachelor's degree in logistics from the Belarusian State University. Fortunately, in my home country, natural disasters are very rare, or even never happened. Thanks to its geographical location, Belarus does not suffer from natural disasters, unlike many other countries for which such natural phenomena as earthquakes, floods, droughts, hurricanes, typhoons, etc. are regular tragedies. Due to this feature, in Belarusian universities the topic of humanitarian logistics is not covered at all, giving way to more popular areas. Therefore, I have never before had to deal with the concept of humanitarian logistics as a separate topic for study.

That is precisely the fact that interested me in the first place. I also believe that the amount of attention given to this topic is disproportionate to its importance. So, I would like to contribute to the development of humanitarian logistics and the dissemination of knowledge and interest among researchers in this field of science.

ABSTRACT

The lexicographical dynamic flow model based on multi-objective optimization using goal programming approach for solving the multi-commodity aid distribution problem will be presented in this work.

Analysis and solution of the problem of the distribution of humanitarian aid in the aftermath of the catastrophe will be carried out on the basis of the collected case stady.

The realistic case study is collected based on the recent disaster in Japan. The creation of this case is also aimed at benefiting the humanitarian logistics community.

The model provides a plan of distribution of humanitarian aid and a realistic distribution schedule for vehicles, taking into account seven goals related to the quantity to be distributed, the cost of the operation, the time of the operation, the equity of distribution for each type of humanitarian aid, the priority of the designated nodes, the minimum arc reliability and the global reliability of the route.

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1.0 INTRODUCTION

1.1 Introduction/motivation/background for the thesis

Humanitarian logistics tasks are a combination of logistics and humanitarian relief. While the private sector focuses more on economic goals, humanitarian logistics focuses on maintaining health, life and living conditions. For example, it deals with transportation, storage and transshipment, as well as the management of humanitarian aid with the main objectives of logistics services and logistics costs. The logistics service ensures that aid is delivered to the people most in need as quickly and reliably as possible, and the low logistics costs ensure that the limited budget for humanitarian relief is not wasted (Schumann-Bölsche 2015).

Humanitarian logistics have their own specific challenges and difficulties that vary depending on the type, location and degree of disaster. In the case of acute severe natural disasters, people need to be rescued and taken care of within a few hours. Lack of information, destroyed infrastructure and the elimination of international assistance are particular problems.

Schumann-Bölsche (2015) notes that in the case of persistent natural disasters, such as regular droughts in some regions of Africa, as well as in case of political crises, the challenge is not so much focused on speed, but on limited financial resources and logistical potential, for example, in seaports or in refugee camps. Political and cultural issues also complicate humanitarian logistics.

The private sector and humanitarian logistics can enrich each other, and the private logistics sector can also learn from humanitarian assistance, for example, in order to provide flexibility and speed in difficult conditions.

The World Heritage Encyclopedia defines humanitarian logistics as a branch of logistics that specializes in organizing the delivery and storage of supplies during natural disasters or complex emergencies in the affected area and people (World Heritage Encyclopedia 2017). Nowadays, logistics plays a huge role and is one of the most important tools in natural disaster response operations, even though it used to be generally used only in commercial supply chains.

During the onset of a disaster, all elements of the system must work according to a proven, ready-made scheme based entirely on logistic principles. The task of the responsible authorities is to is to respond to the request as efficiently as possible and to minimize the response time, execution costs and the number of distribution centers involved. Mobilization centers and brigades are sent to the scene, which in turn manage the delivery of food and organize rescue teams.

Therefore, it is important to simulate a disaster and its various scenarios in advance in order to take appropriate precautionary measures to prevent its occurrence or to assign all possible resources to minimize the damage. However, natural disasters, terrorist attacks, the failure of a nuclear power plant are events that are not so easy to predict, and for this case humanity needs humanitarian logistics, studies within which will allow us to correctly and quickly respond to disasters that have already occurred.

The importance of logistics in disaster preparedness is in line with observations, rehearsal, warning and hazard analysis. However, in humanitarian supply chains, it is extremely difficult to assess the efficiency indicators familiar to business logistics. Demand for such operations is very unpredictable, it is difficult to assess performance and to predict working conditions, and there is a lack of incentives for performance measurement and environmental research, as the sphere is non-commercial.

In our century, nothing is without technology, humanitarian logistics is no exception. The effective development of humanitarian supply chains will not be without the introduction of systems that allow to update information in real time and track the location of goods and objects, wireless communication systems with all participants of the chain, promotion and advertising of donations and investments in this field, improvement of medical technologies (World Heritage Encyclopedia 2017).

Over the past decade, more than 1.5 million disasters of various origins and scales have occurred in the world, with costs amounting to more than one trillion dollars. Some authors believe that humanitarian operations are becoming a major business for some parties and a global problem for others (Overstreet, et al. 2011). It is also alleged that 80% of the operations performed are logistic, so the success of humanitarian operations directly depends on the level of training and qualification of local logistics services and their effectiveness.

The topic of humanitarian logistics has just begun to appear actively in research. Humanitarian aid supplies have recently been recognized as a serious discipline in supply chain management. However, in studies on humanitarian logistics, authors are less and less referring to established concepts of logistics and supply chain management. Thus, emphasizing that this is a separate industry, requiring its own approach and having unique nuances (Overstreet, et al. 2011).

According to the characterization included in the Logistics Operational Guide (LOG) of the Logistics Cluster (2019) «the distribution chain or channel represents the movement of a product or service from the point of purchase to the time it is handed over to the final consumer. Some of the distribution activities embrace materials handling, storage and warehousing, packaging, transportation, etc.» (Logistic Cluster 2019).

Supply chain planning in humanitarian logistics involves defining missions for each of the various organizations that take part in a disaster-response operation. Organizations often focus on sectors such as nutrition or water, hygiene and sanitation. Based on that, organizations determine the type of humanitarian aid they will handle, as well as the specific geographic area or subset of beneficiaries that they will assist (Logistic Cluster 2019). Depending on the nature of the disaster, transportation management for disaster relief can be complex. It depends on budget, coverage of demand, road reliability, equity of distribution, security in the disaster area and other criteria (Ferrer, et al. 2018).

1.2 Research objectives

One of the main problems of interest in disaster management deals with the distribution of humanitarian aid. The planning of such a distribution is done along the different phases of the process, such as pre-disaster and post-disaster phases.

In this work we will focus on the post disaster humanitarian aid distribution. This implies that instead of the immediate aftermath of the disaster, there is some available information that is characterized by high uncertainty. This includes demand, resources required, the state of the infrastructure, the time required to complete the operation, dispersion of resources and high time pressure, that is, short runtime model and short time to prepare the model.

One of the objectives of the study is to investigate and create a realistic case study based on a recent disaster. To assess the extent to which information is available to develop a humanitarian operation.

Further this work is aimed at modeling the problem built. At the same time, the case study will be used to assess the performance of the built model, while new cases for testing new models are always needed in the field of humanitarian logistics. As usually we need to react quickly at the moment of disaster and there is no time for testing, so it is advisable to do it in advance.

In this context, the aim of the problem consists of designing realistic distribution schedule within the available resources and taking into account some efficiency criteria.

1.3 Structure of the thesis

The structure of this thesis is organized as follows.

Chapter 1.0 provides an introduction to the study and discusses the field of humanitarian logistics. Chapter 2.0 provides an overview of the literature reviewed, Subchapter 2.1 describes the theoretical basis used in the study, Subchapter 2.2 introduces the research conducted on the topic under discussion, while Subchapter 2.3 introduces previously developed models to address similar problems. In Chapter 3.0, the reader is introduced to the case study collected specifically for this work. Chapter 4.0 presents the data collected and the methods used. Subchapter 4.1 explains in detail how the data used in the study were obtained and what sources were used for this purpose. Subchapter 4.2 introduces the reader to the research methods and describes the model developed. Chapter 5.0 introduces the information obtained after the problem is solved and applies a comprehensive analysis of the information. Chapter 6.0 discusses the originallity of the model that has been developed. In Chapter 7.0, the conclusions of the research are made, limitations are described, and directions for further research are proposed.

2.0 LITERATURE REVIEW

2.1 Theoretical framework

This section of the chapter aims to introduce the theoretical basis of approaches and algorithms as well as the mathematical concepts and definitions used in this work.

To formulate a model capable of meeting all the set objectives, it is necessary to refer to the methods of multi-criteria analysis.

The Multi Criteria Analysis (MCA), also known as Multi Criteria Decision Analysis (MCDA), is a class of procedures for the analysis of decision or action possibilities within the framework of decision theory. The different methods of MCA are characterized by the fact that they do not use a single superordinate criterion, but a multitude of different criteria to prepare options or alternatives for decision making (Benayoun, et al. 1971). This analysis can be subject to different decision making rules, and here are only the main ones:

<u>Decision rules for multi-criteria problems:</u>

a) *The principle of dominance*

To simplify the decision-making process, those alternatives that are dominated by other alternatives should not be considered. An alternative is dominated if there is at least one other alternative that performs at least as well in all goals and is better in at least one goal.

Different types of dominance can occur, including absolute dominance, state dominance and probability dominance. State dominance of an action alternative A over an action alternative B exists if the result value of A is at least equal to B in every state and is genuinely greater than B in at least one state. Absolute dominance of A over B exists if the worst result value of A is at least equal to the best result value of B across all states. Absolute dominance is the strictest criterion, i.e. it also implies state dominance and probability dominance (Vasin and Morozov 2005).

Strict or absolute dominance exists if the dominant alternative scores better in all goals. An example of maximization problem is shown in Figure 1.

	z_1	z_2	z_3
a_1	10	5	8
a_2	10	6	8
a_3	7	7	7

Figure 1 State dominance example
Source: (Vasin and Morozov 2005)

Alternative 1 (denoted as a_1) is dominated here by alternative 2 (a_2) and no longer needs to be considered. Although alternative 2 is better in state 1 (denoted as z_1) and state 3 (z_3) than alternative 3 (a_3), it is not in state 2, so that alternative 3 is not dominated.

b) Pareto optimality

The concept is named after Vilfredo Pareto (1848–1923). Pareto set or Pareto frontier consists of solutions that are not dominated by any other solutions. In multi-objective optimization, when different targets are in contradiction, the optimal solution is called Pareto optimal, when it is impossible to improve the target without worsening the others.

Then the optimal Pareto solution can be considered as an optimal trade-off between the goals. The set of all Pareto optimal solutions is called the Pareto front as it usually graphically forms a distinct front of points. Solutions that do not lay on the Pareto front are called Pareto-dominated solutions (Costa and Lourenço 2015). Figure 2 shows a convex Pareto frontier, obtained by minimizing the two objectives simultaneously (Cenaero 2002).

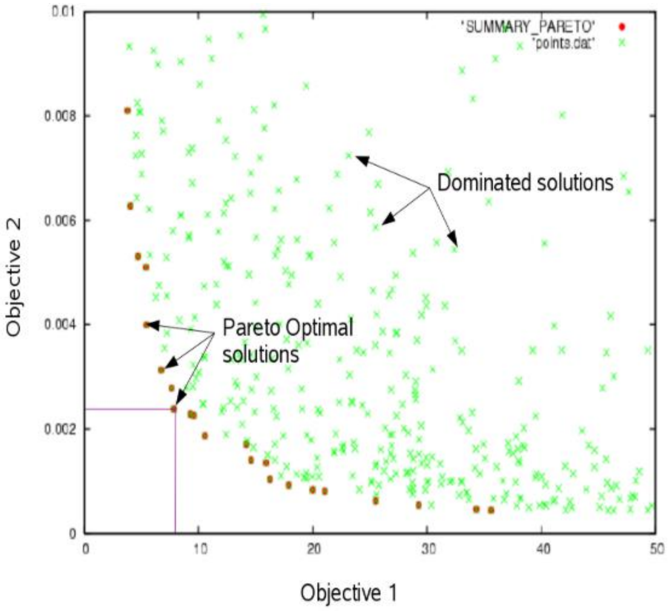

Figure 2 Example of Pareto efficient set
Source: (Cenaero 2002)

c) Lexicographical order

In the lexicographic method (Fishburn 1974), decision-makers are asked to regulate objective functions by relying on their absolute interests. In this procedure, a ranking of objectives is established. First only the most important goal is viewed and evaluated, therefore the procedure is also called goal suppression. If no result is reached because more than one alternative is equivalent with regard to the most important goal, then the next most important goal is looked at and so on. This can lead to implausible results. In the example below (Figure 3), it is assumed that Objective 1 (denoted as z_1) is most important before Objective 2 (z_2) before Objective 3 (z_3).

	z_1	z_2	z_3
a_1	101	0	0
a_2	100	100	100

Figure 3 Example of lexicographic method

Source: (Vasin and Morozov 2005)

Although Alternative 2 (a_2) scores only slightly worse in Objective 1 but significantly better in the other two Objectives, Alternative 1 (a_1) would be chosen according to the lexicographical order.

d) Target weighting

In target weighting, a ranking of targets is also created, but a weighting coefficient must be determined for each target. When making a decision, the various goals are multiplied by the respective weighting factor for each alternative and added together. The alternative that receives the highest value is selected. In contrast to the lexicographical order, however, all target values are taken into account for each alternative. This means that a particularly high value of the second most important target can compensate for a low value of the most important target (Vasin and Morozov 2005).

e) Scalarization

Scalarization method (Wierzbicki 1980) are also often used to obtain optimal Pareto solutions. Since the objective function of a multi-criteria optimization problem has vector values, it is turned into a function with a scalar value using the scalarization function. Thus, the multi-criteria optimization problem is reduced to an optimization problem with one scalar objective function. Mathematically, it can be written down as follows (1).

$$F\left(\vec{f}\ (\vec{x})\right) = \sum_{i=1}^{r} w_i f_i(\vec{x}) \tag{1}$$

Where r – number of an objective criteria,

w_i– weight of an objective criteria i, usually weights are normalized $w_i \epsilon [0, 1]$

$f_i(x)$– utility function of an objective criteria.

f) MaxMin decision rule

The aim is to maximise the minimum degree of achievement of the goal. The mathematical formulation is given in equation (2). To do this, the system searches for the maximum target value in all alternatives and divides all values of the target in the column by this value. In the utility matrix, the values are now normalized to the interval [0..1], i.e. the target value is no longer specified, but rather the relative achievement of the goal compared to the possible maximum. In the example presented in the tables below (Table 1), each alternative (a_1, a_2, a_3) is evaluated according to the minimum relative degree of goal achievement (z_1, z_2, z_3) and the minimum is searched for row by row. The alternative with the highest value is selected (Eisenfür, Langer and Weber 2010).

$$\max_i \left(\min_j \left(\frac{u_{ij}}{\max_h u_{hj}} \right) \right) \tag{2}$$

where u_{ij} – is the utility of alternative i with respect to goal j.

Table 1 Maximin example

	z_1	z_2	z_3
a_1	16	20	5
a_2	4	10	10
a_3	8	8	8
Max	**16**	**20**	**10**

Source: own development

This matrix is now transformed and shown in Table 2:

Table 2 Transformed matrix

	z_1	z_2	z_3	***Min***
a_1	1	1	0.5	**0.5**
a_2	0.25	0.5	1	**0.25**
a_3	0.5	0.4	0.8	**0.4**

Source: own development

This leads to the following order of preference: Alternative 1 (0.5) is better than Alternative 3 (0.4), better than Alternative 2 (0.25). Thus, Alternative 1 is selected.

g) Utility analysis

The utility value analysis is also called point evaluation or scoring model. The additive multi-attribute value function forms the basis for decision-making theory for the utility value analysis. This «assigns a value to each Alternative depending on its attribute values» (Eisenfür, Langer and Weber 2010) . In the end, a total value for each alternative is calculated from the weighted sum of individual values per attribute. The additive multi-attribute value function for calculating the total value of Alternative (a) is shown below (3):

$$v(a) = \sum_{r=1}^{n} w_r v_r(a_r) \qquad (3)$$

where w_r – is a weight of criterion r, and $w_r > 0$

$v_r(a_r)$ – is a rating of Alternative (a) for criterion r.

Further, the condition for the validity of the value function applies:

$$\sum_{r=1}^{\mathrm{n}} w_r = 1 \qquad (4)$$

The expression (4) means that each weight w_r must be greater than 0 and the sum of all weights is equal to 1 (or 100%). The term $v_r(a_r)$ is the value that is assigned to the expression a_r. Eisenfür, Langer and Weber (2010) propose the following example that is given in Table 3:

Three job offers are compared with each other. Two attributes are used for evaluation, working time and salary.

Table 3 Example of attribute rating calculation

Alternative	Salary, a_1	Rating salary, $v_1(a_1)$	Working hours, a_2	Evaluation of working hours, $v_2(a_2)$
Consultant	90 000	1.0	60	0.0
Professor	55 000	0.6	40	0.5
Teacher	35 500	0.0	20	1.0

Source: (Eisenfür, Langer and Weber 2010)

If one now assumes that the salary weight is $w_1 = 0.6$ and for the working hours is $w_2 = 0.4$ we get the following (Table 4):

Table 4 Example of total benefit calculation

Alternative	Weighted salary, $w_1 v_1(a_1)$	Evaluation of working hours, $w_2 v_2(a_2)$	Total value, $w_1 v_1(a_1) + w_2 v_2(a_2)$
Consultant	0.6	0.0	0.60
Professor	0.36	0.20	0.56
Teacher	0.0	0.40	0.40

Source: (Eisenfür, Langer and Weber 2010)

The position as a consultant would be the best since the total value is the highest. The method is called «additive», since in the last step all partial utility values are added. However, for an additive value function to be valid, it must be independent of preference. This means that reducing or increasing one attribute causes a change in the total utility value that is completely independent of the level of the other attributes (Eisenfür, Langer and Weber 2010).

h) Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), also called Saaty method, offers support for a hierarchical target system and is mathematically more demanding but also more precise.

The AHP is «hierarchical» because criteria used to solve a problem are always put into a hierarchical structure. The names for these criteria are characteristics, attributes, alternatives or similar, depending on the requirements. Elements of a hierarchy can be divided into groups, whereby each group only influences a different (higher) group of hierarchy elements and is only influenced by another (lower) one (Saaty 2008).

The AHP is called «analytical» because it is suitable to comprehensively analyze a problem constellation in all its dependencies (Saaty 2008).

It is called «process» because it defines a process-related sequence of how decisions are structured and analyzed. In principle, this process is always the same, which makes the AHP an easy to use decision tool that is equivalent to a routine treatment when used several times (Saaty 2008).

i) Compromise programming

The compromise programming method aims at choosing a solution as close to the ideal as possible, by minimizing the distance to the ideal point (or Yu (1973) referred to the ideal point as the «utopia point»). Yu (1973) and Zeleny (1974) define the ideal solution as any solution that would simultaneously optimize each individual objective (Ringuest 1992).

The most commonly used measure of distance in decision making is the family of L_p metrics. The p value is usually chosen based on heuristic considerations. However, the values $p = 1$ and $p = 2$ are frequently used. In this connection, $p = 1$ implies the longest geometric distance between two points in that the deviations are simply summed over all dimensions. The L_1 metric is referred to as the «Manhattan distance» or «city block» measure of distance (Ringuest 1992).

Thus, the mathematical formulation of the method is presented as follows (5):

$$\min_x L_p = \left[\sum_i w_i^p \left(\frac{z_i^* - z_i(x)}{z_i^* - z_{*i}}\right)^p\right]^{1/p} \tag{5}$$

Where z_i^* – ideal point is an optimal value of each goal i that can be obtain as diagonal of payoff matrix,

z_{*i} – anti-ideal point is the worst value of each goal i, can be taken as worst value in the payoff matrix for each objective,

$z_i(x)$ – is an objective function value of goal i,

w_i – weight of goal i is an importance of each attribute for the decision maker,

p – is the parameter that determines which of the family of L_p metrics to be used in order to obtain different compromise solutions.

The ration of the difference between the objective function value and the ideal value to the difference between the objective function value and the anti-ideal value gives normalized criteria values that then can be assigned weights.

A graphical representation of the compromise solution for the maximization problem with two objectives can be seen in Figure 4.

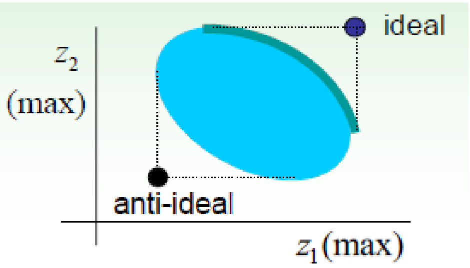

Figure 4 Compromise solution example

Source: (Ferrer, et al. 2019)

j) Goal programming

Goal programming (Charnes and Cooper 1961, Ignizio 1974) approach establishes a specific numeric goal for each of the objective and then attempts to achieve each goal sequentially up to a satisfactory level rather than an optimal level.

Charnes and Cooper (1961) suggested a method for solving an infeasible linear programming problem arising from various conflicting resource constraints (or goals).

In goal programming, instead of trying to maximize or minimize the objective function directly, as in case of a linear programming, the deviations from established goals within given set of constraints are minimized. In this methodology, slack and surplus variables are known as Deviational Variables that means underachievement and overachievement, respectively. These variables are deviations from each goal or sub-goal and they represent the extent to which target goals are not achieved.

The objective function then becomes the minimization of a sum of these deviations, based on the relative importance within the preemptive structure assigned to each deviation. The mathematical formulation is shown in expressions (6) and (7).

$$DV_i = z_i^* - z_i(x) \tag{6}$$

$$\min \sum_{i} (w_i^{+} DV_i^{+} + w_i^{-} DV_i^{-}) \tag{7}$$

Where z_i^* – target value of the goal i

$z_i(x)$ – the objective function value of the goal i

DV_i^+ – the deviation of the goal i to be maximized

w_i^+ – the weight of the deviation of the goal i to be maximized

DV_i^- – the deviation of the goal i to be minimized

w_i^- – the weight of the deviation of the goal i to be minimized

2.2 Humanitarian logistics research

The humanitarian sphere is specific for the implementation of any theory. Therefore, in their studies, Guide and Van Wassenhove (2007) emphasize that at the time of an emergency, decision-makers have to work in conditions of limited information and time. It follows that models that require a lot of time and a large amount of input data are not the best solution. They also note that data collection will be a rather complicated procedure, but all the same, the received data will most likely be of poor quality (Guide and Van Wassenhove 2007, Kunz, et al. 2017). Nevertheless, some researchers have succeeded in developing models successfully applied in humanitarian logistics.

In 2009, inspired by past experience, Carroll and Neu described the state of humanitarian logistics as unstable with a huge number of participants, which creates unpredictability and asymmetry. And they developed a modern model that covered all aspects of logistics and narrowed the gap between the current and necessary, flexible state of humanitarian logistics. They also proposed several universal methods that, in their opinion, lead to “flexibility of cooperation and efficient logistics for responding to natural disasters, which will lead to sustainability and universality” (Carroll and Neu 2009).

The vast majority of humanitarian logistics research focuses on the preparation and planning stages, as well as applied policies and procedures. The studies that develop specific models mainly propose to introduce information technologies into the supply chain. For example, in 2002, a knowledge management framework was developed that serves as a tool for decision makers during a humanitarian operation. It is argued that such a system is self-learning and the more information it accumulates, the better it will work in the future (Overstreet, et al. 2011).

The applicability of the research to the practical side of real life is very important. If the research cannot be used in practice, the importance of such work is immediately devalued. If repeated over and over again, such an occasion may lead to a decrease in the need of practitioners for the work of scientists as a whole (Kunz, et al. 2017).

On this basis, in order to avoid unfoundedness, Chapter 2.3 discusses articles in which authors present their models designed for real-life applications, as well as those tested on realistic case studies.

2.3 Multi-criteria models for aid distribution operations

After reviewing the available literature on the selected topic and examining the proposed approaches to solving such problems in order to formulate a model that can solve the problem posed in this work, let us focus on some of the most relevant studies, which are described below.

2.3.1 Hierarchical compromise model

The group of scientists from the Complutense University of Madrid (Liberatore, et al. 2014), proposed a hierarchical compromise model for the joint optimization of recovery operations and distribution of emergency goods based on a multi-criteria solution approach and a three-level lexicographic optimization method.

This model is aimed at recovery of damaged arcs in post-disaster operations. The model calculates what temporary emergency access roads, roads, tunnels, bridges need to be restored or cleaned in the first place to open a path through them. And how to do this with minimal loss of time and budget costs, while fully satisfying demand and covering all affected areas and sites. The emphasis is on restoration work rather than a distribution plan, so there are assumptions that the capacities of the distribution centers are unlimited and the distribution of products is continuous.

The hierarchical model implies that the highest priority is given to maximizing the satisfied demand for humanitarian aid and helping people in catastrophe, and then other criteria are taken into account. Researchers (Liberatore, et al. 2014) take into account optimization criteria such as maximum service time, total demand in the entire considered area, maximum ransack probability during the delivery of goods along the selected route and the minimum reliability of roads on the selected distribution plan.

The first level of the lexicographic model computes the maximum demand to be met, with the help of which routes and taking into account all the above criteria. At the second level, the model optimizes each criterion individually by minimizing the maximum of normalized criteria deviations from ideal values with the previously found total demand value already fixed, using Chebyshev distances.

At the third level of lexicographic optimization, optimal solutions are selected from a variety of alternatives. To accomplish this, a group of researchers uses the method of minimizing the weighted sum of the normalized deviations of the criteria without losing the results achieved at previous levels.

Liberatore, et al. (2014) emphasize the need to coordinate services involved in restoring transport infrastructure and humanitarian aid delivery services. Moreover, they empirically prove this by conducting the following experiment. They replace the three-level solution described above with three independent sequential models, in the same way that two separate services would make their decisions without coordinating their actions, but working separately. It should be noted that the "gaps" between the sequential solution and coordinated one show how important cooperation between rescue services is when disasters occur, as well as the power of information.

2.3.2 Dynamic flow model

One of the subsequent studies on this topic was conducted by the researchers Tirado, et al. (2014). They proposed a dynamic flow model for solving the aid distribution problem in emergency situations based on a multi-criteria approach and lexicographic method of goal programming. In their work, the authors (Tirado, et al. 2014) propose a model that focuses on building a realistic distribution plan for last mile delivery. This means that the resource allocations and transport infrastructure are known. To do this, they introduce a time horizon, divided into periods, each of which is one minute. This approach allows to get the most realistic distribution schedule. The dynamic model allows vehicles following different routes to visit the same node, to wit, visit a node several times. At the same time the statical model does not imply such optimization.

The decision making process takes place at two lexicographical levels and four criteria are taken into account, such as global distributed quantity, operating time, aid distribution equity and cost. The primary goal of the model is to maximize help for people in need, it is directly proportional to the amount of demand that must be satisfied. The objective function of the first stage is to allocate the planned amount of resources within the available budget. No trade-offs with other optimization criteria are allowed at this level. The solution obtained at the first level is integer, does not require a high computational effort and is calculated quickly.

The second lexicographical level of the model determines the distribution schedule, taking into account the remaining goals. The weights of each criterion can be changed by the decision maker, as an expert in his field. But by default, preference is given to minimizing the execution time of the operation, and then the cost and equity. For a dynamic model, it is very important to correctly define the maximum number of time periods, or rather the length of the time horizon. This should be done for the model to be able to optimize not only the time criterion, but also other criteria. Otherwise, the time horizon can be limited so much that the other criteria will have no any implication. It directly depends on the time of the operation in real life. However, for modeling, it can be determined approximately or experimentally by running the program and checking the result. If a reasonable solution was found within a given time horizon, then it was chosen correctly. If not, then one should make it longer and run the model again. There is another option, in our case, the authors (Tirado, et al. 2014) use the execution time of the operation proposed by the solution of the static flow model (Ortuño, et al. 2011), increased by 10%.

After testing, the dynamic model shows a slight increase in response time and cost, due to the separation of the time horizon into periods, but at the same time creates a realistic schedule for the distribution of humanitarian aid, allowing multiple departures from each node. This schedule allows more people to get help earlier, although their need may not be fully met immediately, in the end, the demand will be completely satisfied by the next vehicle that follows route. Difficulties in solving such a model may appear when the time horizon is strongly increased. This will lead to a problem of high dimensionality, which may require the use of high computer power to obtain a quick solution.

2.3.3 Compromise programming model

In the recent study, a group of researchers (Ferrer, et al. 2018) presented their newest development to the world of science: an application for humanitarian logistics. The application is based on a compromise programming model for multi-criteria optimization in humanitarian last mile distribution. They argue that it is the first model in its field that capable of optimizing as many criteria at the same time, while creating a real schedule for vehicles and, if necessary, forcing them to travel in convoys.

The model under consideration is intended to help in the distribution of humanitarian aid after the disaster, which means that the information involved in the decision-making process contains a high degree of uncertainty. Despite this, the model is deterministic. Therefore, Ferrer, et al. (2018) assume that the parameters entered for the computation will take into account the uncertainty of the current situation.

The model is built on the compromise programming method and takes into account six criteria, such as time, cost, priority, equity, security and reliability. The approach ensures that the obtained solution is a non-dominated or efficient one. Thus, there can be no other solution that will surpass the proposed solution or be equal to it in all criteria. Such a solution is as close to ideal values as possible, within available resources and the current situation. Ideal points are determined by solving the model individually for each criterion, without taking into account the importance of others.

It also implies that the decision maker already has an initial amount of information sufficient to design the mission, for example, the available amount of aid to be distributed and the number and type of vehicles available. The developed model is designed for the delivery of a single commodity, however, it may be a kit with a diverse selection of goods pre-formed at the warehouse. The model makes an individual schedule from the supplier to the demand nodes for each vehicle, calculates what type of vehicle is needed for a particular route. Furthermore, one can set the condition that the rescue organization does not have the necessary type of vehicles in its fleet, in this case the model can take into account the rental of any vehicles and calculate the optimal plan for such a scheme. At the same time, the model allows to construct an operation for several depots, several types of vehicles, takes into account the time of loading and unloading of vehicles, allows transshipment and split delivery.

There are restrictions on the compatibility of certain types of vehicles with certain roads. For example, a large vehicle cannot be assigned to a narrow rural road, etc. If an effective solution requires the use an unreliable arc, the model can appends a convoy and police escort for this route, which affects the cost of the operation. Consequently, the use of unreliable arcs is avoided if the other criteria allow it. It may happen that there are several nodes in a hardly accessible location, so the model will bypass them by all means. In this layout, it is possible to designate such nodes as priority.

Given all of the above, it is easy to conclude that when using the model in real cases, the problem will have a high dimension, since a large number of variables are used in the calculations. Ferrer, et al. (2018) say that in order for the model to provide a fast enough solution, they had to stick with the simple heuristic methods and abandon local search-based metaheuristics and complex evolutionary algorithms, because it would require a very high computational effort. They applied the Greedy Randomized Adaptive Search Procedure metaheuristic algorithm that is widely used for compromise optimization problems to select the best solution. This algorithm was first introduced by Hart and Shogan (1987) as a semi-greedy heuristic. Then it became widespread as the GRASP algorithm after the work of Feo and Resende (1989).

GRASP (Feo and Resende 1989) is based on an elite set of solutions, containing solutions with good values in the objectives. The elite set is initialized with a constructive algorithm and improves after each iteration. The intuition behind this heuristic is that if an element appears frequently in a set of good diverse solutions, it must be good and, thus, should have a higher probability to be selected when building new feasible solutions. Local search is applied to the new feasible solution, if it improves, the elite set updates and replaces one of the former elite solutions (Hart and Shogan 1987), (Ferrer, et al. 2018).

Despite all attempts to simplify the model for quick calculations, the authors (Ferrer, et al. 2018) mention that a powerful computer was used. This model is proposed to be used as a customized application. Otherwise, an ordinary user may not get the desired result, namely a quick and high-quality solution of the humanitarian problem.

Overall, this transportation model application can serve as an excellent tool to assist decision makers in the development of humanitarian operations aimed at distributing goods over a single period. The article brings a fresh perspective and a step forward in the study of humanitarian logistics.

3.0 CASE DESCRIPTION

Humanitarian operation research needs realistic test cases to replicate experiments, validate models and compare results. However, getting realistic data on humanitarian operations is challenging (Pedraza-Martinez and Wassenhove 2016). Confidentiality agreements or high acquisition costs discourage data sharing within the humanitarian operation research community.

The realistic case study was collected and presented in this work with the aim of benefiting the humanitarian operation research area and with hope of having a positive impact for practitioners and beneficiaries. Also, the realistic test cases are available on the website of the research group "Decision Aid Models for Logistics and Disaster Management (Humanitarian Logistics)" of the Complutense University of Madrid (UCM-HUMLOG Research Group 2016). To date, they have scrupulously collected and published for public access data on three natural disasters, such as Famine in Niger (2005), Flood in Pakistan (2010), Earthquake in Haiti (2010). Currently the researchers are working on the earthquake and tsunami that hit Indonesia in 2018.

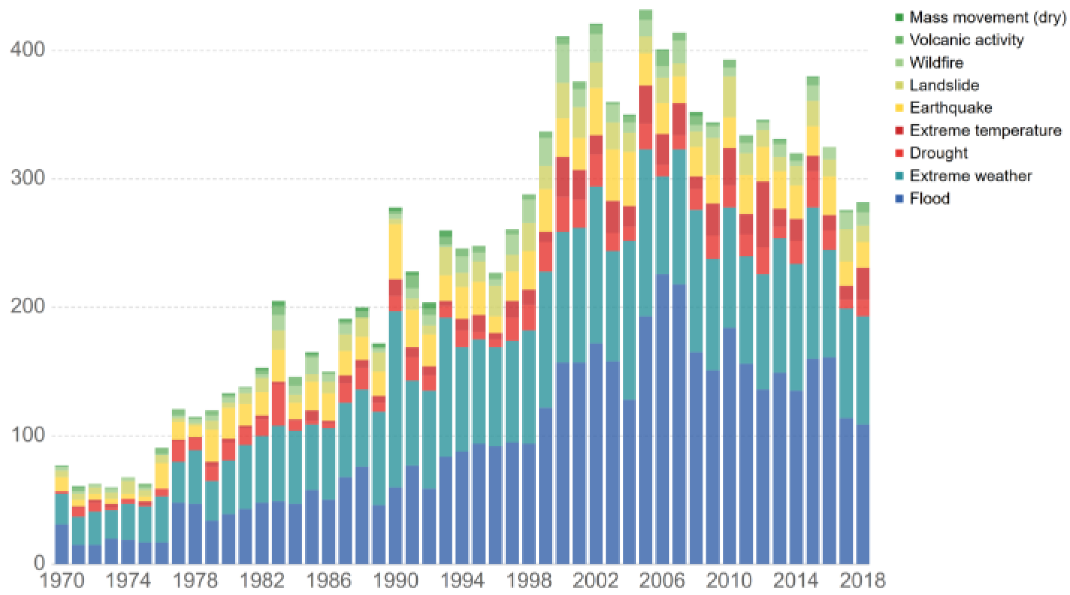

Figure 5 Number of natural disasters by type per year, 1970 to 2018

Source: EMDAT (2019): OFDA/CRED International Disaster Database

On the chart above (Figure 5), you can observe how the activity of natural disasters has been changing around the world for almost half a century. A huge surge in activity can be seen during the 2000s over a decade. After this hapless period of time, humanity seriously began to think about preventive measures that can be applied to reduce the number of victims of natural disasters, which, unfortunately, people are not able to control yet. States and humanitarian organizations around the world have invested a lot of money and efforts to develope modern security measures that would help reduce the number of deaths, destroyed lives and territories in the event of the next natural disaster.

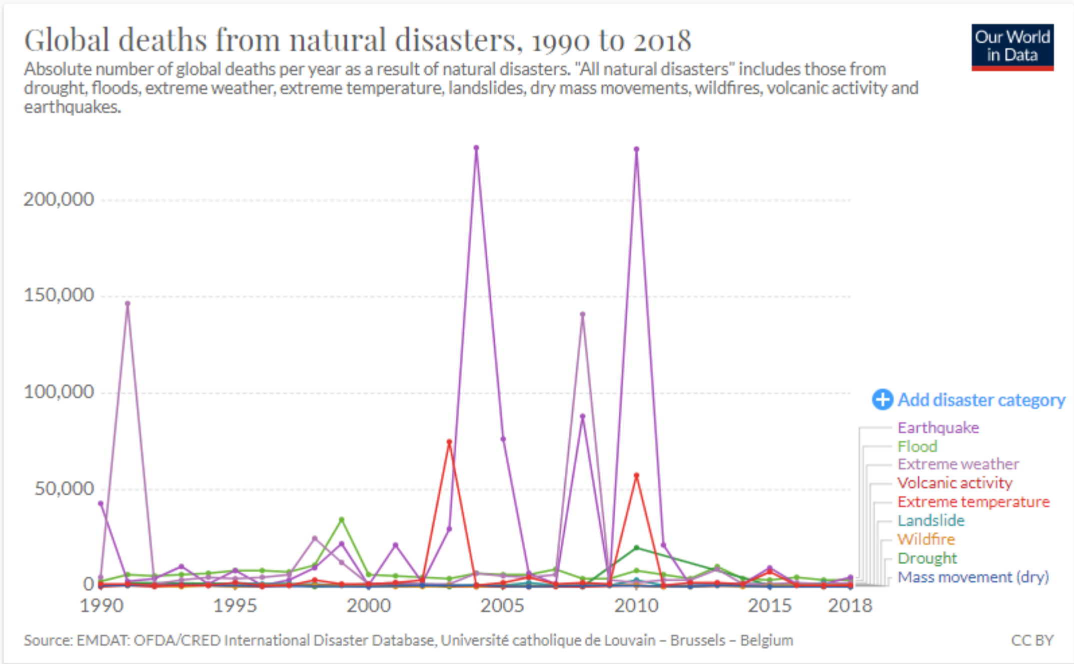

Figure 6 Number of deaths from natural disasters per year, 1990 to 2018

The following graphs (Figure 6, Figure 7) show the change in the total number of deaths over the past 30 years and the average annual number of deaths over decades due to disasters of a certain type, respectively.

The combined analysis of these three charts leads us to the conclusion that the most dangerous natural disasters that have claimed hundreds of thousands of lives are earthquakes.The first graph (Figure 5) shows that earthquakes are not the most frequent disasters, but the proportion of deaths due to earthquakes is the largest in the total. At the same time, floods can be called the most frequent disasters, which can be seen on the first chart (Figure 5). Floods are also among the highest in terms of the number of fatalities, not to mention the number of injured people whose houses were destroyed due to floods and farmers whose harvest was completely lost.

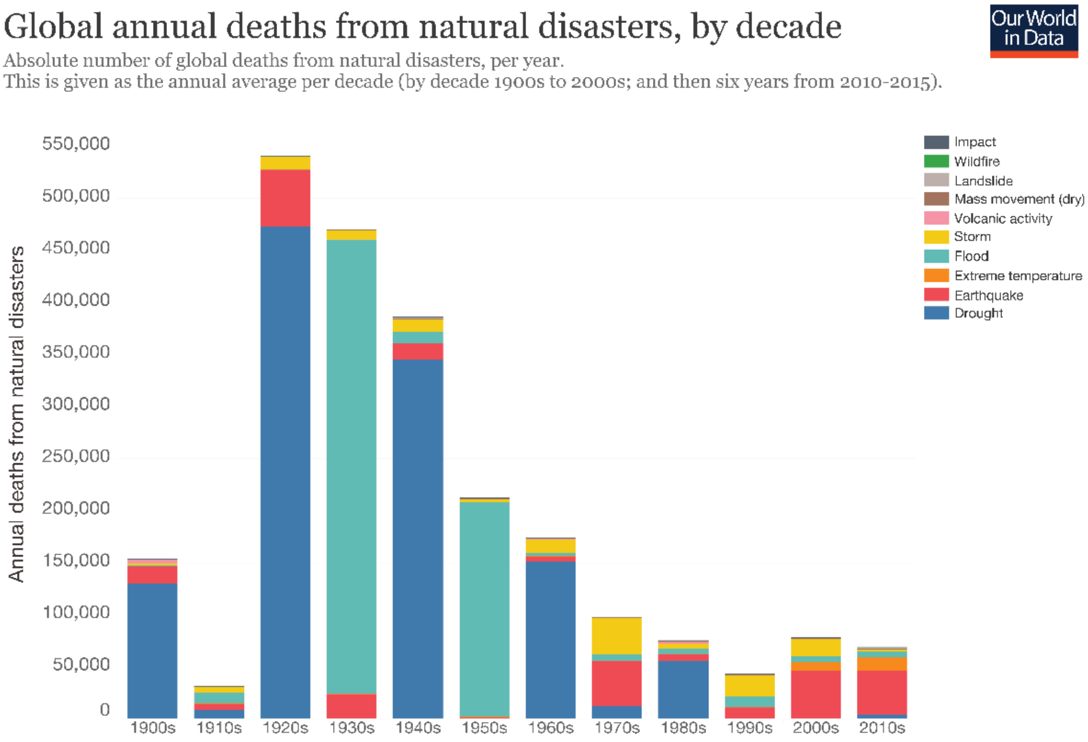

Figure 7 Number of annual deaths from natural disasters, by decade

Source: EMDAT (2019): OFDA/CRED International Disaster Database

Bringing the listed facts together, we can guess what type of disasters will be given attention in this paper. The catastrophe, combining the most destructive factors of earthquakes, floods, landslides and hurricanes, is presented to the attention of readers in this work.

The case study complied for this work is based on one of the recent disaster that shook the world – the typhoon that hit Japan on October 12, 2019. The typhoon was named Hagibis (which means: fast), and Japanese meteorologists call it the most destructive in 60 years. Typhoon Hagibis was an extremely violent and large tropical cyclone that caused widespread destruction across its path, starting from October 6, 2019, up until October 13, 2019.

The 38th depression, 9th typhoon and 3rd super typhoon of the 2019 Pacific typhoon season, it was the strongest typhoon in decades to strike mainland Japan, and one of the largest typhoons ever recorded at a peak diameter of 825 nautical miles (1 529 km). It was also the costliest Pacific typhoon on record, surpassing Typhoon Mireille's (which in 1991 amounted to US$10 billion) record by more than US$5 billion (when not adjusted for inflation) (CSU Department of Atmospheric Science 2020).

Figure 8 The path of typhoon Hagibis over time

In addition, Hagibis was also the deadliest typhoon to hit Japan since Typhoon Tip in 1979, which brought the fatalities number up to 99. Its death toll is marginally higher than that of Typhoon Bess in 1982 (95 fatalities) and Typhoon Tokage in 2004 (98 fatalities) (Hays 2013).

Hagibis caused catastrophic destruction in much of eastern Japan. As shown in Figure 9, the typhoon passed through the most densely populated part of the island, without bypassing Tokyo, the capital of Japan. Tokyo has a population of about 10 million and a population density of about 6 000 people per square kilometer. The Typhoon spilled Tamagawa, the largest river in Tokyo, and caused much damage in its area. More than half a million people were forced to leave their homes, the most severe damage was caused to agriculture and the infrastructure of nearby cities. The storm ripped through a wide area of the country, cutting off electricity and water supplies, causing mudslides and flooding tens of thousands of homes (Japan Meteorological Agency 2019, CSU Department of Atmospheric Science 2020).

Such incidents are protracted, since the damage and consequences of the typhoon can be eliminated for months or even years. According to Emergency humanitation aid organization – Japan Platform (2020), the last shelters for victims of the disaster, who were forced to evacuate from their homes, were closed on March 23, 2020, five months after the disaster.

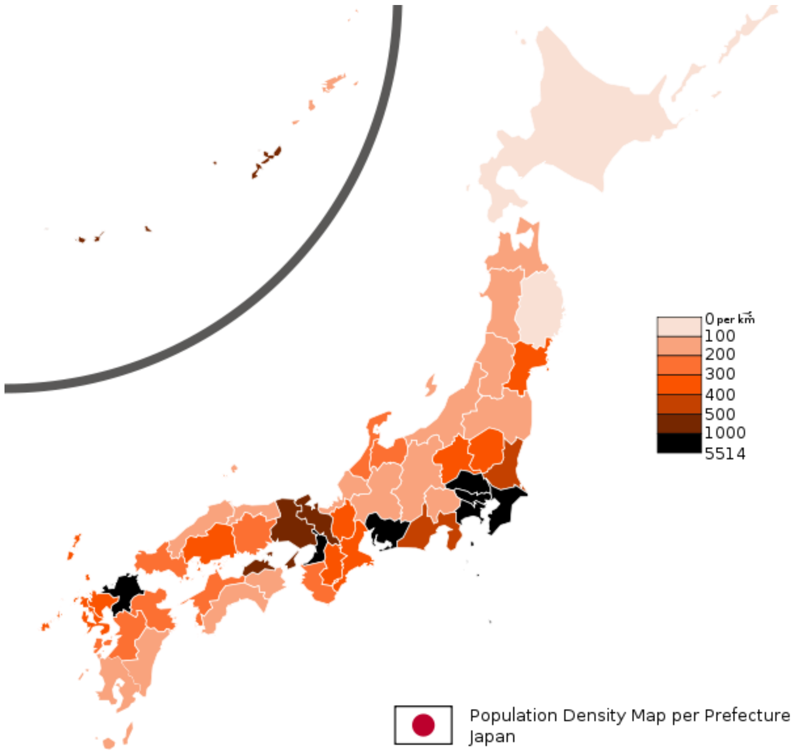

Figure 9 Population density map per Prefecture, Japan

Source: (Statistics Japan 2020)

Comprehensive report from the Emergency Response Coordination Centre (European Commission's Directorate - General for European Civil Protection and Humanitarian Aid Operations 2019) illustrating the most destroyed territories and describing the overall situation on 14 October 2019 can be found in the in Appendix 1.

The railway in Japan is the most frequently used mode of transport, not only by local residents, but also by logistics companies. Japan's national high-speed rail network today has a total length of 3 041 km (The Globalist 2018). Enveloping the entire country, it allows people to overcome very quickly and conveniently long distances from one part of the island to another. However, in accordance with the data provided by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (2020), most of the railway lines in the region under consideration were damaged by the typhoon.

Therefore, the best solution for humanitarian services is to use road transport for their operations. Road transport is much more mobile, compared to railway and ferries, cheaper than helicopters and airplanes, convenient for delivering goods in cities and rural areas. Nevertheless, the success of the operation using vehicles directly depends on the transport infrastructure and the condition of the roads, which could also be badly damaged by the typhoon; as well as on the situation in the region, since the single vehicle delivering humanitarian aid can easily be ransacked. Consequently, to compile a realistic case study, all of the above factors must be considered.

Let us start with the situation in the country during emergencies. After studying the available literature and Internet sources on the subject, there was not a single mention of the aggressive behaviour of the Japanese towards humanitarian aid and humanitarian operations in general. On the contrary, Japan is on a par with the United States and England in the provision of humanitarian assistance to other countries in disasters. Japan also has vast experience in natural disasters and all kinds of emergencies, so their budget has long included an expense for humanitarian operations within their own country.

Therefore, in severe situations for the whole country, people feel confident knowing that the state will do everything possible and necessary help will come on time. So they do not need to be aggressive. In overcoming a huge number of natural disasters, the Japanese help their upbringing culture and mentality.

In March 2011, when the Great Natural Japan Disaster occurred, the international media widely presented stories of the absence violence and looting of stores in the destroyed areas and how people in affected area were waiting in line for relief supplies. Along with public safety wellbeing, the national quality of Japanese people, such as the ability to keep calm and cool without panicking in critical situations, has been praised abroad (Nippon Communication Foundation 2014).

The official statistics on robbery cases recorded in Japan for 12 years are given in Table 5.

Table 5 The rates of robbery in Japan per 100 000 population by years

Year	Value	Variation, %
2016	0,0	-3,87%
2015	0,0	-20,62%
2014	0,0	-8,06%
2013	0,0	-9,99%
2012	0,0	-0,14%
2011	0,0	-8,74%
2010	0,0	-10,67%
2009	0,0	5,49%
2008	0,0	-5,85%
2007	0,0	-10,59%
2006	0,1	-14,70%
2005	0,1	

Source: (Ministry of Internal Affairs and Communications 2020)

For 2016 (unfortunately, no newer data has yet been published), the rate of robbery attacks is 0.0 cases per 100 000 population.

Figure 10 The robbery trend in Japan by years

Source: (Ministry of Internal Affairs and Communications 2020)

According to statistics (Figure 10), in recent years there has been a tendency to reduce the number of such crimes. This makes us acknowledge that the security criterion in this study will be redundant and can be excluded.

As previously suggested, the implementation of a post-disaster humanitarian operation will be most convenient with the help of road transport. Based on this, a humanitarian aid distribution network was built for Tokyo Prefecture. The Greater Tokyo Area is the most populous metropolitan area in the world with over than 38 million people, consisting of the Kantō region of Japan (including Tokyo Metropolis and the prefectures of Kanagawa, Chiba, Saitama, Ibaraki, Tochigi and Gunma) as well as the prefecture of Yamanashi of the neighboring Chūbu region. Thus, it is assumed that humanitarian aid will be delivered to ten regional centers such as Fujisawa, Funabashi, Kasukabe, Kawagoe, Kawasaki, Hachioji, Kofu, Saitama, Chiba and Tokyo.

Let us take a closer look at the characteristics of the built transport network in Chapter 4.1.

4.0 DATA AND METHODS

4.1 Case study data

One of the most important issues is the ability to find relevant and appropriate data for the research. The data for compiling this case study were mainly obtained from secondary sources on the Internet, as well as subjectively determined based on the information studied. The main Internet resources are presented in the list below, and some will be described later in the text:

- "Decision Aid Models for Logistics and Disaster Management (Humanitarian Logistics)" Research Group (UCM-HUMLOG Research Group 2016): http://blogs.mat.ucm.es/humlog/
- United Nations Office for the Coordination of Humanitarian Affairs (OCHA) – World Humanitarian Data and Trends (2018): https://www.unocha.org/
- Emergency humanitarian aid organization – NGO Japan Platform (2020): http://www.japanplatform.org/E/
- Humanitarian Data Exchange by OCHA (2020): https://data.humdata.org/group/jpn
- Japan Meteorological Agency (2019): https://www.jma.go.jp/en/typh/
- Tropical Meteorology Project (CSU Department of Atmospheric Science 2020): http://tropical.atmos.colostate.edu/
- Ministry of Internal Affairs and Communications, Statistics Bureau of Japan (2020) : http://www.stat.go.jp/english/index.html
- Ministry of Land, Infrastructure, Transport and Tourism of Japan (2020): http://www.mlit.go.jp/en/index.html
- OFDA/CRED International Disaster Database (EMDAT 2019): https://www.emdat.be/database
- European Commission's Directorate – General for European Civil Protection and Humanitarian Aid Operations (2019): https://reliefweb.int/map/japan/japan-tropical-cyclone-hagibis-dg-echo-daily-map-14102019
- Statistics Japan, Prefecture comparison (2020): https://stats-japan.com/t/categ/50004
- Open Street Maps, Yandex Maps and Google Maps

As mentioned in the previous chapter, the humanitarian distribution network was built for Tokyo Prefecture. So that humanitarian aid will be delivered to ten regional centers such as Fujisawa, Funabashi, Kasukabe, Kawagoe, Kawasaki, Hachioji, Kofu, Saitama, Chiba and Tokyo. The following characteristics of the transport network are provided.

The transport network consists of 10 demand nodes, 4 supply depots and 58 available connections between locations. The humanitarian aid to be delivered is divided into two categories, food and medicine. Demand for humanitarian aid was calculated in the amount of 2 kg per person, on the assumption that about 10% of the city's population needed help (Appendix 2). Besides, 15% (300 grams per person) of the distributed aid is occupied by healthcare products and medicines, while the remaining 75% is food. Thus, the total demand for food is 2585 tons and the total demand for medicines is 440 tons. The desired amount of humanitarian aid to be distributed is 3025 tons for the operation.

Depots are based in places where humanitarian aid is delivered according to international experience, such as airports, seaports, and a large distribution centers with high capacity. The first depot is at Haneda Airport with 1 100 tons of food and 200 tons of medicine available, the second depot is Narita Airport with 440 available tons of food and 80 tons of medicine, the third depot is Yokohama Port with 230 tons of food and 80 tons of medication available, and the last but not least depot is a Distribution Center specializing in nutrition, 1 270 tons of food is available for distribution there. The total amount of humanitarian aid available is 3 400 tons.

To perform the operation, three types of vehicles with different capacities are utilized. The code names for the vehicles are as follows: *small* vehicles with a capacity of up to 5 tons, *medium* vehicles with a capacity of up to 15 tons and *large* cargo vehicles with a capacity of 25 tons. Moreover, 119 small, 81 medium and 44 large vehicles are available for transportation, which in total is 244 vehicles. Table 7 reflects vehicle characteristics such as capacity, maximum speed, fixed cost per kilometre and variable cost depending on distance, cargo amount and type of product being transported.

The model proposed in this paper (details will be described in Chapter 4.2) provides the ability to give priority to some nodes. Based on a number of experiments that will be discussed later, priority was given to the city of Kofu, node N7, located in an arduous area, and to the city with the greatest demand – Tokyo, node N10.

The summary of all the above data is shown in Table 6 and Table 7.

The planned mission consists of distributing the desired amount of humanitarian aid of 3 025 tons within the available budget of US$1 000 000.

Table 6 Characteristics of the humanitarian operation

Name	Nodes	Demand **demand (ton)**		Supply **q_avail (ton)**		Availability of vehicles of each type			Priority
		food	medicine	food	medicine	**small**	**medium**	**large**	**n_pri**
Haneda Airport	D1			1100	200	50	30	20	
Narita Airport	D2			440	80	12	8	2	
Yokohama Port	D3			230	80	7	13	2	
Distribution Center	D4			1270	0	50	30	20	
Fujisawa	N1	75	10						
Funabashi	N2	105	20						
Kasukabe	N3	40	5						
Kawagoe	N4	60	10						
Kawasaki	N5	255	45						
Hachioji	N6	95	20						
Kofu	N7	35	5						1
Saitama	N8	225	25						
Chiba	N9	165	30						
Tokyo	N10	1530	270						0,8

Source: own development

Table 7 Characteristic and operation costs of the vehicle

Vehicle types	Vehicle capacity **capacity (ton)**	Speed **velocity (km/h)**	Fixed cost **cf (US$/km)**	Variable cost **cv (US$/(km*tonn*product))**	
				food	medicine
small	5	100	20	1	1
medium	15	90	50	1,1	1
large	25	80	70	1,3	1

Source: own development

Figure 11 presents the transport network with labeled demand nodes, supply depots and links that reflect the distance, speed and reliability of roads available for transportation. The interactive map that was built for this work using Yandex Constructor. The map includes a full description of the case and can be found here: https://yandex.com/maps/-/CCQ2F8edtD.

The links are shown in different colors depending on the reliability of the arc: green – reliable arc, the probability of crossing the arc above 70%; orange – the probability of crossing the arc is higher than 50%; and red color indicate that the probability of crossing the arc is less than 50% – unreliable arc, respectively. The different thickness of the links shows the quality of the road. The thicker the arc, the higher the maximum speed of its passage.

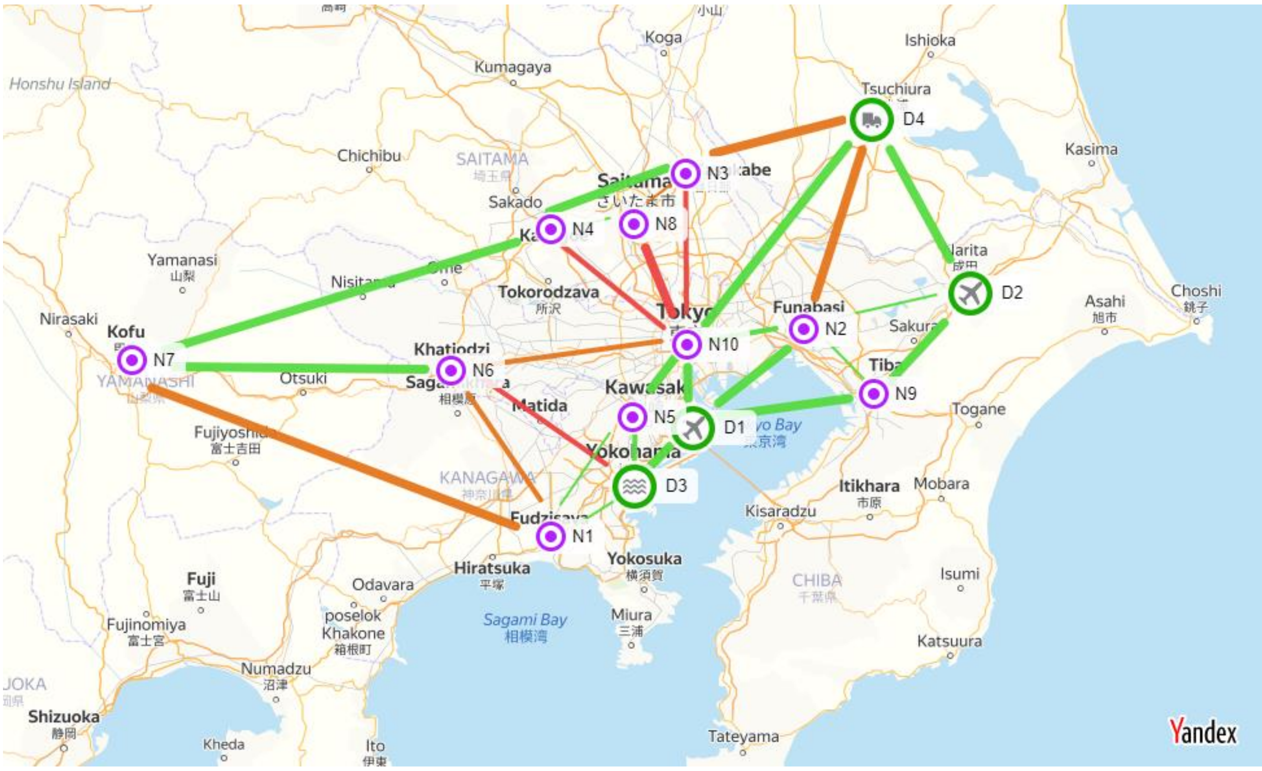

Figure 11 Transport network for the operation

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQ2F8edtD

Source: own development

Information on the distance and maximum speed of the road was collected from Google Maps and Open Street Maps. These sourses provides comprehensive information about the type of road and their quality. Reliability data for the links are the result of subjective conclusions based on the reports of (Ministry of Land, Infrastructure, Transport and Tourism of Japan (2020) on the extent of destruction of certain routes, as well as on the report of European Commission's Directorate – General for European Civil Protection and Humanitarian Aid Operations (2019), which provides the map of destruction showing the epicenters of destroyed area (Appendix 1).

Data on existing links, their distance, maximum speed of the road as well as the reliability of the arcs is provided in the table and can be found in Appendix 3.

4.2 Model description and methods

The developed model is an extended version of the model proposed by Tirado, et al. (2014). The authors are part of HUMLOG Research Group (2016) that has already been mentioned. With the support of the Complutense University of Madrid, the partial funding from the Government of Spain and some mathematical communities (such as I-MATH Consolider (Suomitech 2009), etc.), this research team is developing applications for humanitarian logistics.

They published several interesting works on the topic of humanitarian logistics (Ortuño, et al. (2011), Vitoriano, et al. (2011), Liberatore, et al. (2014), Tirado, et al. (2014), Ferrer, et al. (2018). These works, as well as a review of the current situation of humanitarian logistics in the world, inspired me to create appropriate extensions for the model and bring the model to its final version.)

Starting to formulate a model for solving the research objectives, we must not forget about the safety of services that provide relief and deliver food and medicine to victims of disasters. Now amid the coronavirus pandemic and the resulting catastrophe all over the world, we see especially well how important it is to provide the necessary support from the side of the administration and the government to those who are at the forefront and provide direct assistance to those who need it. This can be done by properly organizing the processes in the organizations involved and timely supplying the personnel with the necessary protective equipment.

In our case, all the facts and rules listed above are relevant, so the proposed model is not only aimed at successfully meeting demand of humanitarian aid in the affected areas after the natural disaster, but also at the security of the services involved in such humanitarian operations. The safety factor is taken into account by introducing the analysis of road reliability. It is not only increases the success level of the mission, but also aims to take care of the participants in the humanitarian operation, eliminating the possibility of an accident on the road.

Of all the methods listed in Chapter 2.1, goal programming turned out to be the closest to obtaining the desired result, and therefore it was used as the main optimization method for the model. However, the model is formulated in such a way that the more criteria are added to the objective function, the more blurred are the boundaries of the importance of the criteria. Consequently, since Japan is one of the most cultured and calm countries in term of the relationship, it was decided not to include such a criterion as robbery probability in this model, and to focus on the reliability of the route.

Notation and mathematical formulation of the model is presented below:

Sets and indices:

Notation		***Description***
N	:	Set of nodes and depots, relief network
A	:	Set of arcs represents existing links within nodes
T	:	Planned time horizon to complete the operation
V	:	Set of vehicles, defined by types
P	:	Set of products
G	:	Set of goals, targets
i, j	:	Indices to refer nodes $(i, j) \in A$ being $i, j \in N$
t, s	:	Indices to refer time periods $t, s \in \{1, .., T\}$
p, d	:	Indices to refer any products $p, d \in P$
f, m		Indices to refer food and medicine in products $f, m \in P$ respectively
k	:	Index to refer vehicle types $k \in V$
g	:	Index to refer goals $g \in G$

Parameters:

Notation		***Description***
dem_{ip}	:	Amount of demand at node $i \in N$ of product $p \in P$, in tons
avq_{ip}	:	Amount of available supply at node $i \in N$ of product $p \in P$, in tons
$dist_{ij}$	:	Length of arc $(i, j) \in A$, in km
$velr_{ij}$	:	Maximum velocity of arc $(i, j) \in A$, in km per hour
rel_{ij}	:	Probability of crossing the arc $(i, j) \in A$, $rel_{ij} \in [0,1]$
cap_k	:	Capacity of vehicle type $k \in V$, in tons
vel_k	:	Maximum velocity of vehicle type $k \in V$, in km per hour
$aveh_{ki}$	:	Number of available vehicles of type $k \in V$ at node $i \in N$

$tveh_k$	:	Total number of vehicle types $k \in V$ available for the operation
tr_{ijk}	:	Travel time of arc $(i,j) \in A$ using vehicle of type $k \in V$
cf_{ijk}	:	Empty travel cost; fixed cost of traveling through arc $(i,j) \in A$ using vehicle of type $k \in V$, per km
cv_{ijkp}	:	Load travel cost; variable cost of traveling through arc $(i,j) \in A$ using vehicle of type $k \in V$, per km and ton of product $p \in P$
pri_i	:	Priority level of node $i \in N$, $pri_i \in [0,1]$
tg_g	:	Target defined by decision maker for criterion g $\in G$; $tg_g \neq 0$
w_g	:	Weight of criterion g $\in G$ defined by decision maker
tm	:	Time measure helps adjust the length of time period
bd	:	Large value to create bounds for some constraints
dvQ	:	Fixed deviation of delivered aid, in tons
q_p	:	Total amount of product $p \in P$ desired to be distributed in the operation, in tons
b	:	Budget available to perform the operation

Variables:

Notation		***Description***
QC_{ijkpt}	:	Load of product $p \in P$ carried from $i \in N$ to $j \in N$ using vehicle of type $k \in V$ and starting in period $t \in \{1,..,T\}$, in tons
QS_{ipt}	:	Load of product $p \in P$ stored at node $i \in N$ at the beginning of period $t \in \{1,..,T\}$, in tons
NTV_{ijkt}	:	Number of vehicles of type $k \in V$ that start traveling from $i \in N$ to $j \in N$ in period $t \in \{1,..,T\}$
NV_{ikt}	:	Number of vehicles of type $k \in V$ available at node $i \in N$ at the beginning of period $t \in \{1,..,T\}$

BT_{ijk} : Binary variable taking value 1 if vehicle of type $k \in V$ travels through arc $(i,j) \in A$, 0 otherwise

BA_{ij} : Binary variable taking value 1 if any vehicle travels through arc $(i,j) \in A$, 0 otherwise

BQ_t : Binary variable taking value1 if load has been delivered in period $t \in \{1,..,T\}$, 0 otherwise

DV_g : Variable shows unwanted deviation of the criterion g $\in G$ from the its target, in units of criterion

DVQ : Variable shows unwanted deviation from desired amount of delivered aid, in tons

Considered criteria:

$Cost$: Total cost of the operation, in dollars

$Time$: Number of time periods required to complete the operation

TP : Time penalties variable adds higher penalties to long operations

EqF : Criterion of equity of food distribution; 0 if food demand of all nodes is completely fulfilled and positive otherwise

EqM : Criterion of equity of medicine distribution; 0 if medicine demand of all nodes is completely fulfilled and positive otherwise

$Prio$: Demand satisfaction priority criterion in the specific nodes; 0 if demand of priority nodes is completely fulfilled and positive otherwise

Rel : Reliability criterion indicates the most unreliable arc used in the operation

GR : Global route reliability criterion shows reliability of the whole set of arcs used in the operation

The model has to satisfy the following constraints:

1. <u>Hard constraints:</u>

   1.1. Constraints related to load:

$$\sum_{j/(j,i)\in A} \sum_{k} \sum_{s\leq t-tr_{jik}} QC_{jikps} + avq_{ip} = \sum_{j/(i,j)\in A} \sum_{k} \sum_{s\leq t} QC_{ijkps} + QS_{ipt} \qquad \forall i,p,t \qquad (8)$$

$$\sum_{i} QS_{ipT} = \sum_{i} avq_{ip} \qquad \forall p \qquad (9)$$

$$QC_{ijkpt}, QS_{ipt} \geq 0 \text{ and integer} \qquad \forall (i,j), \forall k, t, p \qquad (10)$$

Equations (8) are the dynamic load flow conditions that ensure that the load of each product at each node and time period is in balance. Constraint (9) makes sure that distributed and stored load at the end of the operation is equal to the available amount of aid. Equation (10) indicates that load variables should be non-negative, and, in our case, we would like the load variables to be integer.

1.2. Constraint related to travel time:

$$tr_{ijk} = \frac{dist_{ij} * tm}{\min\{vel_k,\ velr_{ij}\}} \qquad \forall (i,j), \forall k \qquad (11)$$

Constraint (11) computes travel time as the maximum number of time periods required to cross the arc, taking into account the speed limit of the arc and the speed characteristics of the type of vehicle, and assumes that the lowest value must be used. The time measure parameter tm is introduced as a tool to manipulate the length of one time period. In this particular model, $tm = 12$, which means that one period of time is equal to 5 minutes.

1.3. Constraints related to vehicles:

$$\sum_{j/(j,i)\in A} \sum_{s \leq t - tr_{jik}} NTV_{jiks} + aveh_{ki} = \sum_{j/(i,j)\in A} \sum_{s \leq t} NTV_{ijks} + NV_{ikt} \qquad \forall i, k, t \qquad (12)$$

$$\sum_{i} NV_{ikT} = \sum_{i} aveh_{ki} \qquad \forall k \qquad (13)$$

$$NTV_{jikt}, NV_{ikt} \geq 0 \text{ and integer} \qquad \forall (i,j), \forall k, t \qquad (14)$$

Constraint (12) creates the balanced flow of vehicles, taking into account the chronological sequence of time periods, the amount of products to be delivered to the node, the type of vehicle and the number of available vehicles in each node at a particular period of time. At the same time, constraint (13) ensures that only accessible vehicles are used for transportation. Equation (14) indicates that vehicle variables should be integer and non-negative.

1.4. Constraint in relation to vehicle-load:

$$\sum_{p} QC_{ijkpt} \leq cap_k \, NTV_{ijkt} \qquad \forall (i,j), \forall k, t, p \quad (15)$$

Condition (15) limits sum of the carried products to the capacity of the vehicle, so that the capacity is not exceeded.

2. <u>Attribute constraints:</u>

2.1. Cost conditions:

$$Cost = \sum_{(i,j) \in A} \sum_{k} \sum_{t} dist_{ij} \, (2cf_{ijk} \, NTV_{ijkt} + \sum_{p} cv_{ijkp} \, QC_{ijkpt}) \quad (16)$$

$$Cost \leq b \quad (17)$$

Equation (16) introduces the cost condition. The model assumes that the vehicles return empty to their original point, in other words, they twice go through the same cheap and reliable route without goods. The fixed cost includes all expenses that do not change throughout the operation, such as renting a vehicle, fuel, salaries of drivers and coordinators of the operation. These components are directly dependent on the type of vehicle. The variable cost includes loading/unloading charge for each type of products and fuel consumption. Total costs depend on the total travel distance, the selected routes, the number and type of used vehicles, the amount and product ratio of distributed aid. Condition (17) bounds the total costs for the operation by the budget and cannot be exceeded. Although, a desired target could be defined by the decision maker.

2.2. Load condition:

$$\sum_{i/dem_{ip}>0} QS_{ipT} \leq q_p \qquad \forall p \qquad (18)$$

Constraint (18) ensures that the maximum amount of each product planned for the operation is not exceeded. Parameter q_p represents the target of the global amount of aid desired to be distributed.

2.3. Equity conditions:

In the previously presented models, the authors did not consider such criterion as the equity of multicomodity delivery, therefore, the proposed approches to calculate the fairness of the distribution of goods between nodes were different. After conducting a series of experiments, we can maintain that the Min-Max goal programing approach provides the most even distribution plan for multi-product cases.

$$EqF \geq 1 - QS_{ifT}/dem_{if} \qquad \forall i/dem_{if} > 0 \qquad (19)$$

$$EqM \geq 1 - QS_{imT}/dem_{im} \qquad \forall i/dem_{im} > 0 \qquad (20)$$

Thus, constraint (19) shows the maximum inequity among the nodes, thereby measures how equitable is the distribution plan in relation to food. Constraint (20) computes the maximum inequity among the nodes in relation to medicine, thereby measures how equitable the medicine aid is distributed.

Using these constraints, the model computes the largest proportion of unsatisfied demand by product among the nodes. The criteria take values of real numbers between 0 and 1, so the variables are equal to 0 if demand of all nodes for the specified product is completely fulfilled, and positive otherwise. According to the goal programming methodology applying in this model, any target cannot take a zero value $tg_{\mathrm{g}} \neq 0$. Therefore, the target of the equity criteria will be a very small value close to zero.

2.4. Time conditions:

2.4.1. Operation time measure:

$$Time \geq t \cdot BQ_t \qquad \forall t > tg_{Time} \qquad (21)$$

In order to deal with the operation time two measures are introduced. Condition (21) represents the number of time period required to complete the operation. As mentioned earlier, in this case, a single period of time is equal to 5 minutes. The target value for the time criterion will be the number of periods during which it is desirable to complete the operation.

2.4.2. Time Penalty measure:

$$TP \geq \sum_{t > tg_{TP}} (t \cdot tg_{TP})^2 \cdot BQ_t \qquad (22)$$

Equation (22) serves to add a high penalty to long operations. The target value for the time penalty variable can be set based on how important it is to reduce the time of the operation, compared with other criteria in the model. If it is necessary to prioritize the $Time$ criterion, then the target value for the TP variable can be extremely small, up to zero ($tg_g \neq 0$). If the time criterion does not take priority in the planned mission, then the goal for the TP may be equal to the target of the $Time$ criterion ($tg_{Time} = tg_{TP}$). Both variables turn into 0 if corresponding goals are achieved and they output as positive values otherwise.

2.4.3. Auxiliary constraints in relation to time-vehicle:

$$tveh_k = \sum_i aveh_{ki} \qquad \forall k \qquad (23)$$

$$BQ_{t+1} \leq BQ_t \qquad \forall t \qquad (24)$$

$$NV_{ikt} - NV_{ikT} \leq \ tveh_k BQ_t \qquad \forall i, k, t \qquad (25)$$

$$NV_{ikT} - NV_{ikt} \leq \ tveh_k BQ_t \qquad \forall i, k, t \qquad (26)$$

$$\sum_{i}\sum_{j} NTV_{ijkt} \leq tveh_k BQ_t \qquad \forall k,t \qquad (27)$$

Binary variable takes value 1 if load has been delivered in period $t \in \{1,..,T\}$, 0 otherwise. Hence, shows how many periods were used for the operation. Constraints (24), (25), (26), (27) make sure that the binary time variable is defined correctly. Equation (23) computes total number of available vehicles of each type in the network and works as a bound for constraints (25), (26), (27).

2.5. Priority condition:

$$Prio = \sum_{i/pri_i>0} pri_i(1 - \sum_{p} QS_{ipT} / \sum_{d} dem_{id}) \qquad (28)$$

Priority appears as a demand satisfaction criterion at specific nodes. Equation (28) weights the sum of the corresponding unmet demand over the all demand nodes by their priority level. Such a criterion in a model that designed to optimize the distribution plan for post-disaster operations can play a crucial role, where the primary goal is to evenly deliver all the aid between the nodes in need. However, the decision maker may know for sure that there are several regions with very difficult access in an extremely unreliable area of the network. In this case, the model may refuse decisions with a lower cost or a shorter operation time, in favor of a solution in which the cost and time attributes deteriorate by a few percent, but it will allow to deliver the necessary amount of goods to needy settlements.

The target of the priority criterion can be a very small value close to zero, or any other value that the decision maker considers appropriate for a particular mission. Priority variable takes value of 0 only if demand of priority nodes is completely fulfilled, and it is positive otherwise.

2.6. Reliability conditions:

2.6.1. Minimum reliability measure:

Natural disasters severely affect the viability of many aspects of the life of the affected population. The obvious fact is that disasters also have a significant destructive impact on transport infrastructure. Therefore, one of the most important criteria in the design of a humanitarian logistics model is reliability. It is necessary to take into account the fact that the degree of destruction of road infrastructure is in great uncertainty after the disaster. One way to simulate this type of uncertainty is to conduct a reliability analysis. In this model, the reliability measure is defined through the probability of a successful route crossing. More precisely, the reliability parameter rel_{ij} is the probability of the traversal of the arc, which directly indicates the safety of the arc. The probabilities are determined separately for each link of the transport network.

$$Rel \leq rel_{ij} + 1 - BA_{ij} \qquad \forall(i,j) \qquad (29)$$

Constraint (29) represents that the worst arc in the distribution plan is considered as minimum reliability measure, in other words, it shows the most unreliable arc used to perform the operation. The target value of the criterion will be a very small value close to zero.

2.6.2. Global route reliability measure:

$$GR = \prod_{(i,j)/\ BA_{ij}>0} rel_{ij} \qquad (30)$$

$$GR = \sum_{(i,j)\in A} \log\ rel_{ij}\, BA_{ij} \qquad (31)$$

Condition (30) reflects global route reliability measure which is computed as product of all the probabilities of arcs among the set of arcs used in the operation. Such an equation assumes that all arcs are independent and have their own reliability values. In order to linearize this expression and allow the model to work with solvers such as CPLEX, the logarithm is applied (31). This criterion (31) significantly helps to increase the reliability of the route, taking into account not only the lowest value of reliability, but also intending to pick arcs with the highest probability throughout the route.

The target value of the GR criterion should be determined on the basis of knowledge that the value is represented by the logarithm. Accordingly, the target might be equal to $\log(0.99) = -0.01$. However, applying the realism of the constructed model, we assumed that all the links used are reliable and have a probability of 0.95. Also, taking into account the number of arcs in the presented case and assuming that at least half of the arcs in the existing transport network will be used to build the optimal solution, the following conclusion was made. Under ideal conditions, the product of all the probabilities for a realistic solution, that is, the global reliability along the entire route, will be less than or equal to 0.30. Thus, as a target value, there is no need to set a value other than $\log(0.3) = -1.2$ and ask the model to achieve unattainable goals.

At the same time, it is worth noting that the goal programming objective function is formulated in such a way that targets cannot be negative values. Consequently, the goal condition for the GR criterion (46) is set so as to avoid negativity, while maximizing the desired criterion. As the result, the target of the GR criterion should be set equal to 1.2. Despite my reasoning, in any other operation, the decision maker can be guided by their own considerations and determine other target values for the criterion.

2.6.3. Auxiliary constraints in relation to arc-vehicle:

$$NTV_{ijkt} \leq bd\ BT_{ijk} \qquad \forall k, \forall(i,j), \forall t \qquad (32)$$

$$\sum_t NTV_{ijkt} \geq BT_{ijk} \qquad \forall k, \forall(i,j) \qquad (33)$$

$$BA_{ij} \geq BT_{ijk} \qquad \forall k, \forall(i,j) \qquad (34)$$

$$BA_{ij} \leq \sum_k BT_{ijk} \qquad \forall(i,j) \qquad (35)$$

$$BQ_t,\ BA_{ij}, BT_{ijk} \in \{0,1\} \qquad \forall(i,j), \forall k, t \qquad (36)$$

The following constraints (32), (33), (34), (35) are introduced to guarantee that the binary variables are defined correctly. Condition (36) says that these variables are binary and they can only take 0 or 1 values.

3. <u>Goal constraints:</u>

3.1. Load goal conditions:

3.1.1. First level: primary goal constraint:

$$\sum_{p}\sum_{i/dem_{ip}>0} QS_{ipT} + DVQ = \sum_{p} q_p \tag{37}$$

Constraint (37) is utilized as the load condition for the first level of the model. Parameter q_p represents the target amount of the aid desired to be distributed. The equation assures that at the end of the operation the sum of delivered goods in all the nodes that have a demand for a particular product should be equal to the quantity of products planned to the distribution, summarized over all products. If the condition is not fulfilled, then a positive value will be assigned to the deviation variable DVQ, equal to the amount of aid that could not be delivered. If the condition is satisfied, the variable will remain equal to zero.

3.1.2. Second level: load goal constraint:

$$\sum_{p}\sum_{i/dem_{ip}>0} QS_{ipT} + dvQ = \sum_{p} q_p \tag{38}$$

This equation is applied to designate the load condition at the second level of the model. After the value of the load deviation is determined, the variable DVQ is no longer involved in the calculations. It is replaced by the parameter dvQ, which fixes the value of the load deviation for the load condition of the second level. Thus, it can be noted that constraint (38) differs from constraint (37) only by parameter dvQ, otherwise performing a similar function in the model calculations.

3.2. Cost goal constraint:

$$Cost - DV_{Cost} \leq tg_{Cost} \tag{39}$$

The presented above equation (39) is used in order to fit total cost to a desired target. By default, we already have a boundary for costs in terms of budget. However, from the real life point of view, a human being always wants not only to keep costs within the available amount of money, but also to save. Therefore, the target value for the cost condition can be set equal to 50% of the budget or any other reasonable amount, according to the decision maker.

3.3. Equity goal constraints:

$$EqF - DV_{EqF} \leq tg_{EqF} \tag{40}$$

$$EqM - DV_{EqM} \leq tg_{EqM} \tag{41}$$

These conditions (40), (41) serve to indicate the goal for equity in the distribution of each type of product in the humanitarian operation. Specifically, they indicate that the maximum deviations between delivered load and demand is intended to be minimized.

3.4. Time goal constraints:

$$Time - DV_{Time} \leq tg_{Time} \tag{42}$$

$$TP - DV_{Time} \leq tg_{Time} \tag{43}$$

The goal constraints (42), (43) are formulated so that the time of the operation is minimized as much as possible.

3.5. Priority goal constraint:

$$Prio - DV_{Prio} \leq tg_{Prio} \tag{44}$$

Since the priority criterion reflects the unsatisfaction of demand for the nodes designated by the priority, the priority goal constraint (44) is aimed at minimizing this value.

3.6. Reliability goal constraints:

$$Rel + DV_{Rel} \geq tg_{Rel} \tag{45}$$

$$GR + DV_{GR} \geq - tg_{GR} \tag{46}$$

Equations (45), (46) are the goal constraints for the reliability criteria. The constraints show that the reliability values are intended to be maximized. The corresponding deviation variables will serve to compare obtained reliability values with the target values.

$$Cost, EqF, EqM, Time, TP, Prio, Rel, DV_{g} \geq 0 \tag{47}$$

Equation (47) indicates that attribute variables take non-negative values. An exception is global route reliability criterion, since it outputs a logarithmic value, and natural logarithm of $x \in [0, 1]$ takes non-positive values.

4. <u>Objective functions:</u>

4.1. The final lexicographical goal programming model:

$$Lex \min z = \left[(DVQ), \left(\sum_{g} \frac{w_{g}}{tg_{g}} DV_{g} \right) \right] \tag{48}$$

The final model is based on a two-phase solving method, known as lexicographical goal programming. The mathematical formulation of the objective function of the model is written in the expression above (48).

Researchers constantly argue about the strengths and weaknesses of this method. However, relying on the studied literature, can be concluded that this is one of the most popular methods for solving this kind of problem. It stands alongside Scalarization, Pareto optimization and Compromise programming. At the same time, studies show that Compromise programming and Goal programming provide are the most relevant methods for multi-criteria optimization. A survey conducted by Jones and Tamiz (2002) shows that in the case of using goal programming to solve real problems, most of them were solved using the lexicographic approach. Also, a while ago Romero (1991) performed a research in which he proved that most of the flaws of the lexicographical goal programming methodology arise due to its incorrect application. At the fact, some properties of the method, interpreted as disadvantages, can turn into advantages for problems in real life.

4.2. The first level model:

The lexicographic goal programming model considers two priority levels among goals. For humanitarian distribution operations, the primary goal is, certainly, the delivery of planned amount of aid to the affected population. However, set conditions, such as a budget, the number of vehicles available for transportation, or a short time horizon may lead to this objective being impossible to achieve.

Therefore, the first level of the model aims to determine the maximum total quantity of goods that can be distributed under existing restrictions. For this purpose, the desired quantity of products to be delivered is set as the target (37), and the model calculates whether it is possible to distribute the entire desired amount of aid or whether there is a deviation from the target.

For all of the above, at the first level of the lexicographical model, the remaining goals defined for the mission are not taken into account, but their constraints must, of course, be included in the model. Simply, they are not optimized on the first level of the solution.

In the matter of fact, the objective function of the first level is to minimize the deviation of the load criterion DVQ and, in the ideal case, it will be equal to zero.

$$\min DVQ \quad \text{s.t. } (8) \text{ to } (29), (31) \text{ to } (37) \qquad (49)$$

Equation (49) shows the model formulation for the first level solution, the objective function and constraints to be included.

4.3. The second level model:

Once the first level of the model has been solved, we know how much of the global load can be distributed with the available set of resources.Therefore, we know the load deviation value that must be fixed in order to proceed to the second level of solution.

$$\min \sum_{g} \frac{w_g}{tg_g} DV_g \quad \text{s.t. } (8) \text{ to } (29), (31) \text{ to } (36), (38) \text{ to } (47) \tag{50}$$

To continue the solving process, the objective function of the model is replaced by the one shown in expression (50), constraint (37) is replaced by constraint (38). Further, the remaining goal constraints from (39) to (47) are added to the resulting model, as shown in expression (50).

In our case, the goals are not represented in the same units of measurement as indicated in the original theory (Chapter 2.1), so the normalization method was implemented in the objective function as follows.

The principle of operation of the second objective function is: by dividing each deviation variable by the corresponding goal, we obtain normalized units for each criterion, such manipulation allows us to work with a percentage expression of satisfaction for each goal. In addition, the criteria are assigned their own weight of importance that shows the preference of each criterion over other criteria for the decision maker. Weights can be set subjectively or by experimental selection after several runs of models and evaluation of the results.

Ultimately, we derive a weighted sum of all goal deviations for each criterion, except the load criterion. And the objective value of the function should be minimized.

The presented model was implemented in AMPL and solved using CPLEX in parallel mode as optimizer (AMPL Optimization inc. 2020).

Although that the model was formulated to meet the research objectives for a specific case study, it can be used for any humanitarian operations with relevant objectives. In other words, for missions aimed at distributing multi-commodity humanitarian aid in the aftermath of the catastrophe, which entailed the destruction of transport infrastructure and the violation of the reliability of roads.

5.0 FINDINGS

5.1 Computational experiments

After running the model for the first lexicographical level, which takes into account only the criterion of maximum quantity to be distributed, the following result was obtained. With available resources, the maximum amount of humanitarian aid that can be distributed is 2945 tons, and the deviation from the target is 80 tons. Nevertheless, for an operation of this magnitude this is very good value, since we are able to deliver more than 97% of desired quantity.

In order to run the model for the second lexicographical level, it is necessary to fix the value of the distributed aid and replace the objective function with the goal programming objective function, as described in Chapter 4.2. We can then proceed to the further calculations.

The pay-off matrix shown in Table 8 is obtained by running the model of the second level to optimize each of the criteria independently. Each row shows the values of attributes when optimizing each of the criteria one by one. The ideal value for each criterion is in the diagonal of the pay-off matrix and is highlighted in bold.

Table 8 Pay-off matrix

Criterion	Cost, $	Time, hour	TP	EqF	EqM	Prio	Rel	GR	
								log	%
Cost	**799 342**	2,5	5525	1	1	1,8	0,52	-2,4	9,4
Operation Time	998 942	**1,7**	1240	1	1	1,79	0,1	-6,9	0,11
Time Penalty	974 028	0,7	**14**	1	1	1,8	0,52	-1,9	13,8
Equity Food	999 112	2,5	5525	**0**	1	0,25	0,1	-7,2	0,07
Equity Medicine	997 901	2,5	5525	1	**0,2**	1,49	0,29	-4,7	0,84
Priority	991 038	2,5	5525	1	1	**0**	0,29	-3,7	2,5
Reliability	998 680	2,5	5525	1	1	0,82	**0,87**	-0,37	69,3
Global Route Rel	997 824	2,5	5525	1	1	0,76	0,87	**-0,21**	**81,1**

Source: own development

The pay-off matrix shows a complex conflict between criteria. For example, it is clearly seen that food distribution equity (*EqF*) is not fully satisfied in any scenario, except where the criterion of the food distribution equity is optimized. However, it can also be noted that in the best scenario this indicator can be reduced to zero, that is, it is completely fulfilled. The situation is the same with the equity criterion (*EqM*) for medicine, but here the best possible option is to satisfy the demand of all nodes by at least 80%.

As can be seen from Table 8, the best value of the cost criterion is given in the scenario with individual cost optimization. While all other scenarios simply satisfy the budget constraint. Therefore, the target value of this criterion can be set as US$800 000.

The maximum time of operation is 2.5 hours (30 time periods), which is associated with the length of time horizon set as an input parameter. At the same time, the minimum reasonable time for the operation is 1.7 hours, i.e. 20 time periods, shown for the scenario that optimizes the *Time* criterion.

The second time criterion (*TP*) is introduced for penalties for long operations and its minimization shows that if we want to reduce the operation time as much as possible, giving preference to the time criterion over other criteria, we can successfully use this attribute as a tool for this. However, further in the analysis (Chapter 5.2) we will see how such a prescription affects the uniformity of aid distribution.

In the best case scenario, it is possible to satisfy the demand of priority nodes by 100%. And the most reliable route in the operation has a minimum probability of crossing the arc of 0.87 with an overall route reliability of 81%.

Based on the data obtained from the pay-off matrix, the operation requirements and the results of the reliability analysis, target values were set for the goal criteria. The target values and other input data for the model are presented in Appendix 5.

5.2 Solution analysis

Table 9 represents the results of the aggregate solutions to show the sensitivity of the model to criterion weights. The first column shows the criteria that have been simultaneously optimized, and the rows contain the results obtained for each of the criteria. Green color indicates the best value of the criteria throughout the computational experiments, and yellow indicates the second best value.

The results of optimization of all considered criteria with criteria weights already determined by the decision maker, are shown in the last row of the table. Thus, the optimal Pareto solution for this problem is obtained. With the help of green and yellow designations it is clearly seen that this solution, although it is a trade-off for some criteria, mainly shows values close to the ideal.

Table 9 Solution result for aggregated goals

Criteria	Cost, $	Time, hour	TP	EqF	EqM	Prio	Rel	GR	
								log	%
Cost & Time & TP	799 802	1,7	14	1	1	1,76	0,52	-1,61	19,8
Cost & Rel & GR	987 939	2,5	5525	1	1	0,74	0,87	-0,21	81,1
Cost & EqF & EqM & Prio	936 175	2,5	5525	0,002	0,2	0	0,1	-8,5	0,02
Cost & Time & TP & EqF & EqM	993 456	1,8	1785	0	0,2	0,024	0,1	-10,1	0,001
EqF & EqM & Prio	999 967	2,5	5525	0,002	0,2	0	0,1	-11,4	0,001
Rel & GR	999 973	6	5525	1	1	0,74	0,87	-0,21	81,1
Optimal solution	**995 107**	**1,8**	**1785**	**0**	**0,2**	**0**	**0,52**	**-3,7**	**2,5**

Source: own development

The following analysis is aimed at identifying demand satisfaction at network nodes, depending on the distribution policy applied. The result of the calculations is presented in the tables above (Table 10), (Table 11).

Table 10 Distribution plan of food for each set of criteria

Node	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Demand, tons	75	105	40	60	255	95	35	225	165	1530
Criteria	*Demand satisfaction, %*									
Cost	140	66	2037	0	480	0	0	0	224	0
Operation Time	286	804	487	0	372	0	0	0	212	1
Time Penalty	0	0	2762	0	521	0	0	0	90	0
Equity Food	100	100	100	100	100	100	100	100	100	100
Equity Medicine	0	57	1412	0	413	0	0	0	396	16
Priority	224	671	2062	0	329	0	134	0	0	0
Reliability	0	123	0	0	90	0	0	0	133	131
Global Route Rel	266	176	0	0	0	0	0	0	0	143
Aggregated criteria	*Demand satisfaction, %*									
Cost & Time & TP	666	414	2925	0	98	0	0	0	90	5
Cost & Rel & GR	266	190	0	0	0	0	0	0	0	142
Cost & EqF & EqM & Prio	100	100	100	100	101	100	100	100	100	99
Cost & Time & TP & EqF & EqM	100	100	100	100	100	100	100	100	100	100
EqF & EqM & Prio	100	100	100	100	101	100	100	100	100	99
Rel & GR	253	190	0	0	0	0	0	0	0	143

Source: own development

Table 11 Distribution plan of medicine for each set of criteria

Nodes	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
Demand, tons	10	20	5	10	45	20	5	25	30	270
Criteria	Demand satisfaction, %									
Cost	0	25	0	0	622	0	0	0	250	0
Operation Time	800	400	0	0	56	0	0	0	583	0
Time Penalty	800	1000	0	0	0	0	0	0	267	0
Equity Food	0	0	0	0	622	0	0	0	267	0
Equity Medicine	100	80	80	80	80	105	80	80	80	80
Priority	0	275	0	0	567	0	500	0	83	0
Reliability	0	400	0	0	178	0	0	0	0	74
Global Route Rel	800	650	0	0	0	0	0	0	0	56
Aggregated criteria	Demand satisfaction, %									
Cost & Time & TP	300	0	0	0	556	0	0	0	267	0
Cost & Rel & GR	800	400	0	0	0	0	0	0	0	74
Cost & EqF & EqM & Prio	80	80	80	80	87	95	120	80	80	80
Cost & Time & TP & EqF & EqM	80	100	80	90	80	80	100	84	83	80
EqF & EqM & Prio	80	80	80	80	91	80	120	80	83	80
Rel & GR	800	400	0	0	0	0	0	0	0	74

Source: own development

Carrying out such an analysis will serve as a good understanding of the situation for the decision maker. In the event that the area is not familiar or the decision maker does not have sufficient experience to assess the situation "by eye" and determine the necessary parameters, the value of goals and weight for the criteria.

By deriving the pay-off matrix and analyzing the resulting distribution plans, it is possible to clearly see which nodes are far away and it takes more time to supply them; which nodes are in a significantly damaged area and the model routes them in such a way as to avoid them by any means; at which nodes the route is laid without much effort and, accordingly, they can be used as transhipment points for the subsequent mission, if the first one has not been 100% fulfilled.

For example, with individual optimization of the Time Penalty criterion, food is delivered in only 3 nodes out of 10, and the demand for medicine is also satisfied for only 3 nodes.

The same is true for aggregate solutions. While minimizing costs and time (Cost & Time & TP), 6 nodes received food delivery, while three of them received delivery in quantities many times greater than their demand, 2 nodes received 90% and 98% of the food demand, and one node did not receive assistance in the amount of 95%, that is, received only

5%. Meanwhile, with this policy, all available medicine was distributed in three nodes (N1, N5, N9), in an amount exceeding their demand.

Let us observe how the construction and reliability of the route depends on the selected optimization policy. Figures 12-16 show maps with distribution plan for each aggregated solution.

Figure 12 Humanitarian aid distribution network for Cost & Time & TP solution

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQdyRbN8D

Source: own development

Using only cost and time criteria to solve this problem leads to the fact that the model seeks to use only the arcs closest to the depots, without paying attention to the equity of humanitarian aid distribution (Figure 12). However, this distribution scheme has turned out to be quite secure in terms of reliability, with a minimum probability of crossing the arc of 0.52 (Table 9). Although considering the remaining indicators it is completely useless in terms of humanitarian logistics.

The policy of aggregating costs and reliability criteria also does not yield the desired results. Figure 13 shows that aid is distributed only to the nodes nearest to the depots. But this time there is even no link between N3 and D4 due to the insufficient reliability of the arc, and it was replaced by the arc N10-D4. With such a distribution scheme, the minimum arc reliability is 0.87 (Table 9).

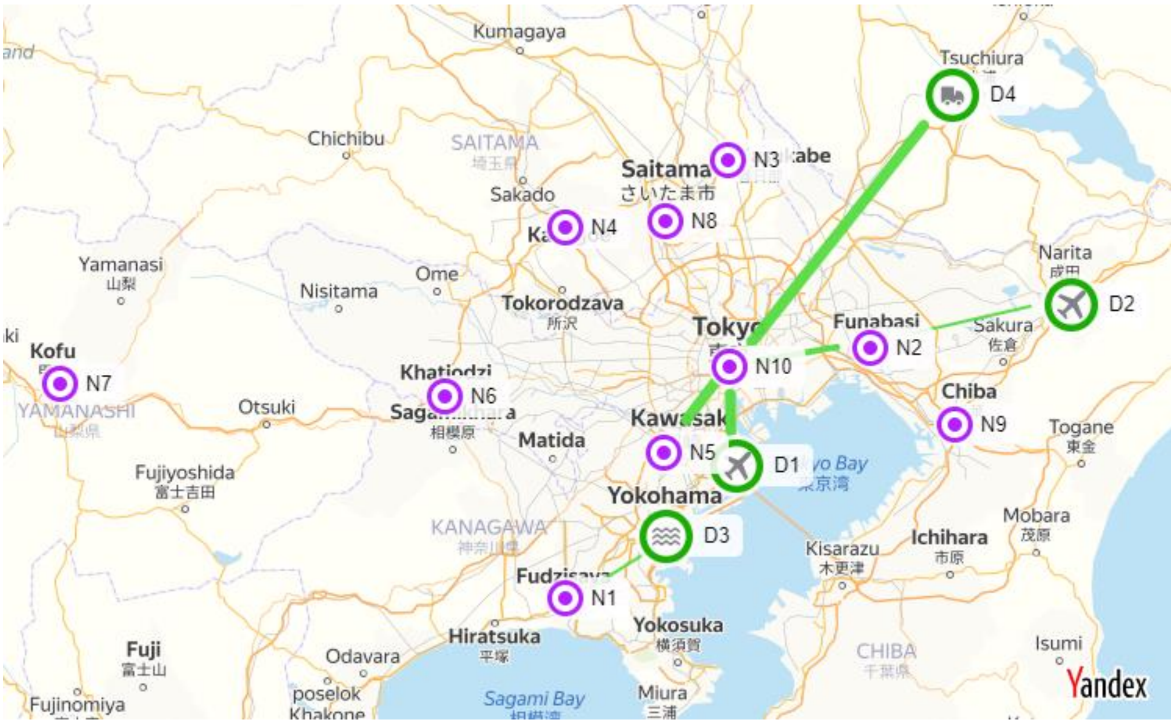

Figure 13 Humanitarian aid distribution network for Cost & Rel & GR solution

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQdyRFuwB

Source: own development

Figure 14 Humanitarian aid distribution network for EqF & EqM & Prio solution

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQdyRVf-C

Source: own development

Optimization of equity criteria for food and medicine, and the priority criterion provides a solution that satisfies the first level of lexicographical model. The food equity criterion has a value of 0.002, which is very close to the ideal point; the medicine equity criterion has an ideal value of 0.2 for this set of restrictions, and the priority criterion takes a value of 0.024, which is also very close to the ideal (Table 9). Meanwhile, we can clearly see on the map (Figure 14) that «red» links were used in the route. This means that such a scheme may be unsafe and unreasonable for the operation.

Figure 15 Humanitarian aid distribution network for Cost & EqF & EqM & Prio solution

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQdyRBj0A

Source: own development

Figure 15 shows a distribution scheme for a solution aimed at minimizing costs and equitable distribution of aid, especially to priority nodes. Such a scheme can be applied for a logistics operation in which it is necessary to minimize costs and satisfy consumers as much as possible, but the delivery time would not be a criterion of efficiency, there are would be no reliability criteria. At the same time, the maximum delivery time is determined by the time horizon and is a limitation of the time criterion for a logistics operation.

If the usual logistics problem of multi-product distribution of production were considered, the delivery scheme shown in Figure 16 would have the status of the optimal one, since this aggregated solution takes into account all the main goals of distribution logistics: delivery cost, delivery speed – delivery in the shortest possible time, as well as equitable distribution of products and their delivery to the final consumer. However, in humanitarian logistics, we cannot allow distribution services to use such a delivery scheme. The map clearly shows that this scheme involves a very large number of unreliable roads. Therefore, distribution according to such a scheme will be unreasonable due to security reasons, and also because it may make it impossible to deliver products to the appropriate nodes and reduce the success of the operation to zero.

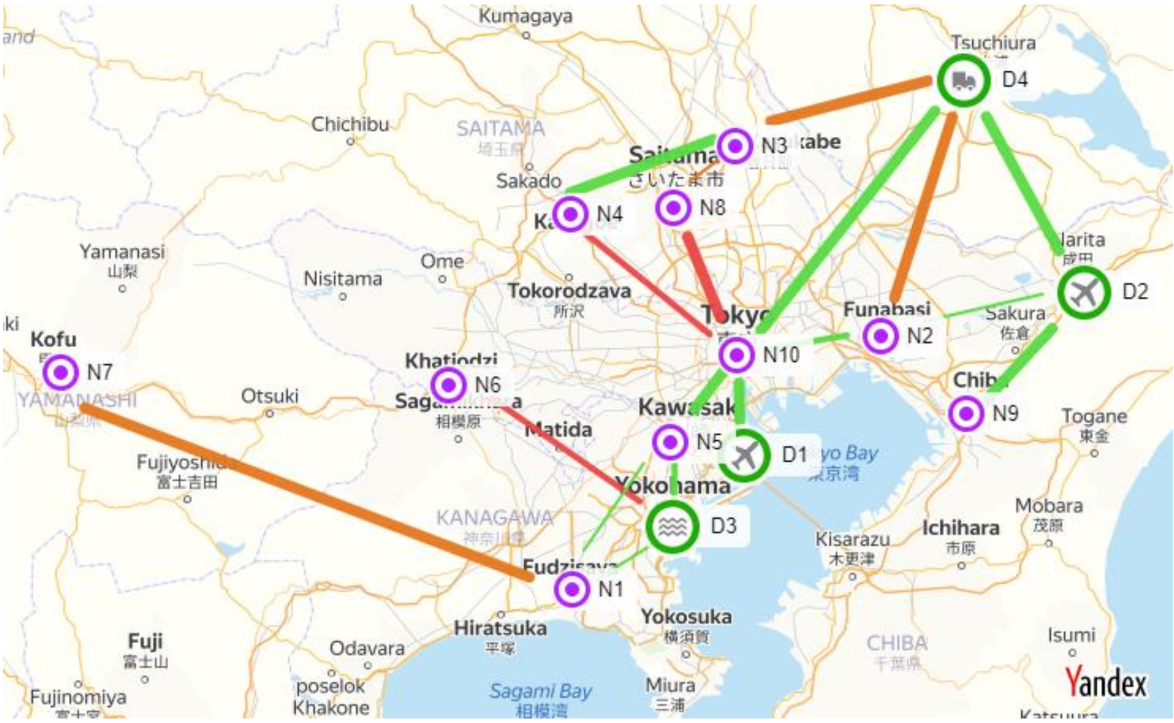

Figure 16 Humanitarian aid distribution network for Cost & Time & TP & EqF & EqM solution

Interactive vertion of the map can be found here: https://yandex.com/maps/-/CCQdyRFtTB

Source: own development

Demonstrating the distribution schemes on the maps, we ignored the Rel & GR aggregated solution. Since if we pay attention to Table 9, we can see that such a solution is absolutely dominated by the Cost & Rel & GR solution, therefore it is no longer of interest for research.

Finally, after analyzing the results of various combined solutions, it is time to move on to the optimal solution.

Based on all the data analyzed, we can observe how easily the objective value of the criterion deteriorates when trying to optimize others. Nevertheless, with the help of well determined target values and goal weights, we managed to get the optimal solution for this problem. The distribution plan for it is shown in Table 12. It reflects the demand for each product in tons and the amount of aid actually received in percent, as well as the completion time for each node. As can be seen from the table, the optimal solution has good results. For example, the demand for food is 100% satisfied for all but one node. This is not surprising, given that Tokyo's demand for food is 1 530 tons, which is 51% of the total quantity of humanitarian aid to be distributied. However, the minimum satisfaction of the demand for medicine among all nodes is 80%.

Also, observing the time indicators, we can conclude that the resulting solution is 27% faster than the maximum allowable time limited by the time horizon. Moreover, we can consider that the operation was performed in 1.83 hours or 110 minutes.

Table 12 Optimal solution: distribution plan for demand nodes

Node	Demand, tons		Satisfaction, %		Completion time, hours
	food	medicine	food	medicine	
N1	75	10	100	80	1,08
N2	105	20	100	100	1,75
N3	40	5	107	80	1,42
N4	60	10	100	80	1,83
N5	255	45	100	82	1,83
N6	95	20	100	80	1,83
N7	35	5	100	120	1,83
N8	225	25	100	80	1,83
N9	165	30	100	83	1,83
N10	1530	270	99	80	1,83

Source: own development

Figure 17 shows a map with all the arcs involved in the optimal routes. In the figure we can see that the proposed routes is reliable enough for a successfully executed humanitarian operation. The minimum probability of crossing an arc is 0.52. The global reliability of the route is 2.5%, which is also a good value considering that the global route reliability is calculated as a product of the probability of all arcs used along the route (Table 9).

The total cost is US$995 107, so we managed to save, but not much, only US$4 893.

Also this solution fully satisfies the set priorities for nodes N7 and N10, which required to meet the total demand of N7 by 100% (priority = 1) and total demand of N10 by 80% (priority = 0.8).

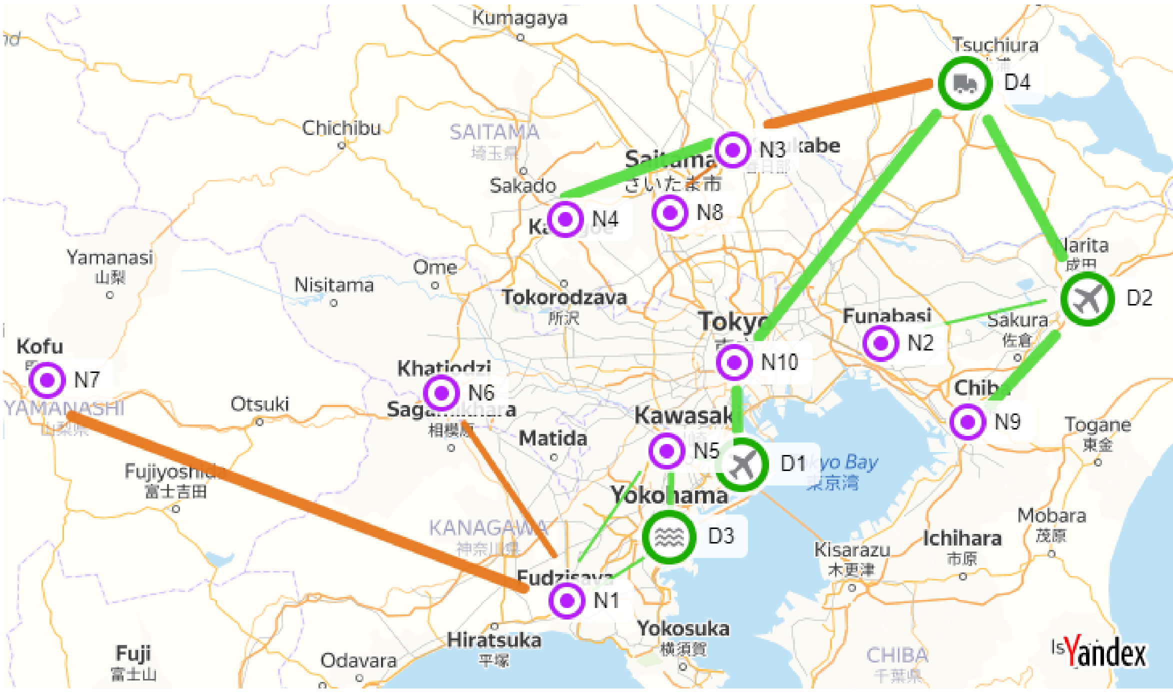

Figure 17 Humanitarian aid distribution network for the optimal solution

The interactive version of the map can be found here: https://yandex.com/maps/-/CCQz5LQNhD

Source: own development

Let us take a closer look at the output data that the model provides and interpret them for our benefit.

Table 13 shows changes in load flow over the time horizon. Based on changes in the load flow, we can analyze which nodes were used as transshipment facilities. In Table 13, the nodes marked in yellow at a certain period of time indicate unnatural load activity: a positive increase in the amount of load in the node, and then negative. This indicates that aids were delivered to the node by one group of vehicles, intended for distribution to other nodes by another group of vehicles. Consequently, the nodes were used as transshipment points.

The model does not directly take into account loading and unloading time in transshipment nodes, however, the time horizon is divided into periods in such a way as to allow a delay of 5 minutes. Nevertheless, in real life a lot will depend on the method of loading and unloading, and, accordingly, on the time of labor: whether the unloading will be carried out by single aid kit, and the kits will be transfered to another vehicle one by one piece, or the goods will be placed on pallets, thus the loading/unloading will be performed many times faster. Also, in cases, where a quick response is required, there are logistical techniques such as overloading an entire container. This requires special equipment and carries additional costs, but contributes to a significant reduction in the operation time.

Table 13 Load flow over time horizon

Time period	Time elapsed, hour	D1	D2	D3	D4	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10
1	0,08	1041	375	295	1225	0	0	0	0	0	0	0	0	0	0
2	0,17	1041	370	295	1180	0	0	0	0	166	0	0	0	0	0
3	0,25	1041	320	295	1180	0	0	0	0	166	0	0	0	0	0
4	0,33	1041	320	280	1180	0	0	0	0	166	0	0	0	0	23
5	0,42	1041	320	230	1180	29	0	0	0	181	0	0	0	0	23
6	0,50	1041	320	205	1180	29	0	0	0	181	0	0	0	95	23
7	0,58	1041	320	85	820	4	0	0	0	166	0	0	0	120	23
8	0,67	1056	320	85	820	4	0	0	0	166	0	0	0	165	23
9	0,75	1056	320	85	650	4	0	45	0	166	0	0	0	165	23
10	0,83	1056	290	40	630	4	0	0	0	166	0	0	0	165	23
11	0,92	1056	195	40	385	19	0	0	0	207	0	0	0	165	23
12	1,00	1060	195	40	285	4	0	0	0	207	0	0	0	165	23
13	1,08	1060	195	40	285	8	0	0	0	207	0	0	0	165	23
14	1,17	1060	195	40	285	83	0	0	45	252	0	0	0	165	23
15	1,25	1060	195	40	285	83	0	0	45	252	0	0	45	165	23
16	1,33	1060	195	40	285	83	0	0	45	252	0	0	45	165	23
17	1,42	595	170	40	285	83	0	177	45	252	25	0	45	165	383
18	1,50	595	170	40	285	83	0	47	45	252	25	0	45	165	383
19	1,58	350	170	0	285	83	0	47	45	252	25	0	45	165	383
20	1,67	0	170	0	285	83	0	47	45	252	25	0	45	165	848
21	1,75	0	170	0	285	83	30	47	45	252	25	0	45	165	848
22	**1,83**	0	170	0	285	83	125	47	45	252	90	0	45	165	1293
23	1,92	0	170	0	285	**83**	**125**	**47**	**68**	**292**	**111**	**41**	**245**	**190**	**1743**

Source: own development

The table (Table 14) shows the number of vehicles that start travelling from node *i* to node *j* at a period of time *t*.

As we can see from the schedule, all available vehicles were used to complete the operation. Some vehicles have been used repeatedly, since according to the schedule, 267 vehicles are used in this distribution schedule, and the total number of available vehicles is 244 (small – 119, medium – 81, large – 44). It can also be noted that the last time period in which the shipment was made is the 20th period, that is, 1.67 hours. And all distribution was completed after two more time periods, that is, 1.83 hours after the start of the operation.

It is assumed that a vehicle may leave the node *i* with the loaded aid or the vehicle may be requested from the node *i* as available one in order to pick up the aid from a nearby node *j*, in which case the vehicle will leave the node *i* empty.

Table 14 Distribution schedule for the operation: number of vehicles

From	To	Vehicle type	Time period																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
D1	N5	small	25																			
		medium	3																			
		large	3																			
	N10	small																				25
		medium																	31		3	
		large	1																		8	9
D2	D4	small		1	1																	
		medium																				
		large	1																			
	N2	small											1									
		medium										2	6									
		large																				
	N9	small	1		9																	
		medium	6																			
		large	1																1			
D3	N1	small																				
		medium				1			5													
		large					2	1														
	N5	small																			8	
		medium	1						3			3										
		large																				
D4	N3	small											9									
		medium	3	3																		
		large									8	1										
	N10	small																				
		medium							24													
		large											8	4								
N1	N6	small																				
		medium												1								
		large							1					2	1							
	N7	small																				
		medium					3															
		large																				
N3	N4	small																				
		medium								3												
		large																	1			
	N8	small																				
		medium										3										
		large																		8		
N5	D1	small																				
		medium							1				3						3			
		large							1													
	D3	small			1																	
		medium																				
		large		1																		
	N1	small																				
		medium		3																		
		large		1																		
N9	D2	small						1														
		medium						6														
		large										1										

Source: own development

Table 15 Distribution schedule for the operation: amount of aid

From	To	Vehicle type	Time period																
			1	2	3	4	5	6	7	8	9	10	11	12	13	17	18	19	20
D1	N5	small	125																
		medium	45																
		large	66																
	N10	small																	125
		medium														465		45	
		large	23															200	225
D2	D4	small		5	5														
		medium																	
		large	25																
	N2	small											5						
		medium										30	90						
		large																	
	N9	small	5		45														
		medium	90																
		large	25													25			
D3	N1	small																	
		medium				15			75										
		large					50	25											
	N5	small																40	
		medium	15						45			45							
		large																	
D4	N3	small											45						
		medium	45	45															
		large									200	25							
	N10	small																	
		medium							360										
		large											200	100					
N1	N6	small																	
		medium												15					
		large							25					50	25				
	N7	small																	
		medium					41												
		large																	
N3	N4	small																	
		medium								45									
		large														23			
	N8	small																	
		medium										45							
		large															200		
N5	D1	small																	
		medium							15				0			0			
		large							0										
	D3	small			0														
		medium																	
		large		0															
	N1	small																	
		medium		45															
		large		25															
N9	D2	small						0											
		medium						0											
		large										0							

Source: own development

According to the presented distribution schedule (Table 14), it is not possible to determine if vehicle is loaded or empty (whether the vehicle is on the route or overcomes a transit node). Therefore, in Table 15, the schedule of aid distribution over time periods is presented.

The schedule (Table 15) does not reflect the amount of load for each product, indicating the total quantity to be delivered from node *i* to node *j* during time period *t.*

In this case, it is assumed that food does not require special storage conditions, such as refrigerators, etc. So food and medicine can be transported simultaneously on the same vehicle. Therefore, to simplify the perception of the process, the data is summarized and the total load for all products is presented.

6.0 DISCUSSION

The model presented in this work is an extended version of the model developed by Tirado et al. (2014). In the basic model, such extensions were added as the ability to carry out multi-commodity delivery, the ability to determine the priority for all desired demand nodes and two criteria for road reliability. The first criterion is responsible for maximizing reliability based on the worst arc used in the distribution route, and the second criterion is aimed at maximizing reliability based on all arcs used in the operation. The ability to calculate travel time as a maximum between the speed limit of the road used and the speed characteristics of the vehicle traveling along it was also added.

The presented model adds the possibility to adjust the length of the time period depending on the preferences of the decision maker. This tool is convenient to manipulate when planning long operations. Since the indicator of effective work of the model is the speed of the program, and with a large number of time periods (or with a long time horizon), the number of alternative solutions significantly increases and the speed of response of the model decreases. To avoid such inconveniences, it is proposed to increase the length of one time period, which in turn will favorably affect the response time of the model and will not significantly affect the quality of the provided distribution plan and schedule.

Vitoriano et al. (2011) applied the priority condition for the model for humanitarian operations. The distinction exists in the fact that the authors implement the criterion of a priority node, while in the model presented in this work, priority can be given to several nodes at once in the same or different degree, depending on the choice of the decision maker. Such a formulation not only allows us to assign priority to several nodes at the same time, but also allows the priority criterion not to conflict with the equity criterion and optimize them simultaneously in the same solution.

Ortuño et al. (2011) also considered a reliability criterion in their paper. However, it is different from that proposed in this paper. The model, proposed by the authors (Ortuño et al. 2011), assumes the use of a security criterion based on the probability of robbery along the route. And the authors believe that the ransack probability can be reduced and the relevance of the safety attribute improved by traveling in a convoy. In connection with this feature of the model, the reliability criterion is also calculated for a convoy traveling through an arc.

However, as we have already justified in Chapter 3.0 that in the presented case study, related to the humanitarian operation in Japan, there is no sense in applying the safety criterion based on the probability of being ransacked and overloading the model.

In my personal opinion, the fact that vehicle can move independently and not be guided by a group (convoy) allows it to be more maneuverable and mobile. This leads to the fact that the vehicle can overcome its route faster, which is an undeniable advantage for humanitarian operations. When traveling in a convoy, the speed of the slowest vehicle must be taken into account. If such a situation occurs that the speed characteristics of the vehicles are different, the entire convoy is obliged to move at a speed not exceeding the minimum of the maximum speeds of the vehicle moving together. This can significantly degrade the performance of the time criterion for long operations.

7.0 CONCLUSIONS

7.1 Research summary

The lexicographical dynamic flow model based on multi-objective optimization using goal programming approach for solving the multi-commodity aid distribution problem has been presented in this work.

The model provides a plan of distribution of humanitarian aid and a realistic distribution schedule for vehicles, taking into account seven goals related to the quantity to be distributed, the cost of the operation, the time of the operation, the equity of distribution for each type of humanitarian aid, the priority of the designated nodes, the minimum arc reliability and the global reliability of the route.

The realistic case was also collected based on the recent disaster in Japan. It was used to solve the problem and to evaluate the work of the developed model. It also aims to bring benefits and advantages to future research on humanitarian logistics.

7.2 Limitations of the study

The case study provides a rough estimate of uncertainty by collecting information from secondary sources. Close cooperation with international humanitarian organizations and rescue services is necessary for more reliable information, as detailed reliable information about a recent disaster is not officially released long after the accident. And most of it is usually confidential.

The model takes into account all criteria necessary for humanitarian operations, except security or the likelihood of not being robbed. For operations with low expected security on some routes, this criterion should be considered essential. For a long time horizon the response time of the model can be significantly longer, the measures described in Chapter 6.0 should be used or the option of splitting a large operation into several smaller ones should be considered, e.g. dividing an affected area into several sections.

Also, the model can be transformed in the following way. The model has no limitation on exceeding the required demand in the node. In order to preserve the possibility of transshipment in transit nodes, it is possible to introduce a limit that allows to exceed the load, for example, by a maximum of 20% of the required amount or to introduce a certain amount, for example, a maximum of 15 tons. Such a contrastraint will not complicate the model, but may be useful for operations with different capacity of the nodes. As in this case, for example, node N10 (Tokyo) requires 51% of distributed aid, overloading for such a node in the neighboring small node can be an impossible task for a small neighbor.

7.3 Suggestions for further research

Considering uncertainties in models for humanitarian logistics can be done in an infinite number of ways, and for an evolving field of logistics such as humanitarian logistics they will all be important and useful.

The study can be continued towards multimodal transportation, as a logistics distribution network usually consists of several types of transport.

Another way to improve the study is to develop a model for evaluating a multi-criteria solutions. This can be done with the Interactive Decision Maps technique. Such a study would move forward not only in the field of human logistics, but also in any field of science that uses multi-criteria decision making analysis.

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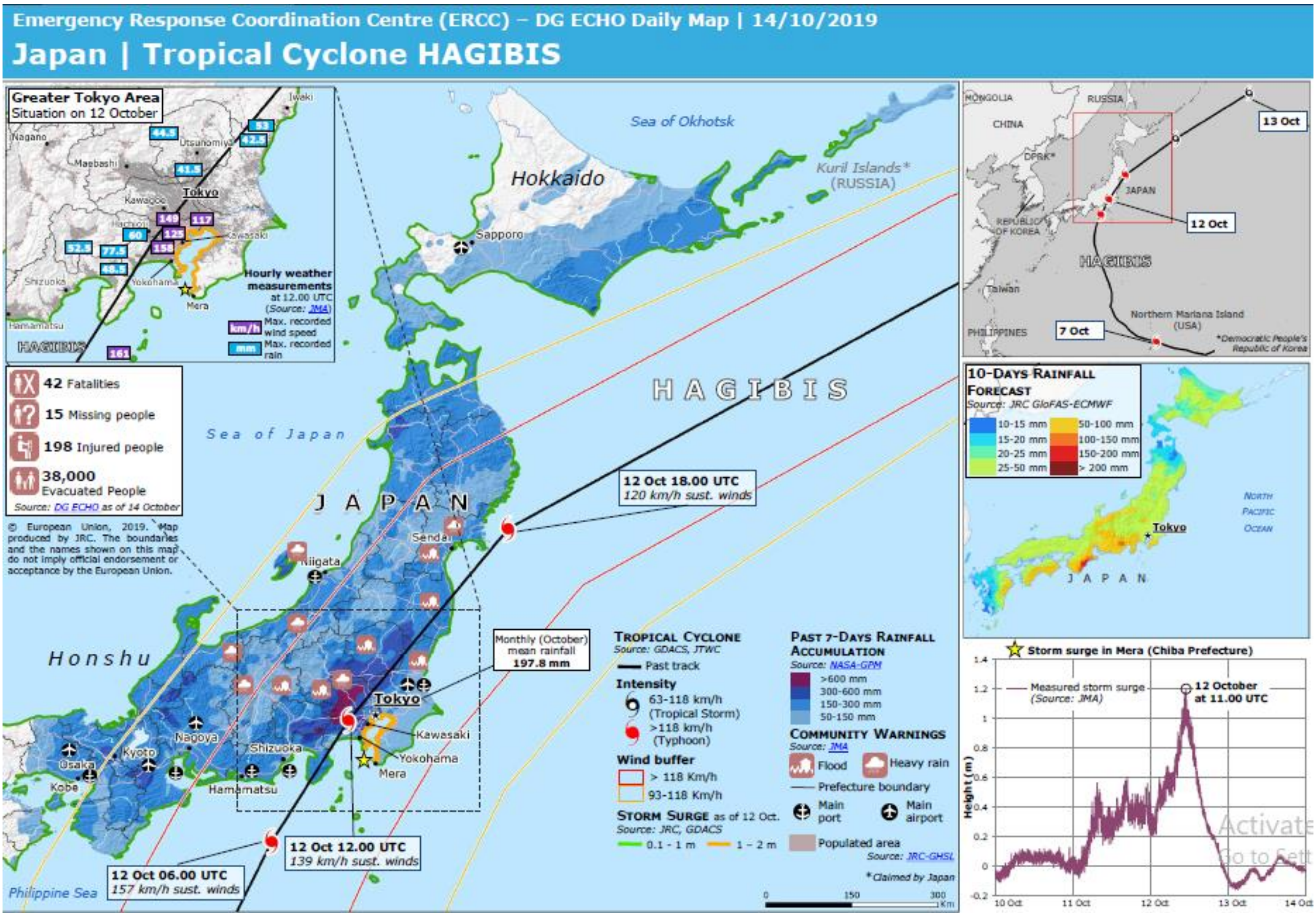
APPENDICES

Appendix 1: Emergency Response Coordination Centrer report



Appendix 2: Case study calculations

The table below shows measurement of demand according to the population of the settlement as 2 kg per person, on the assumption that about 10% of the city's population needed help, with 15% (300 grams per person) being healthcare products and medicines, while the remaining 75% is food.

Name	**Nodes**	**Population**	Demand **demand (ton)**		Supply **q_avail (ton)**	
			food	medicine	food	medicine
Haneda Airport	Depot 1				1100	200
Narita Airport	Depot 2				440	80
Yokohama Port	Depot 3				230	80
Distribution Center	Depot 4				1270	0
Fujisawa	Node 1	423 894	75	10		
Funabashi	Node 2	622 890	105	20		
Kasukabe	Node 3	232 709	40	5		
Kawagoe	Node 4	350 745	60	10		
Kawasaki	Node 5	1 475 000	255	45		
Hachioji	Node 6	577 513	95	20		
Kofu	Node 7	193 125	35	5		
Saitama	Node 8	1 264 000	225	25		
Chiba	Node 9	971 882	165	30		
Tokyo	Node 10	9 273 000	1530	270		

Appendix 3: Network characteristics

Links		Length	Speed	Probability of being available
i	**j**	**distance (km)**	**arc_velocity (km/h)**	**arc_reliability**
D1	D3	25	90	0,88
D1	N2	35	90	0,85
D1	N5	4	50	0,78
D1	N9	50	90	0,89
D1	N10	20	90	0,97
D2	D4	51	90	0,79
D2	N2	45	50	0,99
D2	N9	35	90	0,8
D3	D1	25	90	0,88
D3	N1	26	50	0,99
D3	N5	20	70	0,98
D3	N6	50	70	0,29
D4	D2	51	90	0,79
D4	N2	67	90	0,1
D4	N3	52	90	0,52
D4	N10	70	90	0,87
N1	D3	26	50	0,99
N1	N6	55	70	0,59
N1	N7	130	90	0,61
N1	N5	9	50	0,99
N2	D1	35	90	0,85
N2	D2	45	50	0,99
N2	D4	67	90	0,1
N2	N9	17	50	0,89
N2	N10	22	70	0,99
N3	D4	52	90	0,52
N3	N4	40	90	0,97
N3	N8	20	50	0,56
N3	N10	50	70	0,24
N4	N3	40	90	0,97
N4	N7	150	90	0,79
N4	N8	20	50	0,89
N4	N10	50	70	0,21
N5	D1	4	50	0,78
N5	D3	20	70	0,98
N5	N1	9	50	0,99
N5	N10	19	90	0,79
N6	D3	50	70	0,29
N6	N1	55	70	0,59
N6	N7	98	90	0,88
N6	N10	50	70	0,53
N7	N1	130	90	0,61
N7	N4	150	90	0,79
N7	N6	98	90	0,88
N8	N3	20	50	0,56
N8	N4	20	50	0,9
N8	N10	30	90	0,2
N9	D1	50	90	0,89
N9	D2	35	90	0,8
N9	N2	17	50	0,89
N10	D1	20	90	0,97
N10	D4	70	90	0,87
N10	N2	22	70	0,99
N10	N3	50	70	0,24
N10	N4	50	70	0,21
N10	N5	19	90	0,79
N10	N6	50	70	0,53
N10	N8	30	90	0,2

Appendix 4: Case study model code

```
mod;

param T;                                        #time horizon

set NODE;                                       #set of nodes
set ARC within (NODE cross NODE);               #set of acrs
set VEH;                                        #set of vehicles, defined by type
set PROD;                                       #set of products
set TARGET;


param demand {i in NODE, p in PROD};            #demand at node i of product p, in units of load
param q_avail {i in NODE, p in PROD};           #supply at node i of product p, in units of load

param distance {(i,j) in ARC};                  #length of arc
param arc_velocity {(i,j) in ARC};              #maximum velocity thought arc (i,j) in ARC
param arc_rel {(i,j)in ARC};                    #probability of crossing the arc

param capacity {k in VEH};                      #capacity of vehicle type k, in units of load
param velocity {k in VEH};
param veh_avail {k in VEH, i in NODE};          #number of available vehicles of type k at node i

param total_Nveh {k in VEH} = sum{i in NODE} veh_avail[k,i];
                                                #total number of vehicles that are available for the operation
param time_measure ;
param travel_time {(i,j)in ARC, k in VEH} = (distance[i,j]/(min (velocity[k], arc_velocity[i,j])))*time_measure ;
                                        #periods of time needed to travel from node i to node j with vehicle type k

param fix_cost {(i,j)in ARC, k in VEH};
                #fixed cost of traveling through arc (i,j) by vehicle type k, per unit of length
param var_cost {(i,j)in ARC, k in VEH, p in PROD};
                #cost of traveling through arc (i,j) by vehicle type k, per unit of lenght and load of product p

param n_priority {NODE};

param target {TARGET};
param weight {TARGET};

param bd;                                       #bounds
param Deviation_Q_opt;                          #fixed distribution amount of aid from the 1st level


param quantity {p in PROD};                     #amount of aid desired to be distributed in the operation
param budget;                                   #budget available to perform the operation


var Carried_Q {i in NODE, j in NODE, k in VEH, p in PROD, t in 1..T} >= 0 integer;
                        #load of product p carried from i to j using vehicle type k and starting in period t
var Stored_Q {i in NODE, p in PROD, t in 1..T} >= 0 integer;
                        #load of product p staying (stored or received) at node i in period t

var NTr_Veh {i in NODE, j in NODE, k in VEH, t in 1..T} >= 0 integer;
                        #number of vehicles of type k that start traveling from i to j in period t
var N_Veh {i in NODE, k in VEH, t in 1..T} >= 0 integer;
                        #number of vehicles of type k that are available at node i at the beginning of period t

var BQ {t in 1..T} binary;                      #1 if all load has been delivered in period t, 0 otherwise
var BTr_veh {(i,j)in ARC, k in VEH} binary;     #1 if vehicle type k travels from i to j
var Arc_Use {(i,j)in ARC} binary;               #1 if any vehicle travels from i to j

var Deviation {g in TARGET} >= 0;               #unwanted deviation variable
var Deviation_Q >= 0;                           #delivered aid deviation from desired amount of delivered aid
```

```
var Cost <= budget;                    #total cost of the operation
var Time >= 0;                         #number of time periods required to complete the operation
var Time_Penalty >= 0;                 #additional time variable to add higher penalties to long operations
var Equity_F >= 0;                     #food equity measure, normalized value between 0 and 1;
var Equity_M >= 0;                     #medicine equity measure, normalized value between 0 and 1;
var Priority >= 0;                     #proportion of satisfied demand in the specific nodes
var Min_Reliability >= 0;              #the worst arc used in the operation in terms of reliability
var GL_Route_Reliability;              #global reliability, the whole set of arcs used in the operation


minimize DVQ: Deviation_Q;             #objective function for the 1st level

minimize Sum_Of_Weighted_Deviations: sum{g in TARGET}( weight[g] / target[g] * Deviation[g] )    ;

        #objective function for the 2nd level is to minimize the sum of weighted deviations from the targets

subject to Load_Flow{i in NODE, p in PROD, t in 1..T}: sum{j in NODE:(j,i)in ARC}
        sum{k in VEH, s in 1..T: i<>j and s <= t - travel_time[j,i,k]} Carried_Q[j,i,k,p,s] + q_avail[i,p] =
        sum{j in NODE:(i,j)in ARC} sum{k in VEH, s in 1..T: i<>j and s <= t} Carried_Q[i,j,k,p,s] + Stored_Q[i,p,t];
                                                      #dynamic flow balance consraint for load
subject to Load_Avail {p in PROD}: sum{i in NODE} Stored_Q[i,p,T] = sum{i in NODE} q_avail[i,p];
                                  #constraint ensures that load of product p staying at node i is available

subject to Vehicles_Flow{i in NODE, k in VEH, t in 1..T}: sum{j in NODE:(j,i)in ARC}
        sum{s in 1..T:  i<>j and s <= t - travel_time[j,i,k]} NTr_Veh[j,i,k,s] + veh_avail[k,i] =
        sum{j in NODE:(i,j)in ARC} sum{s in 1..T:  i<>j and s <= t}  NTr_Veh[i,j,k,s] + N_Veh[i,k,t];
                                              #dynamic flow balance constraint for the vehicles

subject to Vehicles_Avail{k in VEH}: sum{i in NODE} veh_avail[k,i] = sum{i in NODE}N_Veh[i,k,T];
                                  #constraint ensures that only available vehicles are used for tranportation

subject to Capacity{(i,j)in ARC, k in VEH, t in 1..T}:
        sum{p in PROD}Carried_Q[i,j,k,p,t] <= capacity[k] *  NTr_Veh[i,j,k,t];
                                              #checks that vehicle capacity is not exceeded

### goal conditions

subject to Cost_Condition:
        Cost = sum{(i,j)in ARC, k in VEH, t in 1..T: i<>j } distance[i,j] *
        (2 * fix_cost[i,j,k] *  NTr_Veh[i,j,k,t] + sum{p in PROD}var_cost[i,j,k,p] * Carried_Q[i,j,k,p,t]);
                                                          #introduction of the cost condition

subject to Load_Condition {p in PROD}: sum{i in NODE: demand[i,p]>0} Stored_Q[i,p,T] <= quantity[p];
                              #constraint ensures that the max amount of planned load is not exceeded

subject to Equity_Food_Condition {i in NODE: demand[i,'food']>0}:
                                  Equity_F >= 1 - (Stored_Q[i,'food',T]/demand[i,'food']);

subject to Equity_Med_Condition {i in NODE: demand[i,'medicine']>0}:
                                  Equity_M >= 1 - (Stored_Q[i,'medicine',T]/demand[i,'medicine']);
                                              #measures how equitable the distribution plan is

subject to Linear_OT {t in 1..T: t > target['Time']}: Time >= t * BQ[t];
                              #represents the number of time period required to complete the opeeration

subject to Penalty_OT:
        Time_Penalty = sum{t in 1..T: t > target['Time_Penalty']}((t - target['Time_Penalty'])^2)* BQ[t];
                                                      #adds high penalties to the long operations


subject to BQ_definition {t in 1..T-1}: BQ[t+1] <= BQ[t];

subject to N1 {i in NODE, k in VEH, t in 1..T}: N_Veh[i,k,t] - N_Veh[i,k,T] <= total_Nveh[k] * BQ[t];

subject to N2 {i in NODE, k in VEH, t in 1..T}: N_Veh[i,k,T] - N_Veh[i,k,t] <= total_Nveh[k] * BQ[t];

subject to NL {k in VEH, t in 1..T}: sum{i in NODE, j in NODE}  NTr_Veh[i,j,k,t] <= total_Nveh[k] * BQ[t];
```

```
subject to Prior_Condition: Priority = sum{i in NODE: n_priority[i]>0}
        n_priority[i]*(1 -(sum{p in PROD}Stored_Q[i,p,T]/sum{d in PROD}demand[i,d]));
                                                #increases the relevance of nodes with difficult access


subject to BiContr9 {k in VEH,(i,j)in ARC, t in 1..T}:  NTr_Veh[i,j,k,t] <= bd* BTr_veh[i,j,k];

subject to BiContr10{k in VEH,(i,j)in ARC}: sum{t in 1..T}  NTr_Veh[i,j,k,t] >=  BTr_veh[i,j,k];

subject to BiContr11{k in VEH,(i,j)in ARC}: Arc_Use[i,j] >= BTr_veh[i,j,k];

subject to BiContr12{(i,j)in ARC}: Arc_Use[i,j]<= sum{k in VEH} BTr_veh[i,j,k];


subject to Worst_Case_Rel {(i,j)in ARC}: Min_Reliability <= arc_rel[i,j] + 1 - Arc_Use[i,j];
                                        #the worst arc used in the operation in terms of reliability

subject to Global_Rel: GL_Route_Reliability = sum{(i,j)in ARC} log(arc_rel[i,j]) * Arc_Use[i,j];
                                        #reliability for the whole set of arcs used in the operation


subject to Load_Goal_1st:
        sum{p in PROD, i in NODE: demand[i,p]>0} Stored_Q[i,p,T] + Deviation_Q = sum{p in PROD}quantity[p];
                                                        #quantity to be distributed on the 1st level


subject to Load_Goal_2nd:
        sum{p in PROD, i in NODE: demand[i,p]>0} Stored_Q[i,p,T] + Deviation_Q_opt = sum{p in PROD}quantity[p];
                                                        #quantity to be distributed on the 2nd level


subject to Cost_Goal: Cost - Deviation['Cost'] <= target['Cost'];

subject to Equity_Goal_Food: Equity_F - Deviation['Equity_F'] <= target['Equity_F'];

subject to Equity_Goal_Medicine: Equity_M - Deviation['Equity_M'] <= target['Equity_M'];

subject to Time_Goal: Time - Deviation['Time'] <= target['Time'];

subject to TP_Goal: Time_Penalty - Deviation['Time_Penalty'] <= target['Time_Penalty'];

subject to PrNodes_Goal: Priority - Deviation['Priority'] <= target['Priority'];

subject to Rel_Goal: Min_Reliability + Deviation['Min_Reliability'] >= target['Min_Reliability'];

subject to GR_Goal: GL_Route_Reliability + Deviation['GL_Route_Reliability'] >= - target['GL_Route_Reliability'];
```

Appendix 5: Case study input data

```
data;

param T := 30;

set NODE := D1 D2 D3 D4 N1 N2 N3 N4 N5 N6 N7 N8 N9 N10; #set of nodes
set VEH := small medium large;                           #set of vehicles, defined by type
set PROD := food medicine ;                              #set of products


param:  TARGET:          weight  target :=
        Cost             1       800000
        Time             1       20
        Time_Penalty     1       5
        Equity_F         2       0.001
        Equity_M         2       0.001
        Priority         1       0.001
        Min_Reliability 2        1
        GL_Route_Reliability 1   1.2
        ;


param Deviation_Q_opt := 80;                             #fixed distribution amount of aid from the 1st level

param quantity := food 2585 medicine 440;                #amount of aid desired to be distributed in the operation

param budget := 1000000;                                 #budget available to perform the operation

param bd := 100000;                                      #bounds for some constraints
param time_measure := 12;                                #ensures that each time period is 5 minutes

param n_priority default 0 := N7 1      N10 0.8;         #priority coefficients

param demand default 0 (tr)
        :        N1      N2      N3      N4      N5      N6      N7      N8      N9      N10     :=
        food     75      105     40      60      255     95      35      225     165     1530
        medicine 10      20      5       10      45      20      5       25      30      270     ;

param q_avail default 0 (tr)
        :        D1      D2      D3      D4      :=
        food     1100    440     230     1270
        medicine 200     80      80      0       ;


param capacity := small 5 medium 15 large 25    ;
param velocity := small 100 medium 90  large 80 ;         #maximum velocity of the vehicle type j


param veh_avail default 0
        :       D1      D2      D3      D4      :=
        small   50      12      7       50
        medium  30      8       13      30
        large   20      2       2       20      ;
```

```
                                                                        #maximum velocity thought arc (i,l)
param:  ARC:            distance        arc_velocity    arc_rel :=      #how reliable an arc is
        D1 D3           25              90              0.88
        D1 N2           35              90              0.85
        D1 N5           4               50              0.78
        D1 N9           50              90              0.89
        D1 N10          20              90              0.97
        D2 D4           51              90              0.79
        D2 N2           45              50              0.99
        D2 N9           35              90              0.8
        D3 D1           25              90              0.88
        D3 N1           26              50              0.99
        D3 N5           20              70              0.98
        D3 N6           50              70              0.29
        D4 D2           51              90              0.79
        D4 N2           67              90              0.1
        D4 N3           52              90              0.52
        D4 N10          70              90              0.87
        N1 D3           26              50              0.99
        N1 N6           55              70              0.59
        N1 N7           130             90              0.61
        N1 N5           9               50              0.99
        N2 D1           35              90              0.85
        N2 D2           45              50              0.99
        N2 D4           67              90              0.1
        N2 N9           17              50              0.89
        N2 N10          22              70              0.99
        N3 D4           52              90              0.52
        N3 N4           40              90              0.97
        N3 N8           20              50              0.56
        N3 N10          50              70              0.24
        N4 N3           40              90              0.97
        N4 N7           150             90              0.79
        N4 N8           20              50              0.89
        N4 N10          50              70              0.21
        N5 D1           4               50              0.78
        N5 D3           20              70              0.98
        N5 N1           9               50              0.99
        N5 N10          19              90              0.79
        N6 D3           50              70              0.29
        N6 N1           55              70              0.59
        N6 N7           98              90              0.88
        N6 N10          50              70              0.53
        N7 N1           130             90              0.61
        N7 N4           150             90              0.79
        N7 N6           98              90              0.88
        N8 N3           20              50              0.56
        N8 N4           20              50              0.9
        N8 N10          30              90              0.2
        N9 D1           50              90              0.89
        N9 D2           35              90              0.8
        N9 N2           17              50              0.89
        N10 D1          20              90              0.97
        N10 D4          70              90              0.87
        N10 N2          22              70              0.99
        N10 N3          50              70              0.24
        N10 N4          50              70              0.21
        N10 N5          19              90              0.79
        N10 N6          50              70              0.53
        N10 N8          30              90              0.2
        ;
```

```
param fix_cost
        :         small   medium  large   :=
        D1  D3    20      50      70
        D1  N2    20      50      70
        D1  N5    20      50      70
        D1  N9    20      50      70
        D1  N10   20      50      70
        D2  D4    20      50      70
        D2  N2    20      50      70
        D2  N9    20      50      70
        D3  D1    20      50      70
        D3  N1    20      50      70
        D3  N5    20      50      70
        D3  N6    20      50      70
        D4  D2    20      50      70
        D4  N2    20      50      70
        D4  N3    20      50      70
        D4  N10   20      50      70
        N1  D3    20      50      70
        N1  N6    20      50      70
        N1  N7    20      50      70
        N1  N5    20      50      70
        N2  D1    20      50      70
        N2  D2    20      50      70
        N2  D4    20      50      70
        N2  N9    20      50      70
        N2  N10   20      50      70
        N3  D4    20      50      70
        N3  N4    20      50      70
        N3  N8    20      50      70
        N3  N10   20      50      70
        N4  N3    20      50      70
        N4  N7    20      50      70
        N4  N8    20      50      70
        N4  N10   20      50      70
        N5  D1    20      50      70
        N5  D3    20      50      70
        N5  N1    20      50      70
        N5  N10   20      50      70
        N6  D3    20      50      70
        N6  N1    20      50      70
        N6  N7    20      50      70
        N6  N10   20      50      70
        N7  N1    20      50      70
        N7  N4    20      50      70
        N7  N6    20      50      70
        N8  N3    20      50      70
        N8  N4    20      50      70
        N8  N10   20      50      70
        N9  D1    20      50      70
        N9  D2    20      50      70
        N9  N2    20      50      70
        N10  D1   20      50      70
        N10  D4   20      50      70
        N10  N2   20      50      70
        N10  N3   20      50      70
        N10  N4   20      50      70
        N10  N5   20      50      70
        N10  N6   20      50      70
        N10  N8   20      50      70
        ;
```

```
param var_cost :=
[*,*,*,food]
        :        small   medium  large   :=
        D1  D3   1       1.1     1.3
        D1  N2   1       1.1     1.3
        D1  N5   1       1.1     1.3
        D1  N9   1       1.1     1.3
        D1  N10  1       1.1     1.3
        D2  D4   1       1.1     1.3
        D2  N2   1       1.1     1.3
        D2  N9   1       1.1     1.3
        D3  D1   1       1.1     1.3
        D3  N1   1       1.1     1.3
        D3  N5   1       1.1     1.3
        D3  N6   1       1.1     1.3
        D4  D2   1       1.1     1.3
        D4  N2   1       1.1     1.3
        D4  N3   1       1.1     1.3
        D4  N10  1       1.1     1.3
        N1  D3   1       1.1     1.3
        N1  N6   1       1.1     1.3
        N1  N7   1       1.1     1.3
        N1  N5   1       1.1     1.3
        N2  D1   1       1.1     1.3
        N2  D2   1       1.1     1.3
        N2  D4   1       1.1     1.3
        N2  N9   1       1.1     1.3
        N2  N10  1       1.1     1.3
        N3  D4   1       1.1     1.3
        N3  N4   1       1.1     1.3
        N3  N8   1       1.1     1.3
        N3  N10  1       1.1     1.3
        N4  N3   1       1.1     1.3
        N4  N7   1       1.1     1.3
        N4  N8   1       1.1     1.3
        N4  N10  1       1.1     1.3
        N5  D1   1       1.1     1.3
        N5  D3   1       1.1     1.3
        N5  N1   1       1.1     1.3
        N5  N10  1       1.1     1.3
        N6  D3   1       1.1     1.3
        N6  N1   1       1.1     1.3
        N6  N7   1       1.1     1.3
        N6  N10  1       1.1     1.3
        N7  N1   1       1.1     1.3
        N7  N4   1       1.1     1.3
        N7  N6   1       1.1     1.3
        N8  N3   1       1.1     1.3
        N8  N4   1       1.1     1.3
        N8  N10  1       1.1     1.3
        N9  D1   1       1.1     1.3
        N9  D2   1       1.1     1.3
        N9  N2   1       1.1     1.3
        N10 D1   1       1.1     1.3
        N10 D4   1       1.1     1.3
        N10 N2   1       1.1     1.3
        N10 N3   1       1.1     1.3
        N10 N4   1       1.1     1.3
        N10 N5   1       1.1     1.3
        N10 N6   1       1.1     1.3
        N10 N8   1       1.1     1.3

[*,*,*,medicine]
        :        small   medium  large   :=
        D1  D3   1       1       1
        D1  N2   1       1       1
```

```
D1  N5    1         1         1
D1  N9    1         1         1
D1  N10   1         1         1
D2  D4    1         1         1
D2  N2    1         1         1
D2  N9    1         1         1
D3  D1    1         1         1
D3  N1    1         1         1
D3  N5    1         1         1
D3  N6    1         1         1
D4  D2    1         1         1
D4  N2    1         1         1
D4  N3    1         1         1
D4  N10   1         1         1
N1  D3    1         1         1
N1  N6    1         1         1
N1  N7    1         1         1
N1  N5    1         1         1
N2  D1    1         1         1
N2  D2    1         1         1
N2  D4    1         1         1
N2  N9    1         1         1
N2  N10   1         1         1
N3  D4    1         1         1
N3  N4    1         1         1
N3  N8    1         1         1
N3  N10   1         1         1
N4  N3    1         1         1
N4  N7    1         1         1
N4  N8    1         1         1
N4  N10   1         1         1
N5  D1    1         1         1
N5  D3    1         1         1
N5  N1    1         1         1
N5  N10   1         1         1
N6  D3    1         1         1
N6  N1    1         1         1
N6  N7    1         1         1
N6  N10   1         1         1
N7  N1    1         1         1
N7  N4    1         1         1
N7  N6    1         1         1
N8  N3    1         1         1
N8  N4    1         1         1
N8  N10   1         1         1
N9  D1    1         1         1
N9  D2    1         1         1
N9  N2    1         1         1
N10  D1   1         1         1
N10  D4   1         1         1
N10  N2   1         1         1
N10  N3   1         1         1
N10  N4   1         1         1
N10  N5   1         1         1
N10  N6   1         1         1
N10  N8   1         1         1
;
```