BACHELOR THESIS

Humanitarian Drone Logistics after a flooding event

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WINGS FOR AID

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PREFACE

Dear reader,

This thesis contains the research with the title “Humanitarian drone logistics after a flooding event”. I performed this research project as my graduation assignment for the bachelor program Industrial Engineering and Management at the University of Twente. This thesis is part of a collaboration research project with the foundation Wings For Aid and the University of Twente, the research was performed from February 2022 until July 2022.

First of all, I would like to thank Robert van Steenbergen for acting as my first supervisor from the University of Twente. He always provided me with lots of insights, feedback and new ideas. I appreciated the availability and the simplicity of scheduling meetings. Besides, I would like to thank Martijn Mes for his efforts acting as my second supervisor. Finally, I want to thank my friends and family for supporting me during the process.

Kinds regards,

Xander Bon

Enschede, September 2022

MANAGEMENT SUMMARY

The collaboration between the University of Twente and the foundation Wings For Aid initiated the research project researching last mile drone logistics for humanitarian aid. Wings For Aid is currently developing a cargo drone system for humanitarian aid, their mission is to deliver relief goods in disaster areas with their in-house developed MiniFreighter cargo drone. The research project aims to study historical disasters and evaluate the potential impact drones could have in the relief operations. As a contribution to the research project, the flood of the Netherlands in 1953 is researched. The thesis examines the potential impact drones could have on the relief operation after a disaster with similar characteristics as the flood. To accomplish this the following research question is formulated:

"What are the expected effects of using cargo drones in a relief operation after a disaster with the characteristics of the flood of the Netherlands in 1953?"

First, a contextual analysis is performed. This analysis is performed in order of gathering the complete picture of the disaster and its relief operation. With this full situational image, the simulation model later on can be constructed to represent the real-life situation as realistic as possible. Additionally, all relevant input data regarding the disaster and its relief operation linked to the themes; Geographical information, People & demand, Supply chain network and Vehicles & UAVs is gathered and transformed.

The contextual analysis is followed by a literature study regarding coordination mechanisms, a mechanism representing the logistical coordination of the relief operation after a flood. In the literature study, relevant literature in the subject areas of heuristics for solving vehicle routing problems, humanitarian and heterogeneous fleet coordination mechanisms and last mile distribution in humanitarian relief are examined. With the insights gained from the literature study, the heuristic for the vehicle allocation process is constructed.

When all the necessary input data forming the building bricks of the simulation model were gathered, the data is transformed such that it fits the simulation model format. This is followed by the construction of the simulation model itself. After the conceptual model is completed the model was validated by Ronald van Gent. He is an experienced aerial engineer who was involved in the ideation phase of Wings For Aid.

Once the simulation model was validated and insights gathered, the experiments in the form of interventions with respect to the base model are formulated. The performance results of the base model serve as the benchmark for the interventions in order of examining the effects they have. The base model includes the limitations resulting from the extreme weather in 1953, it deploys one Hercules c130 cargo aircraft to carry out the relief operation and Naval Airfield Valkenburg is selected as humanitarian hub resulting in all dropping flights ascending from this airfield. Considering the interventions, consistently one variable is changed within the experiment to be able to assess the effects this specific change has on the performance results of the relief operation as a whole. The performance results or Key Performance Indicators (KPIs) that are selected to represent the performance of a relief operation, are the total cost in euros and the total duration in hours of the entire relief operation. After all experiments are formulated, they are executed and their corresponding results are gathered.

From the results of the experiments, a few conclusions can be drawn. The first is that the deployment of humanitarian drones along side a cargo plane positively effect the cost performance of a relief operation after a flooding event. Adding the drones alongside the plane to the relief operation, without including the extreme windspeeds result in a decrease in total operational costs of 6.7%. Meanwhile, the total duration of the relief operation increases with 4.8% compared to the scenario where only the plane is deployed. Certain locations are chosen to be satisfied by cargo drones based upon costs perspective, but due to speed and capacity limitations require a longer time before the complete demand of the specific location is satisfied. Another conclusion made is, assigning a specific airfield as humanitarian hub has significant effects on the performance results of the relief operation. With selecting a different humanitarian hub instead of Naval Airfield Valkenburg, the total cost of the relief operation show a decrease of 19.5%-21.3% and the total duration of the relief operation decreases with 1.4%-2.8% with respect to the base model. From extended analysis, we conclude that the locations with characteristics of having a smaller demand in relief goods and are located closer to the humanitarian hub are favourable to be served by cargo drones. With this conclusion a trade-off occurs. The relief operation performed from Airbase Woensdrecht deploying both vehicles, results in the least amount of operational costs, but takes 47 minutes longer to complete.

Additionally, a relief operation after a disaster containing the same characteristics as the flood of the Netherlands in 1953, is not favourable to be performed by humanitarian drones only. This since only deploying drones results in the total operational costs, being 129% higher then the cheapest relief operation included within this research. In addition, a remarkably longer duration time of the entire relief operation compared to other strategies was observed. Followed from the capacity limitations of the UAVs, requiring them to perform numerous flights in order of satisfying the total demand of a single location. Concluding that for operations with substantial demands such as the relief operation after the flood of the Netherlands in 1953, it is favourable to include relief vehicles with bigger capacities along side the UAVs. At last, we can conclude that humanitarian drones during the relief operation after the flood of 1953 could not have been a large contribution. Due to the extreme weather limitation experienced by the UAVs with respect to those experienced by the Hercules c130 plane. This shows by the robust Hercules c130 plane satisfying all locations demands, thereby completing the entire relief operation, before the MiniFreighter drone is able to ascend at all. Subsequently, we can conclude that the limitation of the windspeed has a significant effect on the performance of the MiniFreighter during certain specific relief operations.

For future research, we suggest to extend the model by including cargo drones normally operating in a different work field. Cargo drones that normally operate in the retail industry can be called and deployed within a relief operation if a disaster strikes. Thereby, significantly increasing the number of available drones. With this research multiple humanitarian hubs should be included that all cover a certain sub-region of the disaster area. The humanitarian drones can load new relief goods in various depots creating an airbridge and possibly decreasing the total travel distance. Additionally, future research regarding the robustness of the cargo drones such that they can take off with greater windspeeds, could be beneficial for the performance results during relief operations after a flooding event.

Table of contents

Preface 2
Management summary 3
List of figures and tables 7
Introduction 8
1.1 Organizations involved 8
1.2 Problem context 9
1.2.1 Core problem 10
1.2.2 Norm and reality 10
1.3 Research questions & problem-solving approach 10
1.3.1 Main research question 10
1.3.2 Problem solving approach 10
1.3.3 Scope 12
1.3.4 Research questions 13
1.4 Deliverables 14
2. Contextual analysis 15
2.1 Analysis of relief operation 15
2.2 Analysis required input data 17
2.2.1 Geographical 18
2.2.2 Population and demand 18
2.2.3 Supply chain network 19
2.2.4 Vehicles and UAVs 20
3. Literature study 21
3.1 Coordination mechanisms 21
3.1.1 Construction heuristics 22
3.1.2 Improvement heuristics 22
3.1.3 Humanitarian coordination mechanisms 23
3.1.4 Heterogenous fleet coordination mechanisms 25
3.1.5 Last mile distribution in humanitarian relief 25
3.2 Systematic literature review 26
3.3 Conclusions 27
4. Simulation model 29
4.1 Conceptual model 29
4.1.1 Logistical coordination extensions 29
4.1.2 Assumptions and simplifications 35
4.1.3 Process flowchart 36
4.2 Validation 37
4.2.1 Field expert 37
4.2.2 Insights 37
4.2.3 Conclusions 38

4.3 Experimental setup 39
4.3.1 Base model 39
4.3.2 Interventions 39
4.4 Results 40
4.4.1 KPI selection 40
4.4.2 Base model 42
4.4.3 Interventions 42
5. Conclusions 46
5.1 Conclusions 46
5.2 Research limitations 47
5.3 Future research 47
6. References 48
Appendix A: Input data 51
A.1: Available airplanes 51
A.2: Flight assignments 51
A.3: Dropping locations Operation WANO 51
A.4: Vehicle characteristics 52
Appendix B: Systematic literature review 52
B.1: Key concepts 52
B.2: Search strings 52
B.3: Exclusion and inclusion criteria 53
B.4: Findings systematic literature review 53
Appendix C: Algorithmic structure/ pseudocode heuristic 54
Appendix D: Heuristic code 57

LIST OF FIGURES AND TABLES

Figure 1: The MiniFreighter designed by Wings For Aid. 8
Figure 2: UAV based delivery system by MiniFreighter UAV 8
Figure 3: The disaster areas of the flood of the Netherlands in 1953 9
Figure 4: Phases of the Seven-Step Approach for Conducting a Successful Simulation Study 11
Figure 5: Phases of the CRISP-DM process model........ 11
Figure 6: Involved airfields in relief operation in Zeeland........ 16
Figure 7: Overview containing number of locations revealed per hour 19
Figure 8: The C130 Hercules cargo aircraft 20
Figure 9: The MiniFreighter designed by Wings For Aid 20
Figure 10: Logic flowchart heuristic 31
Figure 11: Process flowchart of the model construction 36
Figure 12: Graph of total cost of relief operation per intervention in euros. 41
Figure 13: Graph of total duration of relief operation per intervention in hours........ 41
Figure 14: Costdivision per vehicle type intervention 6 & 7 45
Figure 15: Locations served by UAVs with Rotterdam The Hague Airport as humanitarian hub. 45
Figure 16: Locations served by UAVs with Airbase Woensdrecht as humanitarian hub. 45

Table 1: Windspeeds per date and time during relief operation 32
Table 2: Take-off ability per wind direction for both aerial relief vehicles. 32
Table 3: Performed interventions. 40
Table 4: Results of performed interventions. 41
Table 5: Locations characteristics........ 43

INTRODUCTION

This chapter introduces the organizations involved, the problems with their contexts and the corresponding research questions. Additionally, the research approach with its limitations, validity and reliability will be explained.

1.1 ORGANIZATIONS INVOLVED

Within this bachelor's research, the University of Twente acts as the main supervisor and client. However, a crucial collaboration exists with the foundation Wings For Aid. The collaboration initiated a research project researching last mile drone logistics for humanitarian aid, the research project aims to study historical disasters and evaluate the potential impact drones could have in the relief operations. Wings For Aid is developing a cargo drone system for humanitarian aid. Currently, the first 5 production units are being produced within their facilities in Italy. Wings For Aid has a strong network with humanitarian and other overarching organizations such as the Red Cross, the World Food Programme, the United Nations and the Dutch Airforce. Their mission is to deliver relief goods in disaster areas with the MiniFreighter (See Figure 1), this is an Unmanned Aerial Vehicle (UAV) designed by Wings For Aid.

MiniFreighter

The UAV is a humanitarian drone that can be deployed in relief operations. The aircraft is designed to carry 160 kg of relief goods in self-landing boxes of 20 kg each. It has a cruise altitude of 1500 ft and drops the relief goods at 300 ft. To serve the victims as quickly as possible, the aircraft has a top speed of 125 km/h and a range of 500 km. See Figure 2 for the delivery operation in the system.

Figure 1: The MiniFreighter designed by Wings For Aid (WFA, MiniFreighter).

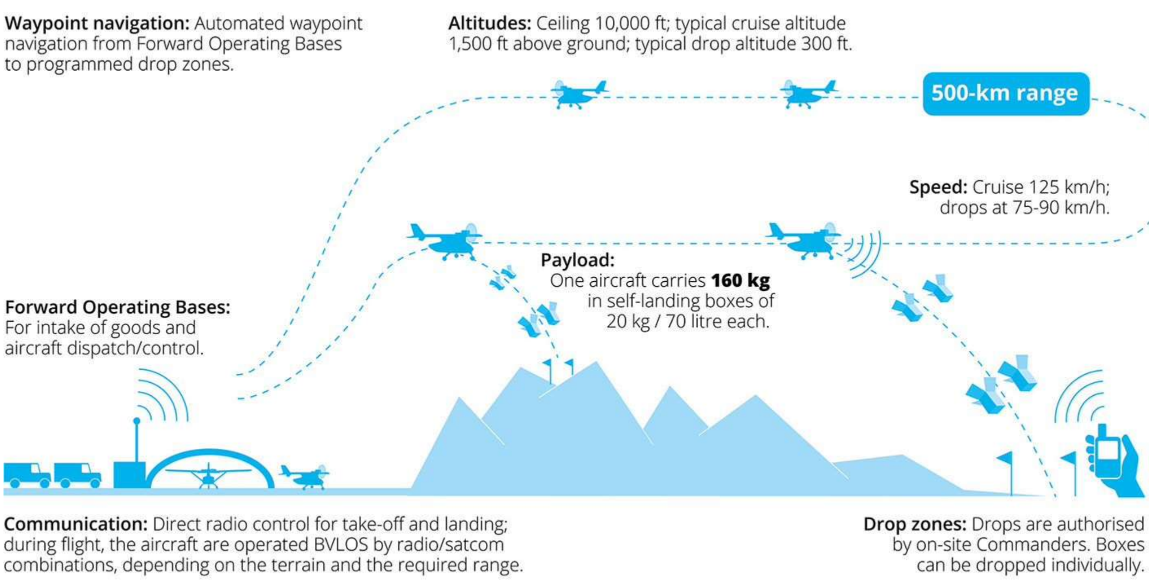


Figure 2: UAV based delivery system by MiniFreighter UA (WFA)

The University of Twente is actively researching historical disasters to get a more thoroughgoing image of the contributing factor of humanitarian drones in the relief operations. The research needs to be performed following certain standards such that results can be generalised and can contribute to the future operations of Wings For Aid, as well as to any other research into relief operations.

1.2 PROBLEM CONTEXT

The flood of the Netherlands started during the weekend of Saturday 31 January to Sunday 1 February 1953. A storm tide raged across the northwest European shelf and flooded the low-lying coastal areas of the countries around the North Sea. The peak high waters occurred during the night and the storm surprised many people in their sleep. The resulting disaster in terms of loss of life and damage to infrastructure was enormous (Gerritsen, 2005). No formal disaster plan was ever written for a disaster of this magnitude. When the dikes succumbed in more than 150 places in Zeeland, Zuid-Holland and Noord-Brabant, it resulted in unclarity of who was responsible leading to chaos and improvisation. Additionally, all the communication channels were inactive due to the weekend, which meant that no form of warning signal could be sent to the sleeping inhabitants for the disaster they were about to endure.

Apart from the communication issues, a great number of other problems arose. When the news spread throughout the Netherlands a substantial stream of people that wanted to help came up and moved to the disaster area. This introduced new logistical problems as the capacity of the road and rail networks were heavily overloaded. Due to this overcapacity, a lot of humanitarian aid could not be delivered to the still accessible locations. Besides the still accessible locations, a significant portion of the disaster area could not be reached due to the flooded and destroyed infrastructure. More than 150.000 ha of land was inundated causing severe damage to infrastructure and farmland (Rijkswaterstaat, sd), see Figure 3 which displays the disaster areas of the flood. At that time, there was just one helicopter in the Netherlands, additionally, old and tiny boats were used to deliver relief goods and evacuate over 72.000 people.

As a consequence of all the obstacles mentioned above, the large-scale rescue and relief operation including the complex closure of the dikes required the successive nine months. Rescue procedures and humanitarian aid came for a lot of victims too late which led to, among other factors, the passing of 1836 people.

Even though the disaster occurred under significantly different circumstances as to modern times within the Netherlands, certain characteristics of the disaster remain to be one of the biggest challenges developing nations currently face.

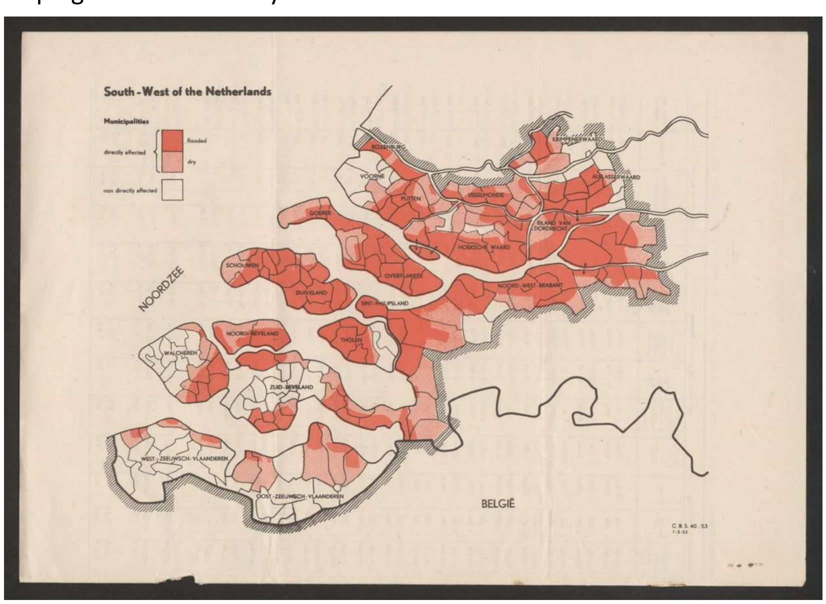


Figure 3: The disaster areas of the flood of the Netherlands in 1953 (CBS, 2019)

1.2.1 Core problem

In the past decades the information systems innovated in a manner that no one would have expected in 1953. Numerous disaster plans were created and the biggest Dutch piece of engineering was constructed, the Delta Plan. Purely based on the prevention of such a disaster as the flood of 1953. Even though a flood ruining the Netherlands in modern times is highly unlikely, less developed countries often need to battle the water. With these floods one characteristic remains the same: nearly the entire road and rail network within the disaster area will be inoperative. A relief operation by water can be manageable, however, most likely not able to serve and rescue the victims in time. The quickest way of transporting the relief goods is through the air. A innovative way of transporting cargo through the air is presented by the introduction of humanitarian cargo drones. This way of distributing relief goods in disaster areas could form the solution regarding efficient relief operations after disasters in the future.

The problem coming with predicting this aerial solution, is the lack of knowledge regarding the impact humanitarian cargo drones. Therefore the core problem is defined as "The knowledge gap regarding the possible impact humanitarian drones could have on a relief operation after a flooding event".

1.2.2 Norm and reality

The reality is that there exists a knowledge gap regarding the possible impact humanitarian cargo drones could have on the relief operation after a flooding event. From this follows the norm, being that the knowledge gap is filled and the impact of humanitarian cargo drones is known to society. By doing so the found knowledge can be used for future disaster management.

1.3 RESEARCH QUESTIONS & PROBLEM-SOLVING APPROACH

Within this chapter the main research question and the corresponding problem solving approach are described. From this main research question multiple sub-questions are derived, the combination of answers to the sub-question should answer the main research question.

1.3.1 Main research question

The goal of this main research question is to examine the impact humanitarian drones could have on a relief operation after a flooding event such as the flood of the Netherlands in 1953. Considering this research, focussing on the introduction of humanitarian drones that can distribute relief goods without making use of the ground level logistical routes that most likely will be inoperative. What can be the added value if these kind of rescue resources are deployable when certain disasters occur. The following main research question is formulated:

"What are the expected effects of using cargo drones in a relief operation after a disaster with the characteristics of the flood of the Netherlands in 1953?"

1.3.2 Problem solving approach

The problem solving approach contains the structured manner of how the research is planned to be executed. This is done following a certain methodology in order to keep this structured planning with the stated way of approach and corresponding activities.

Methodology

The methodology that will be used to tackle this research will be the Seven-Step Approach for Conducting a Successful Simulation Study and the CRISP-DM model which stands for Cross Industry Standard Process for Data Mining (S. Chick, Averill M. Law, 2003) (R Wirth, 2000). Within these methodology frameworks there exist two reference models which provides the structured overview of the phases of both methodologies, see Figure 4 and Figure 5. Within the data mining project there exist multiple phases that can be entered or re-entered following multiple routes.

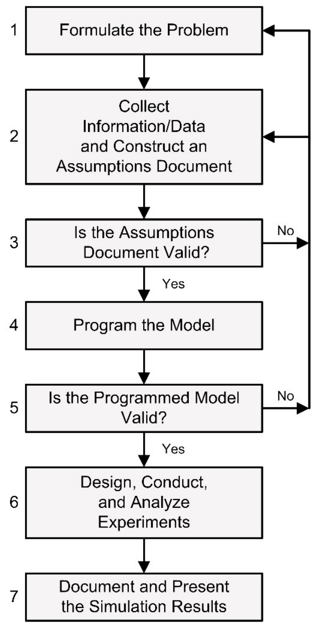


Figure 4: Phases of the Seven-Step Approach for Conducting a Successful Simulation Study

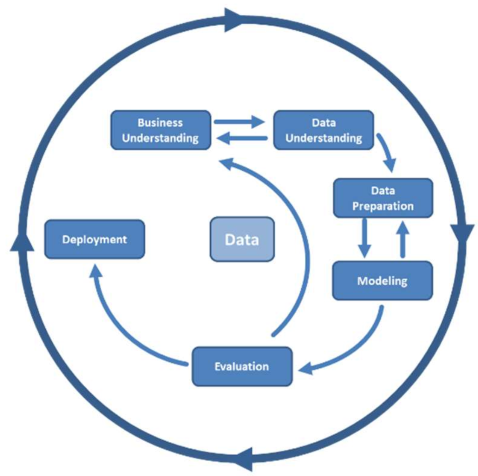


Figure 5: Phases of the CRISP-DM process model (R Wirth, 2000).

Research phases

The research phases are related to a combination of the two figures above, this including the strengths of both the simulation study and data mining methodology.

First phase:

To be able to answer the main research question the problem situation and its context need to be analysed. This will be done by performing a historical study in order to get the complete image of the situation of the flood in 1953.

Second phase:

In the second phase of the research the important numerical data regarding the flood and its relief operation should be gathered and stored. This crucial data serves as the building bricks of the simulation model. A simulation model is used since it serves certain characteristics that are required for modelling relief operations. Uncertain circumstances can be modelled, certain impacts events have on the operation can be analysed and multiple strategies can be evaluated. For this model to be as realistic representation of the situation we want to simulate the input data should be gathered, this will be done by performing a quantitative literature study. Examining all the relevant sources regarding the flood and retrieving the numerical data that can be used to build the most realistic simulation model possible.

Third phase:

The gathered data should be prepared and transformed so it can be used for the model that can deliver the solution. However the data gathered from the flood is outdated and can be challenging to implement.

Fourth phase:

The fourth phase entails the modelling of the simulation model, meaning the implementation of the gathered and transformed data within the model ensuring it to be a realistic representation of reality. The selection of KPIs is of great importance and will directly effect the conclusion. The simulation study is chosen based upon the wide variety of experiments that can be run, this ensures that the effects of humanitarian drones on the relief operation can be examined in the most elaborate way.

Fifth phase:

Within the fifth phase the programmed model is being examined on validity. This is done before the experiments are being performed as their could be some adjustments necessary to the model in order to make it more realistic. The validity process is done by an expert from the relevant work field that can indicate the imperfections and simplifications of the programmed model. This is exploratory research as the expert is interviewed on his opinion regarding the constructed model, the results are qualitative.

Sixth phase:

When the programmed model is approved, the designing and conducting of the experiments is executed. These experiments present the results of the relevant cases that are being tried with there corresponding factors and conditions. This research phase contains experimental research, since multiple experiments are performed with their results contributing to the answer of the research question. The results of the performed experiments are thoroughly analysed.

Seventh phase:

Within this phase the conclusion answering the main research question is formulated and processed into documentation that is presentable as the final version of the performed research. This research phase is a causal-comparative research as the results of the simulation experiments will be compared and examined if there are any causal relations that can contribute to the conclusion.

1.3.3 Scope

An entire relief operation after a flood contains many means of transportation and a large number of stakeholders. The inclusion of all elements of the disaster and its relief operation is impossible for this project. Therefore, the scope of the research is based upon certain relevant characteristics of the disaster itself being the relevant natural characteristics of the flood of the Netherlands in 1953 and the inclusion of one aerial relief operation after the flood of the Netherlands. The research questions regarding the relief operation therefore solely include aerial elements, any other way of transportation is excluded.

1.3.4 Research questions

To answer the main research question mentioned in Section 1.3.1 multiple research question are derived. Afterwards, some of the research questions are split up into multiple sub-questions. The combination of the answers to the research- and sub-questions should answer the main research question and conclude this research.

Phase 1. Researching the contextual situation of the Netherlands flood of 1953.

Research question:

"What happened during the relief operation after the Netherlands flood of 1953?"

Phase 2. Researching the relevant data of the Netherlands flood of 1953.

Research question:

"What is the Geographical information of the disaster area of the flood of 1953?"

Sub-questions:

1. Which available imagery can be used to model the disaster area?

Research question:

"What was the population and humanitarian demand of the disaster area of the flood of 1953?"

Sub-questions:

1. What was the spread of the population density over the area?
2. What was the demand of relief goods out of the disaster area?

Research question:

"How was the supply chain network organised in the vicinity of the disaster area of the flood of 1953?"

Sub-questions:

1. Where were the humanitarian logistics hubs in the vicinity of the disaster area?
2. Where were the points of distribution that could be used during and after the flood?
3. What were the flying routes in and around the disaster area?

Research question:

"What are the characteristics of the vehicles and UAV's that are relevant to this research?"

"Which coordination mechanisms exists that are applicable to the combination of the logistical situation of 1953 and the use of humanitarian drones?"

"Which logistical coordination mechanisms fits best to the combination of the logistical situation of 1953 and the use of humanitarian drones?"

Phase 3. Preparing the gathered data.

Research question:

"How can we develop a model that encompasses all relevant data regarding the 1953 relief operation?"

Phase 4. Modelling the model.

Research questions:

“Which adjustments should be made to transform the framework to the desired model?”

“Which KPI’s are of importance to answer the main research question?”

“Which experiments does the model need to be able to perform?”

Phase 5. Validating the model

Research question:

“Are there any imperfections or so-called simplifications and assumptions in the study that deviate the model from the situation in 1953?”

Phase 6. Performing experiments and analysing results

Research question:

“What performance results can be expected with performing the simulation model?”

Phase 7. Conclusions

When all research questions are answered we draw conclusions and combine them to formulate an answer to the main research question. Besides, limitations of this research and recommendations for future research are given.

1.4 DELIVERABLES

- **Simulation model**
  A simulation model constructed in the Tecnomatix Plant Simulation 16.1 software. The model simulates the relief operation after the flood of the Netherlands in 1953.
- **Report containing findings about contribution of humanitarian drones**
  The report should contain findings on the significance of humanitarian drones in disasters like the flood of the Netherlands.

2. CONTEXTUAL ANALYSIS

Within the following section the context regarding the thesis is being analysed and described. This ensures inclusion of the complete picture during the research. The analysis is performed by performing the first two research phases and answering their corresponding research questions. Phase 1: researching the contextual situation of the Netherlands flood of 1953 and Phase 2: researching the relevant data of the Netherlands flood of 1953.

2.1 ANALYSIS OF RELIEF OPERATION

First the definition of disaster relief is described whereafter the elaboration of the stakeholders involved and the corresponding day-to-day military operation is given.

Definition of disaster relief

Disaster relief is defined by The United Kingdom Ministry of Defence as "the organized response to alleviate the results of a catastrophe. The aims are to: save life; relieve suffering; limit damage; restore essential services to a level that enables local authorities to cope; and set the conditions for recovery." (Wagemans, 2017).

Relief operation 1953

Numerous stakeholders were involved with the relief operation of the Netherlands flood in 1953. The first groups of people that responded Saturday night were the mussel fishermen in the neighbouring cities of the heaviest affected areas. The fishermen navigated between the flooded barns with their fishing boats to evacuate the first people. It was not for Sunday morning before the first organised humanitarian aid came to practice. The two organisations that contributed the most to the relief operation are described below.

Red Cross (Netherlands)

From the beginning onwards it became clear that the Red Cross was not prepared for such a disaster. Resulting in the lack of crucial supplies in the disaster depots for battling a flood such as boots, life jackets and rubber boats. Additionally, due to capacity limitations, the relief operation from the Red Cross was solely active at the outskirts of the disaster areas, which resulted in the only function of the Red Cross being taking in and care for the victims that came to the emergency hospitals themselves or were brought by civilians. Even though the hard work of the Red Cross was crucial and necessary, it was simply not enough for a disaster of this magnitude.

Military

Together with the Red Cross, the military came in action on Sunday morning following an disorderly process as well. At Sunday morning 03:00, multiple hours after the disaster first struck, the first army detachment came to rescue victims at the city Raamsdonksveer. At 04:00 the Marine Corps joined the rescue operation and travelled to Nieuwekerk aan de Ijssel and Capelle aan de Ijssel. It took a while before the military realised the immensity of this disaster, but after a few hours the commander in chief summoned all serving soldiers on leave and permission to return to their battalions. This message delivered by an exceptional radiobroadcast led to the accumulation of a 10.000 soldier force, all together battling the flood from the sky, land and water.

OPERATION WANO

The most significant relief operation performed by the Dutch Military was Operation WANO (Watersnood) and was executed by The Royal Netherlands Airforce. Due to the complete loss of communication the disaster needed to be mapped. Leading to aerial assessments flights from the airports Gilze-Rijen and Woensdrecht making pictures of the disaster areas and delivering them to the headquarters (Watersnoodramp 1953 operatie WANO, 2019).

Naval Airfield Valkenburg

Even though the airports Gilze-Rijen and Woensdrecht made great efforts, the most significant relief operation took place from naval airfield Valkenburg, an overview is given in Figure 6. The airfield

functioned as the coordination centre for all the relief flights during the entire relief operation executed from the sky (Defensie M. v., 1953-1955).

Figure 6: Involved airfields in relief operation in Zeeland

Day-to-day operation

Sunday 1-2-1953; On Sunday morning the disaster had struck and the storm was still of tremendous force, on the new only available runway there was a crosswind of around 50 knots. Resulting in the available airplanes being unable to take off. The first two airplanes took off around 16:30 to drop 3 rubber boats over Oude-Tonge.

Monday 2-2-1953; The relief operation from Valkenburg finally started to run smoother from Monday. The complete available military force was deployed to load the airplanes with relief supplies. Besides the rescue flights that were performed to evacuate people from their flooded homes, 46 dropping flights were carried out. With these dropping flights 39 rubber boats, 9.000 sandbags, 5.575 loafs of breads, 1.000 litres of water, 4.1 tons of food and 150 kg medicines were dropped over the disaster areas.

Tuesday 3-2-1953; Tuesday was a turning point in the relief operation, the dropping flights were significantly increased and support from all around the world arrived on naval airfield Valkenburg. This increased the available airplanes and relief goods ready for the relief operation, see Appendix A.1 for the overview containing the exact amount of available airplanes per day of the relief operation.

Wednesday & Thursday 4&5-2-1953; These two days included the absolute peak of the entire relief operation on airfield Valkenburg. In total these two days around 235 flight hours were carried out over 174 different dropping flights. See Appendix A.2 for the overview containing the exact flight assignments per day of the relief operation.

Friday 6-2-1953; On Friday some airplanes that possessed limited cargo capacity were no longer deployed since it was no longer economically justifiable.

Monday 9-2-1953; The number of dropping flight assignments decreased drastically over time and on Monday the 9th the international, KLM and other civil organisations was stopped. The remaining flights were all carried out by the Royal Netherlands Airforce.

Tuesday 17-2-1953; Tuesday 06:00 all flight operations on Navel Airfield Valkenburg connected to the relief operation of the flood were terminated.

Total; In total 464 flights were carried out with a corresponding 706 flight hours.

Dropping operation on the ground

The operations executed by the personnel on the ground at Airfield Valkenburg was intense. Most dropping flights were carried out during the day, during night-time all the relief goods for the next day were prepared into packages in the available hangar. Airplanes would return to the airfield, land, tank, load the relief goods and take-off again.

Disruptive influence

The relief operation experienced trouble from civil airplanes, most likely from airport Gilze-Rijen that flew over the disaster area without any known purpose. They were a disruptive influence on some of the dropping flights performed by airplanes from Airfield Valkenburg.

2.2 ANALYSIS REQUIRED INPUT DATA

Definition of input data

"In a simulation project, the ultimate use of input data is to drive the simulation. This process involves the collection of input data, analysis of the input data, and use of the analysis of the input data in the simulation model. The input data may be either obtained from historical records or collected in real time as a task in the simulation project" (Delia U, 2005).

Main operation

In order of researching the effects humanitarian drones could have had in the relief operation of the flood of 1953, a specific operation is chosen to investigate. The relief operation WANO from Naval Airfield Valkenburg is chosen to further investigate within this research, considering all the airdropping flights that were carried out during this particular operation and Naval Airfield Valkenburg being the coordination centre of the relief operation nation wide.

Required input data

In order of examining which input data is relevant for the simulation model that simulates the relief operation after the flood of the Netherlands, certain sub-themes of input data for the simulation model are analysed. This is accomplished by answering the research questions corresponding to these sub-themes.

2.2.1 Geographical

The research question that should be answered within the geographical theme is: *What is the Geographical information of the disaster area of the flood of 1953.* Initially the dimensions of the geographical area which is included in the research is determined. The longitude range is between 3.4°- 4.8° and the latitude in between 51.3°- 52.2°. Every relevant location to the research is included within these dimensions. Furthermore, the theme could be split up into certain subdivisions. These can be formulated as existing road networks, damaged structures and the imagery of the disaster area. Whereas the disaster of 1953 had great impact on the landscaping of the Netherlands it also led to a practically inoperative road network. This presents a trade-off, is the road network of the disaster area still relevant to include within the simulation model? As the road network is mostly inoperative and the rail network being demolished as well, it effects all road and rail related relief vehicles. Therefore, Operation WANO including solely aerial vehicles due to its dropping operations, results in the road and rail network being redundant to include. The last subdivision of the geographical theme is imagery. By adding the imagery of the disaster area, the simulation model will visually be more realistic. This has no further effects on the experimental results. Nevertheless assists the work towards a realistic model since it can indicate which locations are flooded and damaged, this effects the level of demand of the victims in that specific location. To conclude, solely the imagery subdivision can be classified as relevant input data for this specific disaster and will be included within the simulation model.

2.2.2 Population and demand

The corresponding research question is: *What was the population and their humanitarian aid demand during the disaster of the flood of 1953?.* The population and demand section of the simulation model contains the back bone of the research regarding the relief operation. It contains the number of inhabitants of the specific region, the date and time of when the region was hit and their corresponding demand of relief goods. These subdivisions are all important pillars of the relief operation and therefore are crucial to include within the simulation model. The specific regions that are chosen to investigate are the dropping locations of the relief dropping flights ascended from Airfield Valkenburg. These dropping locations all are strictly administered by the Ministry of Defence and stored in the Dutch national archive (Defensie M. v., 1953-1955), see Appendix A.3 for the specific dropping locations. Due to the technological capabilities available in 1953 no exact coordination's of the dropping locations were recorded. The coordination's of the most populous area within the specified dropping region are chosen to be included. By implementing these populous areas as dropping coordinates, the assumption is made that the highest number of people can be helped with the relief goods. Considering the populations of the disaster areas in 1953, these numbers could for the most part be found in the populations documentation made by the government (statistiek, 1953). The remaining populations are approximated using data from 1950 and applying the population growth percentage over the following three years within the region (Nederlands Interdisciplinair Demografisch Instituut, 2003), see Appendix A.3 containing a table with all the dropping locations and their populations during the relief operation. The corresponding demand level per region is calculated based upon the total amount of available relief goods and the population of the region, see Appendix A.2 for the table containing the calculations for the total amount of relief goods in kg. Following this strategy of dividing the relief goods evenly over the victims serves the "equal allocation principle" (B. Balcik B. M., 2008). This strategy is chosen based on the reports of the military stating that chaos was present and no fair division in relief goods based upon actual demand was made. The available vehicles were loaded at the airport and unloaded in the next location, resulting in a complete disproportional supply of relief goods to certain locations. When the relief goods are being assigned to a location based upon their population the allocation will be more equal. The date and time when the locations were first hit by the disaster is approximated using a timelapse developed by the University of Delft which simulated the course of the flood in 1953 (Hoes, 2018). These date and times are included within the model and forms the initialisation of the demand request per location. An overview of the number of locations revealed per hour during the relief operation, entailing the number of locations that first encountered the water at that particular hour, is given in Figure 7.

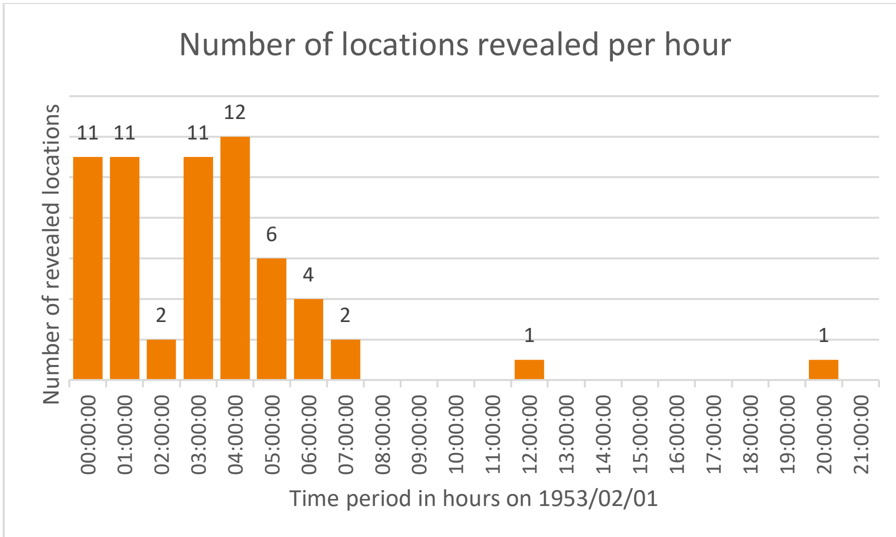


Figure 7: Overview containing number of locations revealed per hour

2.2.3 Supply chain network

The research question which should be answered within this subtheme is: *How was the supply chain network organised in the vicinity of the disaster area of the flood of 1953?.* Dividing the supply chain network into subdivisions result in the important elements: humanitarian logistics hubs, points of distribution and flying routes. The humanitarian logistics hubs are of significant importance to the simulation model, for their important role in further distributing relief goods to the other locations. Within operation WANO the most important humanitarian logistics hub was Naval Airfield Valkenburg. At the airfield all the relief goods arrived, were loaded onto the airplanes and flights took off. The airfield therefore was the coordination centre of the entire relief operation (Defensie M. v., 1953-1955). Within the simulation model Naval Airfield Valkenburg is assigned the main humanitarian logistic hub. Although Airports Woensdrecht and Gilze-Rijen had air operations as well, it was mainly focused on the aerial assessments flights thereby not participating in the relief operation of dropping goods. Even though the aerial assessment flights are of great importance for indicating the demand for relief goods, they did not directly participated in the dropping operations and therefore will be excluded from this research. The locations of different airfields such as Rotterdam The Hague Airport and airbase Woensdrecht could be included in the experiments phase to examine the effects distances of the hub to the dropping locations can have on the performance results of the relief operation. The inclusion of specific travel routes would scale down to the flying routes, this since only aerial vehicles are included in the research. Considering these routes, the flying routes do not experience any hinder from obstacles that are caused by damage of the disaster. Besides, it is not necessary for the vehicles to land since the operation entailed dropping the relief goods in the disaster areas. The possible flying routes are the routes ascending from Airfield Valkenburg to the first location, followed by an assigned next location or returning to the Airfield. The included vehicles being aerial vehicles the distances are assumed to be Euclidean.

2.2.4 Vehicles and UAVs

The research question that should be answered is *"What are the characteristics of the vehicles and UAV's that are relevant to this research?"* The input data for the vehicles and UAVs section will solely consist of the characteristics of the vehicles used within the simulation model. For the humanitarian drones the MiniFreighter developed by Wings For Aid is considered, see Figure 8. These characteristics are known and will be included in the model, see Appendix A.4. Contradictory, for the simulation study to be valuable for Wings For Aid and the University of Twente it is required to disregard the vehicles that were used back in 1953. Due to the limitations of the resources that were available back then, the performance difference between the drones and the outdated aircrafts is to significant to be valuable for this research. When modern day technology is included this research can be generalised and used for planning and optimizing relief operations for similar natural disasters, such as the flood of the Netherlands.

To include modern day technology the Lockheed C130 Hercules is chosen, see Figure 9. This aircraft is repeatedly deployed during humanitarian dropping operations and is currently available in the Netherlands. The aircraft has some fitting specifications that include being the perfect aircraft for dropping in high risk areas and corresponding landing and ascending field capabilities. The characteristics of the C130 Hercules will be included within the simulation model, see Appendix A.4. Although certain helicopters were deployed as well during Operation WANO, they are excluded from this research. They are excluded because helicopters are mostly deployed to perform rescue missions due to their stalling power and winch. For this research solely vehicles that operate in dropping operations are included, being the MiniFreighter and the C130 Hercules.

Figure 9: The MiniFreighter designed by Wings For Aid (WFA, MiniFreighter).

Figure 8: The C130 Hercules cargo aircraft (Defensie)

3. LITERATURE STUDY

In this chapter, a literature study is conducted regarding overarching coordination mechanisms and mechanisms specific for humanitarian relief operations containing a heterogeneous fleet of relief vehicles. The research is based upon answering the following research questions.

"*Which coordination mechanisms exists that are applicable to the combination of the logistical situation of 1953 and the use of humanitarian drones?"*

"Which logistical coordination mechanism fits best to the combination of the logistical situation of 1953 and the use of humanitarian drones?"

Some adjustments and extensions that could result in a more fitting logistical heuristic within the coordination part of the model are described. To conclude the literature study a systematic literature review is conducted.

3.1 COORDINATION MECHANISMS

Firstly the definition of a coordination mechanism is given and an explanation on what coordination mechanisms entail. Whereafter, multiple examples are listed on the different problems and heuristics.

Definition of coordination mechanism

" A coordination mechanism is a certain set of methodologies that is applied to manage various dependencies among the activities. Dependencies in supply chain can be managed by coordination mechanisms and thus better performance of supply chain can be obtained. Coordination mechanisms are widely applicable in industry as they eliminate barriers of supply chain performance (Stern, El-Ansary, & Coughlan, 1996) and help in attaining the desirable performance (Kumar & Seth, 1998)." (Srivastav, 2006, p. 1)

The coordination mechanism serves the purpose of determining which rescue vehicle is carrying out which task, the time the task needs to be carried out and in which particular order. Due to the availability of vehicles, differences in locations and their corresponding demands, a complex vehicle routing problem occurs. Implementing the best allocation of tasks to the different vehicles, the problem is optimized resulting in the best consecutive routing schedule.

Vehicle Routing Problem

The vehicle routing problem (VRP) was firstly introduced in 1964 for solving a logistical problem. It was designed to serve a set of customers, geographically dispersed around the central depot, using a fleet of trucks with varying capacities. The VRP is the most studied and used logistical coordination method in Operations Research. This popularity led to the VRP being a simplified framework for most of the coordination mechanisms, a lot of extensions and adjustments were made to the initial mechanism for it to be valuable in modern society. Such as time-dependent travel times, time windows for pickup and demand information that changes dynamically over time (Kris Braekers, 2016). In order of solving the vehicle routing problem multiple tools can assist. At first, an algorithm can be used. This is a structured, step-by-step approach for finding a solution to a specific problem. The algorithm will find the exact optimal solution. However, due to its strict step-by-step approach it considers every possible solution and therefore requires a lot of time and capacity. Contradictorily, heuristics can be considered. Heuristics are a more practical approach of solving a problem without the guarantee to find the optimal solution. Heuristics are often used in big complex routing problems with lots of iterations, or when there is limited time available. In this research only heuristics are considered, due to the amount of iterations and the resulting time and computing power limitations.

Within the segment of heuristics a distinction can be made between construction heuristics and improvement heuristics. Both subjects along with a number of examples are described below.

3.1.1 Construction heuristics

These heuristics builds a tour according to some rules without trying to improve them. They can be used to construct an initial schedule which later on can be improved. Some examples of construction heuristics are the Nearest Neighbour, Cheapest Insertion, Farthest Insertion.

Nearest Neighbour

Given a collection of data points and a query point in an m-dimensional metric space, find the data point that is closest to the query point (Kevin Beyer, 1998). When given an example, the heuristic ensures that the first location that is served from a depot is the location with the closest distance to the depot. The second location that will receive the goods is the location that is nearest to the first location. Whereafter every new location is the chosen based on being the nearest location to the last one served. This strategy is executed until all locations demands are satisfied or supply is exhausted. Due to its simplicity the nearest neighbour heuristic is the most applied heuristic in solving vehicle routing problems (VRPs). However, the heuristic regularly performs suboptimal which lead to a longer route then necessary (L. Raya, 2020). Even though other heuristics often perform better, the nearest neighbour heuristic is regularly used as a starting point for constructing a fitting heuristic for the specific routing problem. Due to the heuristic being easily extendable to respect the problem characteristics and setting.

Cheapest Insertion

The Cheapest Insertion Heuristic (CIH), is a heuristic that builds a tour of a small particle with minimum weight and is successively added with a new point until all the points are successfully passed (L. Virginayoga Hignasari, 2018). This heuristic is build upon the objective of adding the least amount of cost by adding the next location. It loops over all the optional locations and selects the cheapest to be included in the tour. This cheapest insertion cost is often calculated based on multiple factors, such as distance, travel speed and hourly cost of the specific vehicle. The cheapest insertion heuristic is a popular construction heuristic known for being fast, producing decent solutions, simple to implement and easy to extend handling complicated constraints (A. Mansour, 2017).

Farthest Insertion

Using the farthest insertion heurist entails selecting the site having the farthest distance to the depot as the first location. This first location is also regarded as the seed location from where the rest of the route is constructed. When considering the next location the decision is made based upon the distance of the other locations to the closest location that is already part of the route. When these distances are found the one with the farthest distance is chosen to be the next insertion. As well as the cheapest insertion is the farthest insertion known for its decent solutions and is often selected as the construction heuristic for certain logistical optimization problems.

3.1.2 Improvement heuristics

Improvement heuristics require an initial solution or route whereafter it systematically tries to improve this specific tour by using certain strategies. Examples are Simulated annealing and Tabu search.

Simulated annealing

This method is build upon the strategy of selecting worse options over the current better option with a certain probability. This could lead to a global optimum which could not have been found using the hill climbing method. The hill climbing method only includes a next solution if the outcome is better then the current outcome. Resulting in left out options due to a possible first decrease of the outcomes before the results get better. By proceeding even after a worse option then the current one, other options could present themselves as better alternatives.

Tabu search

When tabu search is performed certain options that are already revisited, will be excluded from the possibilities. This entails that these options can not be considered for an arranged period of time or steps. For a similar reason as simulated annealing ensuring the examination of all options, by excluding local optima and therefore being able to find the global optimum.

Fitting construction heuristic

The Cheapest insertion heuristic (CIH) is chosen to be the construction heuristic. Reasoning behind selecting this heuristic is that the CIH generally provides better results then the Nearest Neighbour Heuristic and fits better to the situational characteristics then the farthest insertion. This since it includes the costs for every new addition to the route instead of simply selecting the nearest or farthest location as next location. This heuristic can be used as the construction heuristic, extending or adjusting it with situational characteristics which realistically represent the logistical coordination heuristic for the relief operation after the flood. Additionally, this research does not have the primary objective to optimize the humanitarian relief operation. The objective states, analysing the effects humanitarian drones have on certain relief operations. Therefore, the consideration for a specific heuristic is not solely based upon the optimization capabilities, rather for the ability of representing the real situation in 1953.

3.1.3 Humanitarian coordination mechanisms

This section contains the elaboration and relevant literature regarding humanitarian logistical coordination within relief operations. The humanitarian supply chain includes the entire relief operation and can be very different from the well-studied commercial supply chains literature. Nevertheless, the humanitarian logistics face problems that have been successfully studied in the past. By understanding the humanitarian context, relevant hand high impact research in this area can be generated for the Operations Research (OR) community (Van Wassenhove L. , 2006).

Elaboration on humanitarian coordination mechanisms

A typical humanitarian supply chain consists of a range of logistics activities and processes, including procurement, transport, tracking and tracing, customs clearance, local transportation, warehousing, and last mile delivery (Thomas, 2003). The particular “humanitarian environment” makes logistics a challenging field. Humanitarian logistics has the challenge of allocating scarce resources to complex operations in the most efficient way (Van Wassenhove L. a., 2012), while considering invisible and/or qualitative factors (Van Wassenhove L. , 2006), under severe restrictions and random and imprecise information (Barbarosoglu, 2004).

This section presents some supply chain management (SCM) initiatives that could specifically improve humanitarian logistics. Contextual knowledge of the flood and its relief operation is included to check the relevance to the research.

1. Bullwhip effect

The Bullwhip effect being the phenomenon describing how small fluctuations in demand at retail level can have big implications at distributor levels, occurs often within relief operations. Resulting from one of the biggest challenges for a humanitarian relief operation being the lack of valuable data. Generally, the most valuable data during the relief operation is regarding the demand of relief goods of the population in the disaster areas. This data is most of the times is incomplete, scarce or completely missing. By knowing the demand of a location the allocation of relief goods to the specific location can be optimized and the bullwhip effect intercepted. Within the case of the flood of 1953 the demand of a specific location is generalised by dividing the total amount of goods over the amount of locations based upon their populations. The model therefore serves the “equal allocation principle” (B. Balcik B. M., 2008). This generalisation is naturally not possible when disaster recently struck, however dividing available goods over the already known locations can serve as an outcome.

2. Push-Based Supply chains

These supply chains with donors pushing their relief goods and unsolicited donations to the disaster areas are naturally what happens in times of crisis. However, often it is not the best strategy. By pushing all the goods to the disaster areas the capacities of the warehouses are exceeded and bottle necks present themselves (Luk N. Van Wassenhove, 2010). Regarding this research and the situation of 1953, all the relief goods were collected within a hangar on Naval Airfield Valkenburg. Although the situation was uniquely pressing the capacity never was exceeded. There was a boundary of a push-pull strategy within the relief operation, were the goods that could be delivered by the available planes were pulled from the hangar and dropped at the specific location. Besides the generalisation of including the MiniFreighter drones and the modern cargo planes Hercules c130 within the research, also the time when disaster struck in 1953 is estimated. This results in the push-pull strategy, pushing all the available goods to the hangar where all the relief goods are stored and administered followed by pulling the demanded relief goods from the hangar when the specific location is demanding them.

3. Standardization

Apart from humanitarian logistics, stays standardization beneficial for supply chains as a whole. It therefore also improves the humanitarian supply chain. The standardization of the fleet would improve the relief operation since the vehicle lifecycle management would be standardized which results in increasing speed of response and decreasing operating cost. (Luk N. Van Wassenhove, 2010). The fleet that is considered within this research is standardized to only two vehicle types being the MiniFreighter and the Hercules c130.

4. Information integration

As mentioned before the data set available to the coordination of the relief operation is of great importance. The integration of the information collected from the various resources such as maps, flood predictions, reports and images are important for the relief operation to be swift and direct. Including modern technology it is possible to predict disaster areas and up-to-date population numbers.

5. Postponement

Using standard designs that can be customized right before delivery, would add value to humanitarian logistics. An example would be keeping vehicles in a centralized standard pool and customize or use them based upon the requirements of the country/operation (e.g., GPS systems, telecom, interior accessories) and the local conditions (weather, terrain, safety requirements) (Luk N. Van Wassenhove, 2010). With respect to the relief operation performed in 1953, including the weather conditions within the logistical coordination seems interesting. This since the force of the storm during the days of the operation was immense, reaching windspeeds of 50 knots. This could have an effect on the performance of the fleet. The power of the MiniFreighter logically is lower as the power of the Hercules

C130 plane and therefore could experience more hinder during a heavy storm. This could reflect in the cruising speed of both vehicles or the ability to ascend during these periods of heavy storms. By researching the effect of weather conditions to the different vehicles and including them as variables in the task allocation process the relief operation could be more realistic and therefore optimized.

3.1.4 Heterogenous fleet coordination mechanisms

When heterogenous fleets are concerned the focus is on the amount of different vehicle types that are deployable in the relief operation. This availability of multiple vehicles with different characteristics and limitations effect the coordination mechanism that is used within the model. In this research two different vehicles with their corresponding characteristics are included, requiring the model to include a heterogenous fleet coordination mechanism.

Definition of heterogenous fleet

The buyer operates a fleet of heterogeneous vehicles with different loading volumes and fuel consumption behaviours, which s/he uses for picking up products at the suppliers (Christoph H. Glock, 2015).

Unlike in commercial systems, the relief system is likely unable to optimize the vehicle fleet, in terms of numbers, capacity, and compatibility after an emergency event. Additionally, the number of vehicles being unlimited could possibly lead to an unlimited amount of drones flying to all the different locations at the same time and dropping their cargo to end the relief operation. This would be infeasible considering the capacity of the airfield and the possibility of one drone dropping relief goods being insufficient to match the demand of the location. Hence, for relief operations it is stated that the vehicle fleet is comprised of a limited number of vehicles with different characteristics. Each vehicle can be differentiated based on capacity, speed, and compatibility with various arcs in the network. In addition, each vehicle can complete multiple deliveries in a single planning period and each demand location can be visited multiple times (with the same or different vehicles) in the same planning period.

3.1.5 Last mile distribution in humanitarian relief

The following section contains the relevant literature about last mile distribution in humanitarian relief. Due to the fact that drones deliver the relief goods directly to the victims, all flights ascending from Naval Airfield Valkenburg that drop relief goods, can be classified as last mile distribution of the relief operation. It therefore is one of the most import pillars of the coordination mechanism in the model.

Definition of Last Mile Relief Distribution

Last mile distribution is the final stage of the relief chain; it refers to the delivery of relief supplies from Local Distribution Centers (LDCs) to the people in the affected areas (demand locations) (B. Balcik B. M., 2008).

Within the research into the coordination mechanisms for last mile distribution in humanitarian relief operations, it becomes evident that the resource allocation including the inventory management and vehicle routing scheduling are closely interrelated and should be jointly considered. In this respect, the last mile distribution problem is a variant of the inventory routing problem (IRP). When inventory management is being conducted in the warehouses and there are recurring demands at the locations the inventory routing problem is presented. The main decisions in the IRP are the customer delivery times, the number of items to be delivered at each visit, and the delivery routes. Following the routing problem a extended variant of the nearest neighbour heuristic can be used to find the possible route (B. Balcik B. M., 2008).

During a relief operation, resource levels, vehicle availability and demand parameters all maintain to be uncertain and difficult to forecast. These supply- and demand-related uncertainties prevent the possibility of readily determining the duration of the distribution activities. In other words, the length of the planning horizon is variable and unknown a priori. The planning horizon therefore begins once the LDC is able to begin delivering relief supplies to demand locations and ends when the demand is completed or supply is exhausted. (B. Balcik B. M., 2008)

Because resources are limited in disaster relief environments, unsatisfied demand is common. The objective is to develop an efficient resource allocation mechanism that minimizes suffering while achieving equity in relief aid distribution among affected areas. To quantify the real cost of unsatisfied and late-satisfied demand of each person (or groups of people) in disaster relief situations is very difficult. However, assigning a relative penalty cost factor to each delivery at each location introduces the possibility to model population vulnerabilities and distribute supplies accordingly. (B. Balcik B. M., 2008)

3.2 SYSTEMATIC LITERATURE REVIEW

The separate topics discussed in this chapter add up to the research into coordination mechanisms for the last mile distribution of dynamic heterogeneous fleets in humanitarian relief operations. Within this systematic literature review these topics are researched in several combinations with the objective of finding additional insights that contribute to the conclusion of a logistical strategy for the disaster modelling. The components of the systematic literature review such as the key concepts, search strings, exclusion criteria and used papers can be seen in Appendix B.

For a humanitarian supply chain to function, resilience is required. This can be acknowledged by the fact that these supply chains are subject to dynamic changes is demand levels and quick responses. Therefore humanitarian supply chains and its coordination mechanisms should incorporate the PR^2 and the R^4 principle. By including these import factors when constructing the coordination mechanisms for a relief operation certain pitfalls can be prevented. The pillars of the principles consist out of PR^2: Preparedness, Response and Recovery & R^4: Robustness, Resourcefulness, Redundancy and Rapidity. These models aims to quantify multiple criteria's including: the system preparedness, its response, its recovery and its resourcefulness. Combining the criteria's presents the possibility to quantify to what level the system can cope with the disaster and its relief operation. Some inclusions of the R^4 are regarding the resourcefulness which entails the capacity to perform supplies deployment and rapidity being the ability of a system to return to its initial state. (Duhamel, 2016)

By including multiple-stage programming and heuristics the use of the computational capacity is optimized. The complexity of the calculations are not significantly increased, however lead to more accurate measures which can be utilized. Implementing multiple-stage programming to solve the logistical challenge is achieved by dividing the complex problem into multiple sub-problems. When vehicle routing problems are considered the first stage or sub-problem could be to examine the amount of vehicles necessary to satisfy demand per vehicle type. When this calculation is performed, the results can serve as input data for the second stage or sub-problem that could plan the route for each of the separate vehicles. Hereby the computational power is utilized at full capacity one problem/stage at a time. (Alem, 2016) (Ferrer, 2016)

Coordination mechanisms for relief operations are greatly build upon the warehouses or distribution centres within the disaster areas. Naji-Azimi (2012) advocates that introducing Satellite Distribution Centres (SDC) could form a solution for certain logistical challenges within relief operations. SDC are sub-warehouses that all serve the demand of a specific area in the complete disaster area. The supply of goods through these SDC, covering the complete disaster area, is executed by the DC which is the central distribution centre. By introducing these SDC the area is split up into multiple subdivisions and last mile logistics can be less complicated. A requirement for the introduction of SDC is that the complete disaster area should of significant size, thereby ensuring the positive effect of dividing the overall area (Naji-Azimi, 2012).

When related literature is reviewed it can be concluded that the coordination mechanism of a relief operation is a complex routing problem, where a fair amount of additional factors regarding the resilience of the system need to be included within the decision making process. Numerous strategies are presented that split up the overall problem in order of attaining comprehensible sub-problems that can serve as input data for the next stage.

3.3 CONCLUSIONS

In this literature study, literature regarding overarching coordination mechanisms and specific literature regarding humanitarian relief operations using heterogeneous fleets is reviewed. In order of answering the research questions:

"*Which coordination mechanisms exists that are applicable to the combination of the logistical situation of 1953 and the use of humanitarian drones?"*

"Which logistical coordination mechanism fits best to the combination of the logistical situation of 1953 and the use of humanitarian drones?"

According to the literature, we found the following about Supply Chain Management (SCM) initiatives that could optimize the humanitarian relief operation:

1. A combination of a Push-Pull strategy is maintained during the dropping operation. A push strategy is performed when all the relief goods are shipped to the hangar on Airfield Valkenburg, whereas the dropping itself is a pull strategy since the relief goods are sent when the location is sending the demand request.
2. The inclusion of the weather conditions to the task allocation process is valuable since the extreme weather conditions during the relief operation in 1953. These conditions could have a big impact on the performance of the available vehicles, in ways of cruising speed and ability to ascend.

Additionally, we found the following about humanitarian heterogenous fleets:

1. The number of vehicles used in the relief operation is limited due to the limitations that come along with a relief operation and its intensity. Besides, if the fleet was unlimited and no costs constraints were included all locations would just be served at the same time with relief vehicles of any sort being send to every single location.

Afterwards, the following insights are gained about last mile distribution in humanitarian relief:

1. The planning horizon of the distribution activities are uncertain due to the numerous unknown factors. This results in the planning horizon starting when the LDC (Airfield Valkenburg) can deliver relief goods and ends when all demand is met or supply exhausted.
2. Relative penalty factors for unsatisfied demand at the specific locations can be incorporated in the model in order of examining population vulnerability.

Lasty, the systematic literature review delivered the following insights:

1. The resilience level is an important factor to examine when constructing and managing a humanitarian supply chain.

2. Comprehensible logistical problems can be created by dividing the overall problem situation into multiple stages or sub-problems.

Best coordination mechanism fit

The construction heuristic that that will be incorporated within the simulation model is the Cheapest Insertion Heuristic. This heuristic will serve as guideline however a tailored heuristic representing the real life situation is required. The guideline heuristic will be extended in order of increasing the level of representation. These extensions can be, introducing multiple stage programming serving the comprehensibility and including the effects of the weather conditions during the relief operation on the performance levels of the different vehicles.

4. SIMULATION MODEL

Within this section an elaboration regarding the conceptual model and its validation is given. In addition, the experiments that are being performed are listed with corresponding argumentation and descriptions.

4.1 CONCEPTUAL MODEL

In order of answering the research question; "*How can we develop a model that encompasses all relevant data regarding the 1953 relief operation?"* a simulation framework is selected. This framework is developed to model historical disasters and in particular their relief operations (Robert M. van Steenbergen, 2020). The conceptual model of the flood of the Netherlands is built using this simulation framework as a starting point. The framework can be filled with the necessary data regarding a specific historical disaster. Within numerous sections, the framework can be extended to ensure a realistic representation of the real situation. An elaboration regarding the input-data specified per layer of the flood is described in the second chapter of this research, the contextual analysis. This conceptual model section will further elaborate on the translation of the data to the model, the corresponding simplifications, assumptions and trade-offs made.

4.1.1 Logistical coordination extensions

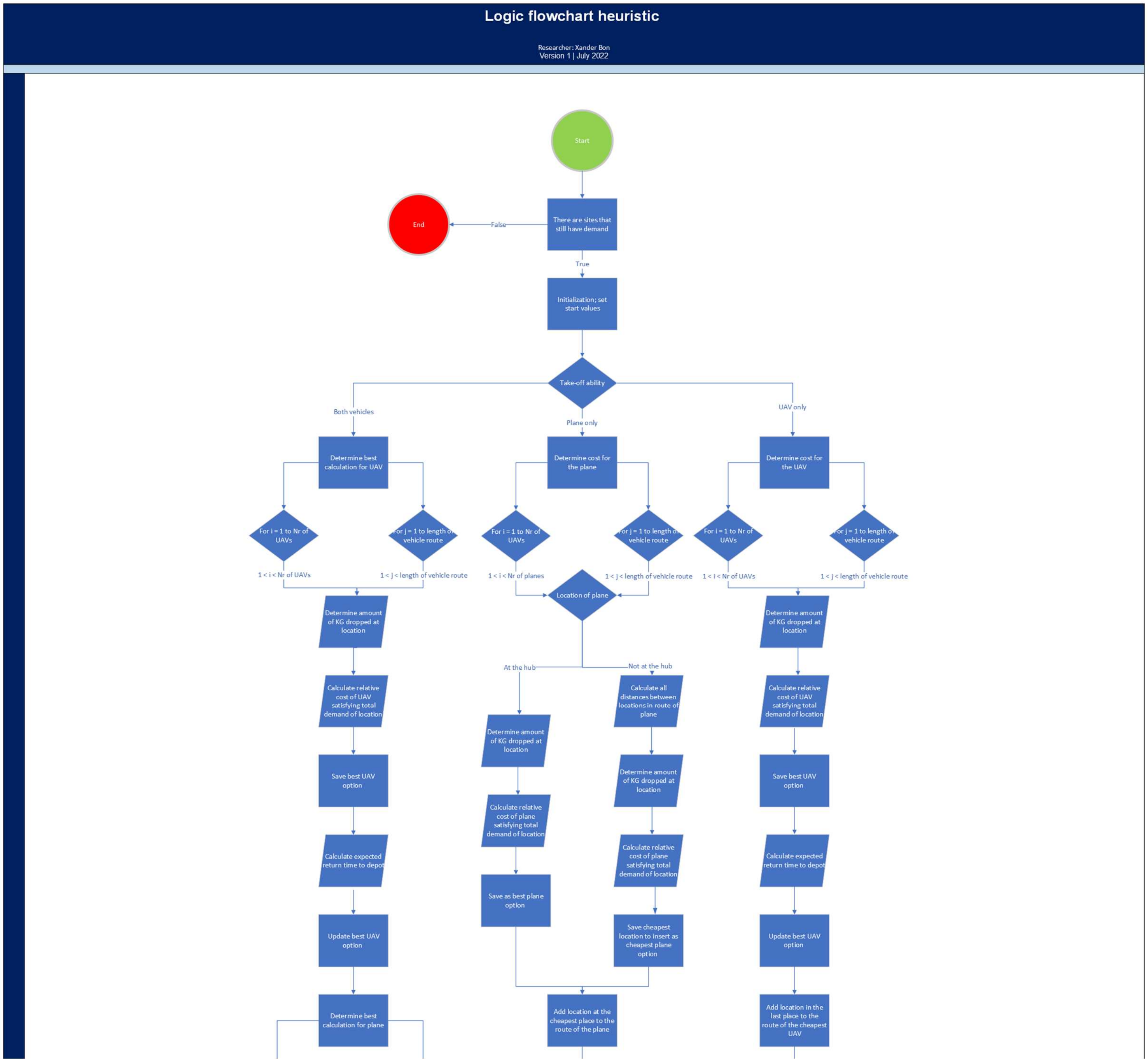
A complete new coordination mechanism is constructed which represents the relief operation after the flood. Within this section the location reveal is described, a logic flowchart of the logistical coordination heuristic is presented whereafter each procedure of the heuristic is described in sub-sections.

Location reveal

The planning of a logistical operation that serves certain locations, naturally starts with an overview containing the locations that have a demand and still need to be served. These locations present themselves to a system in a certain manner. The model is refreshed every hour, whereafter every location that was hit by the disaster within that particular hour, is added to a list with locations that currently have a demand in relief goods. This system is called a dynamic system, since its characteristics change depending on the time it finds itself in. The system is chosen based upon the current technology and the dynamic manner a flood travels. Current technology allows us to quickly communicate, this results in locations immediately requestion relief goods once struck by a disaster. Besides, floods tend to choose unpredictable paths when travelling inland requiring dynamic decisions. The system being dynamic requires the demand list to be updated every specific time period. Within the simulation model this list is called, the open request list. On this overview the locations are ordered based upon the time they were hit by the disaster, with the earliest location claiming position one. The first location on the list is planned to be satisfied first, applying a First In, First Out strategy. This strategy is chosen based upon the system being dynamic and locations revealing themselves to the model when they get hit by the disaster. Within the flooding disaster scenario it is chosen that the demand of the location that suffers the longest, is satisfied first.

Logic flowchart heuristic

The flowchart presented in Figure 10 describes every step the heuristic takes when a location is on the open requests list, up until the final step when the location is assigned to a specific vehicles route. Additional information regarding the heuristic in the form of the pseudo code and the final code written within the simulation model, can be found in Appendix C and Appendix D.



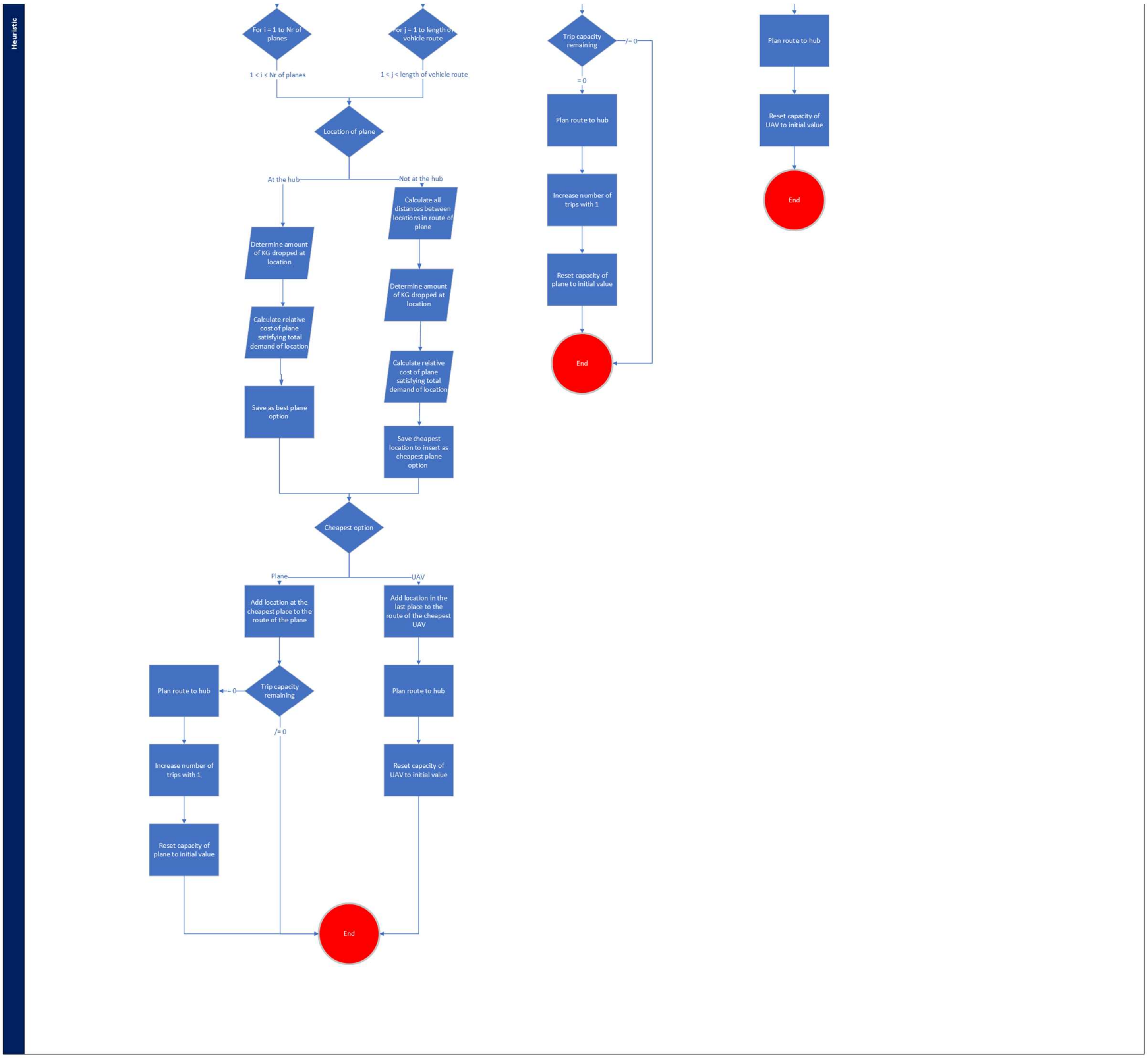


Figure 10: Logic flowchart heuristic

Vehicle allocation

By choosing the first location on the open requests list as first dropping location, the main choice that needs to be made in the task allocation process is regarding the particular relief vehicle that is deployed to satisfy the locations demand. By including several different factors in the decision making process a realistic task allocation can be ensured. The weather condition, availability, costs and take-off constraints are included in deciding which vehicle is deployed to satisfy a locations demand.

WEATHER CONDITION

The first factor that is included, is regarding the necessity of including the weather condition that form certain limitations for relief vehicles. The inclusion of weather condition as first decision factor is due to its direct limitation, which can result in vehicles being excluded from the possibilities. Thereby concluding the decision making process. To be able to include weather condition within the model, specific input data regarding the weather condition is required. Due to the reports made by the Netherlands Armed Forces the significance of the extreme storm during the relief operation became known. Resulting in the windspeed during the relief operation in 1953 being the weather condition which is included in the research. At the time only one meteorological measurement station located in the vicinity of the disaster area was operatable. The station was located in the south of Zeeland and was able to accurately measure the windspeeds. Over the period of 01-02-1953 until 12-02-1953 the average windspeeds in knots per hour, during three-hourly time intervals are analysed. The input data is transformed and included within the model, see Figure 9. By including the weather condition its limitations are included as well, the limitations that come with extreme windspeeds are regarding the take-off ability of aerial vehicles. Aerial vehicles ascending from a runway which geographically lays with the wind approaching the vehicle from the front or the back is favourable. Because vehicles can take off with higher wind speeds with respect to runways experiencing crosswind (wind approaching the vehicle sideways). During the relief operation after the flood the only available runway on Naval Airfield Valkenburg was experiencing a strong crosswind with maximum windspeeds of 41 knots, see Figure 10. The corresponding take-off ability of the two included relief vehicles can be seen in Table 1.

	datetime 1	integer 2	string 3	string 4
string	DateTimeRevealed	WindSpeed	Takeoff ability drones	Takeoff ability hercules c130
1	1953/02/01 00:00:00.0000	41	0	0
2	1953/02/01 03:00:00.0000	39	0	0
3	1953/02/01 06:00:00.0000	38	0	0
4	1953/02/01 09:00:00.0000	37	0	0
5	1953/02/01 12:00:00.0000	32	0	1
6	1953/02/01 15:00:00.0000	29	0	1
7	1953/02/01 18:00:00.0000	28	0	1
8	1953/02/01 21:00:00.0000	28	0	1
9	1953/02/02 00:00:00.0000	23	0	1
10	1953/02/02 03:00:00.0000	15	1	1

Table 1: Windspeeds per date and time during relief operation measured from weather station 310 in Vlissingen (KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT (KNMI))

Image relief vehicle		
Name relief vehicle	MiniFreighter	Lockheed C130 Hercules
Take-off ability crosswind	20 kts	35 kts
Take-off ability frontwind	30 kts	65 kts

Table 2: Take-off ability per wind direction for both aerial relief vehicles.

and only one vehicle can take off. Every time a new location needs to be assigned to a vehicle the heuristic checks if at that point in time the particular vehicle can take off. When neither vehicle can take-off the decision making process will be terminated and the location will remain at the top of the list. If only one vehicle can take off, the heuristic checks if there is a vehicle of that particular vehicle type available and adds the location to its route if there is one available. When both vehicles can take off the decision making process continues by examining the remaining factors.

Availability

When the weather condition form no limitation the next factor can be examined. If and when the vehicle is available to satisfy the locations demand. The check for availability includes multiple characteristics for each vehicle, however there are some differences. These differences and the corresponding decision making process is described in this section.

<u>Availability UAVs</u>

Check 1: Is there an UAV located at the hub?

If there is an UAV that is located at the hub it entails that it does not have any location assigned to its route yet and therefore is still located at the starting location, the humanitarian hub. Since the full demands per location are consistently significantly higher than the capacity of a drone, a single location can be assigned to the route of an UAV and when the location is reached and the relief goods are dropped the UAV returns to the hub to reload. The first UAV that is found to be available at the hub is selected, upon which in the next phase the corresponding costs are calculated.

Check 2: Expected return time to depot

In the case of no available drones at the hub a second check is performed. The expected return times to the hub of all the operational drones are calculated. The results are analysed and the drone that returns to the hub in the least amount of time is selected as available UAV for the cost calculation in the next phase.

<u>Availability plane</u>

Check 1: Is there a plane located at the hub?

In the same manner as in the drone scenario, the first check is if there is a plane located at the hub. When a plane is located at the hub it is available for the allocation of a location. However, when a location is assigned to the plane it does not immediately take off, this due to its significant capacity limitation. The capacity of the Hercules C130 plane is 19.000 kilo of cargo, resulting in the fact that a single plane trip can regularly satisfy multiple locations demands. When a plane is still located at the hub the plane is selected, upon which in the next phase the corresponding costs are calculated.

Check 2: Does the new location fit inside the existing route of the plane?

When the plane already has a location assigned to its route, the second check is performed. All already operating planes are checked if there is a plane that could satisfy a locations demand by adding the location to its already existing route. The options are examined and if there is a positive result the vehicle is selected, upon which in the next phase the corresponding costs are calculated.

COSTS ELEMENT

The next phase in the decision making process is regarding the cost aspect. The main consideration is to check which vehicle is cheapest to perform the dropping operation and satisfy its demand. This cost function is performed for the vehicles resulting from the previous phase. The results of the cost function for both vehicles can be compared whereafter the final decision can be made. Within the cost function the combined costs for satisfying a locations entire demand for a specific vehicle is calculated. The components that build up this cost function can be seen in the function below:

$$T_y = (X_y^1 + X_y^2 + L_F + U_F) * P_y + U_V * D_y$$

T_y= Total amount of time T to satisfy demand of location y

X_y^1= Travel time from previous location to location y

X_y^2= Travel time from location y to next location

L_F= Fixed loading time

U_F= Fixed unloading time

P_y= Number of trips to satisfy demand of location y

U_V= Variable unloading time

D_y= Total demand of location y

$$C_y^x = T_y * H_x$$

C_y^x= Total costs for vehicle x to satisfy demand of location y

H_x= Hourly operating costs of vehicle x

The total costs for a certain vehicle to satisfy the locations full demand is compared whereafter the cheapest vehicle is chosen. The location is assigned to the specific vehicle and inserted to its route.

INSERTION IN ROUTE

When the location is assigned to the UAV it is added to the route of the cheapest found UAV. The location is added at the end of the route of this found UAV whereafter a trip to the hub is planned to reload the UAV with new relief goods. Considering the situation of the plane, the place of the location in its possibly existing route is determined when the cheapest option of the plane is calculated. When the location is assigned to the plane, the location is added to the route of the plane at the position where it will add the least amount of cost to the routes total cost.

TAKE-OFF CONSTRAINT

The best fitting relief vehicle for the dropping operation is found. The drone can immediately take off when its at the hub or can take off when it first returns to the hub and finishes reloading. When the plane is considered, it seems to be illogical to instantly take-off when a first location with a small-scale demand is assigned to the plane. In this manner it could occur that the plane is taking-off and landing again after every single trip. To prevent this a constraint is added, the plane will take-off when the dropping assignments allocated to the plane exceed at least 50% of the planes capacity. By implementing this, the plane can stay operatable for a longer amount of time and changes increase that locations will be added along the way.

4.1.2 Assumptions and simplifications

1. *Geographical Information*

- The longitude and latitude range of the disaster area are for min latitude 51.3 and max latitude 52.2, for min longitude 3.4 and max longitude 4.8.
- Natural characteristics as the wind speed, aera specifications and time intervals of operation WANO are included as basis for the researched relief operation after the flood.

2. *People Demand*

- The dropping locations performed and reported by operation WANO are regarded as the dropping locations within this research.
- The exact coordinates of the dropping are based upon the highest populated location within the area, thereby assuming to help the most amount of people.
- The unequal distribution of relief goods in 1953, because of chaos and pilots dropping all the relief goods in the nearest town available, result in a different demand level per specific area. The demand level of the population in a specific area is approximated by the total amount of available relief goods during Operation WANO, whereafter the total number of relief goods is divided by the population numbers of the particular disaster areas of 1953. Thereby following the equal allocation principle.
- The time that the demand per location presents itself to the system is based upon a simulation/timelapse made by Delft University of Technology (Hoes, 2018). When a certain area gets hit by the water for the first time their demand starts to exist and therefore becomes visible to the simulation model.

3. *Supply Chain Network*

- Naval Airfield Valkenburg is considered as main hub within the research due to the operation which is examined and singlehandedly performed by this airfield.
- Two additional airfields are included within the experiments to examine the effects on the relief operation. Rotterdam The Hague Airport and airbase Woensdrecht are included.
- The feasible routes are from the hub to an assigned location followed by another assigned location or the return to the hub.
- All included dropping locations can be reached and visited from any other location, the distances between these locations are assumed to be Euclidean.

4. *Vehicles UAVs*

- The included vehicles are the MiniFreighter drone from Wings For Aid and the Hercules c130, due to the popularity of the Hercules as relief cargo aircraft and the drone research being in collaboration with Wings For Aid.
- The outdated vehicles that were available in 1953 are excluded from the research since they do not contribute towards a generalisation of this research that can be used for similar disasters in the future.
- The substantiated assumption, based upon insights given by a test pilot of Wings for Aid, is made that the MiniFreighter can take-off with a cross-wind up until 20 knots and a frond wind of 30 knots. Considering the cargo aircraft, insights given by an aviation consultant conclude that its cross-wind limitation is 35 knots and the frond wind limitation is 65 knots.
- Other effects caused by extreme windspeeds and it direction, such as change in total travel time is excluded from the research.
- Although aerial vehicles are included helicopters are excluded from this study, this due its primary function of being a rescue vehicle instead of a relief vehicle participating in dropping operations.
- The insight was given by Ronald van Gent, that considerations regarding deployable vehicle numbers should be based upon the capacities of all vehicle types. Resulting in 1 Hercules c130

aircraft having the same cargo capacity with respect to 40 MiniFreighter UAVs. These vehicle numbers are included within the experiments based upon the availability of the Hercules c130 aircrafts and capacity limitations on the airfields. A more detailed explanation is given in the validation chapter.

5. *Logistic Planning Control*

- The assumption is made that the relief operation is a dynamic relief operation. Entailing that new locations are constantly presenting themselves to the system and characteristics of the system depend on the time it finds itself in.

4.1.3 Process flowchart

This process flowchart presented in Figure 11 shows the design of the model and the way it is constructed.

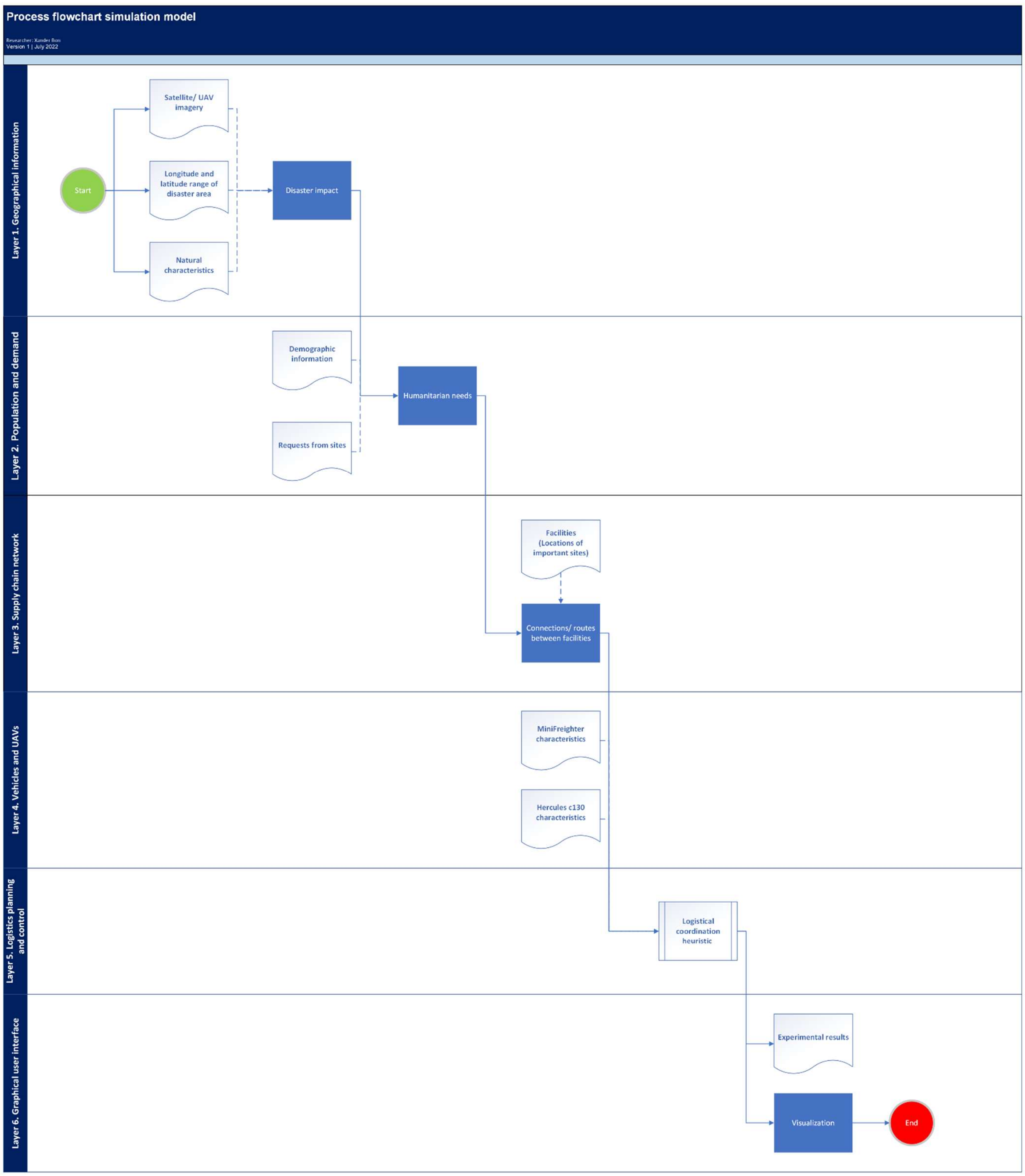


Figure 11: Process flowchart of the model construction

4.2 VALIDATION

The next important step constructing the simulation model is regarding the validation of the model. By validating the model the constructed model is checked if it correctly represents the real-life situation. Within this research, the simulation model should correctly represent the relief operation after the flood of the Netherlands in 1953. The model is validated by introducing a relevant field expert. Presenting all the assumptions made within the model to the expert and checking together if they were made accordingly.

4.2.1 Field expert

The field expert that was selected to validate the model is Ronald van Gent. He is an experienced aerial engineer, bringing a lot of expertise in radar technology and swarming. Additionally, Ronald van Gent was involved in the ideation phase of Wings for Aid and therefore could deliver an insightful perspective on the trade-off between the use of the MiniFreighter (UAV) and the Hercules C-130 cargo aircraft.

4.2.2 Insights

Firstly the contextual information regarding the disaster and model was discussed, upon which Ronald van Gent had a few clarification questions. When these were answered the in-depth validation was started. The structure of the validation was based upon the different layers within the simulation model. With these layers the input data used and the assumptions and simplifications made were elaborated on. The following insights were gained:

- Due to the big concentrations of demand during this disaster, big shipments need to be delivered to the different locations. In contrast to the development goal of the MiniFreighter, which was to deliver smaller quantities of cargo (maximum capacity of 160kg) to more specific locations. However, the flood of the Netherlands required a tremendous amount of relief goods which results in the fact that an UAV would require a significant number of flights to certain location to satisfy its demand. This naturally is included within the research.
- When take-off limitations are considered, an UAV has the advantage that it can take off with a rather short runway. This could result in an UAV being able to take off from a taxiway instead of the runway. This still is dependable on the windspeed which on its turn is a disadvantage for the UAV since it can only take off to around 20 knots cross wind and 30 knots front wind. This in comparison to the Hercules who is less flexible on the runways but can take off with greater windspeeds.
- The windspeed is effecting the vehicles cruising speed. The effects on the UAV are significantly larger then the effects on the Hercules due to the maximum cruising speed of both vehicles. A new trade-off is introduced; up until what windspeed it is still viable to take off with an UAV. Windspeed in knots can directly be subtracted from the cruising speeds in knots, in dialogue it is concluded that when windspeeds exceed 75% of the max cruising speed of the UAV it is no longer viable to take off. Resulting in an viability limit of around 50 knots, however the implemented take-off limit is 20 knots. The take-off limit covers the viability limit since the drone is unable to ascend with windspeeds beyond 20 knots, thereby eliminating the unviable to ascend scenario.
- Due to the range and cruising speeds of the UAV it is advantageous for a drone operation to minimalize the distance between the hub and the locations. Therefore it could be valuable to include other airfields as hubs and run the simulation to examine the effects. Possible airfields are:
    - Zestienhoven, Airport Rotterdam The Hague
    - Woensdrecht Airport

- The insights of the system being dynamic with the locations presenting themselves to the system when struck by the disaster, is regarded as the logical representation of the real life situation. The decision making process regarding the specific relief vehicle to assign to a location is validated as well.
- Given the scale of the disaster and corresponding demand for relief goods it is expected that a relief operation solely performed by UAVs is not viable nor desirable.
- The UAV system is a distributed system given the flexibility in simultaneously landing and taking off with multiple drones. Conversely, taking off with a Hercules C130 cargo aircraft is an operation on itself. When the distributed system is considered it can be concluded that a significant amount of drones can be simultaneously operatable.
- When the number of UAVs needs to be determined a rule of thumb can be applied basing the amount of drones on the total cargo capacity of the different vehicle types. Therefore the amount of deployable UAVs should be based upon the max capacity of the Hercules which is 19000 kg, this results in about 120 drones. This number should then be divided by three since indicated by Ronald van Gent an UAV can due to the operational limitations of the Hercules c130 generally perform three flights in the time a cargo aircraft can perform one. Resulting in roughly 40 deployable drones with respect to one Hercules C130 cargo aircraft.
- For future research, when cargo UAVs are widely accepted within multiple different supply chains throughout the world, it could be beneficial to program these drones to be deployable in a relief operation when a disaster occurs. Thereby significantly increasing the number of available drones that can contribute at the same time.

4.2.3 Conclusions

The overall takeaway from the validation process is that the simulation model represents the relief operation after the flood with respect to modern day technology to a certain level that it is validated for this research. Some insights of the validation process regarding certain experiments will be taken into account. The subjects that will be included are the possibility of different airfields/humanitarian hubs, the number of operatable UAVs, the flexibility of the UAVs system.

4.3 EXPERIMENTAL SETUP

In this section the performed experiments and the reasoning behind them are explained. The experiments are deviated from the research goal and the corresponding results should support a final conclusion. The research goal is to asses the effect humanitarian drones have on a relief operation after a disaster with similar characteristics as the flood of the Netherlands in 1953. The research question answered in this section is "*Which experiments does the model need to be able to perform?"*. The base model and performed interventions are described, an overview containing the different interventions and their corresponding characteristics is given in Table 2.

4.3.1 Base model

To start off a base model is constructed. A base model enables the research to retrieve initial results with a corresponding starting scenario. The base model represents the real-life situations in the most basic manner including all assumptions and simplifications. The vehicles that are deployed in the relief operation of the base model, is one Hercules c130 aircraft. By reasoning that the effects of humanitarian drones on a certain relief operation is researched, the base model which serves as a benchmark can therefore not contain any humanitarian drones in its relief operation. The natural circumstances of 1953 translated into the take-off limitations are included within the base model ensuring the realistic representation of the real-life relief operation. In addition, Airfield Valkenburg is chosen as humanitarian hub since the benchmark should represent the initial airfield the dropping operation was performed in during the relief operation of 1953.

4.3.2 Interventions

In this section the performed interventions to examine the effects they have on the performance results of the base model are described.

INTERVENTION 1

In order of examining the effects UAVs have on the relief operation a natural first intervention is, to recreate the base model and swapping the deployed vehicles. In this manner the performance results can be analysed, of a relief operation with the exact same characteristics as the base model would be completely performed by UAVs only instead of the plane.

INTERVENTION 2

The second intervention covers the scenario where the weather condition does not partake within the relief operation. This scenario could present itself when a flood occurred however no accompanying storm with extreme windspeeds would be present. Within the intervention the plane is deployed to which the locations can be assigned. By excluding the weather condition the relief operation can start immediately after the first location is visible to the simulation model and appears on the request open list. The entire operation is performed from Airfield Valkenburg since only one variable should be changed at a time for a result to be valuable for concluding the research question.

INTERVENTION 3

The third intervention is similar as the second one, however substitute the plane with 40 humanitarian cargo drones that are deployed to perform the relief operation.

INTERVENTION 4

The fourth intervention contains the operability of both relief vehicles without the inclusion of the weather condition. This delivers insights in the scenario where no accompanying storm is present and both vehicles can be chosen to satisfy a locations demand. By performing this experiment the relief operation can start immediately with the decision process of assigning locations to the different vehicles and vehicles types. This scenario too operates from Airfield Valkenburg, the changed variable to the relief operation is the addition of a second vehicle.

INTERVENTION 5

Within the fifth intervention a combination of all previous interventions is made. Both vehicles are deployable, the weather condition is included and the operational airfield is Airfield Valkenburg. This scenario presents the nearest representation of the real-life relief operation containing UAVs.

INTERVENTION 6 & 7

The sixth and seventh intervention is based upon intervention 4. This intervention is chosen based upon the ability to generalise the result such that it can be used for disaster management in the future. The scenario deploying both aerial vehicles and excluding the extreme windspeeds is likely to occur during a flooding event and therefore presents the most insightful results. Within the sixth and seventh intervention the location of the humanitarian hub from where the dropping operation operates is changed. Presenting to possibility to examine the effects the change has on the performance results of the relief operation. For the sixth intervention it is changed into the coordinates of Rotterdam The Hague Airport and for the seventh intervention into the coordinates of Airbase Woensdrecht.

INTERVENTIONS

Number intervention	Wind limitations	UAVs	Plane	Number of vehicles	Logistical hub
Base model	X		X	1 Plane	Valkenburg
Intervention 1	X	X		40 UAVs	Valkenburg
Intervention 2			X	1 Plane	Valkenburg
Intervention 3		X		40 UAVs	Valkenburg
Intervention 4		X	X	1 Plane 40 UAVs	Valkenburg
Intervention 5	X	X	X	1 Planes 40 UAVs	Valkenburg
Intervention 6		X	X	1 Plane 40 UAVs	Rotterdam
Intervention 7		X	X	1 Plane 40 UAVs	Woensdrecht

Table 3: Performed interventions.

4.4 RESULTS

In this subsection the results per experiment/intervention are described. An overview containing all the results per experiment is given in Table 3.

4.4.1 KPI selection

Two important KPIs are selected to examine the effects of certain interventions to the performance results of the base model, being the total cost of the relief operation and the total duration of the relief operation in hours. Answering the research question, "*Which KPI's are of importance to answer the main research question".* These KPIs successfully cover the important areas of a relief operation, being the efficiency in time and costs. The primary objective of a relief operation is to deliver relief as soon as possible within the available resources. Minimizing the amount of hours the total operation takes, the quicker all inhabitants demand together is satisfied. This is included with the total duration of the relief operation in hours KPI. Although relief operations regularly operate under great amount of pressure and urgency, costs always remains to be an important pillar of any operation. Therefore, the total costs of the relief operation calculated by the operational costs of the deployed vehicles is included as second KPI. An overview containing the results for each KPI per intervention can be seen in Figure 12 and Figure 13.

Number intervention	Total cost of relief operation	Total duration relief operation in hours
Base model	€207.490	25:49:24
Intervention 1	€346.762	55:35:22
Intervention 2	€206.599	20:47:45
Intervention 3	€346.762	29:40:04
Intervention 4	€192.698	22:11:05
Intervention 5	€207.490	25:49:24
Intervention 6	€155.088	21:53:56
Intervention 7	€151.716	21:35:46

Table 4: Results of performed interventions.

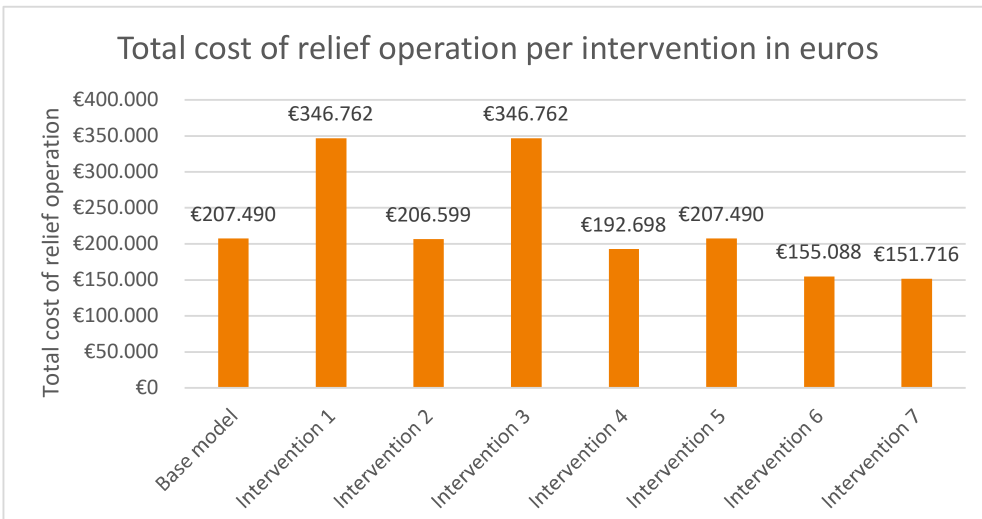


Figure 12: Graph of total cost of relief operation per intervention in euros.

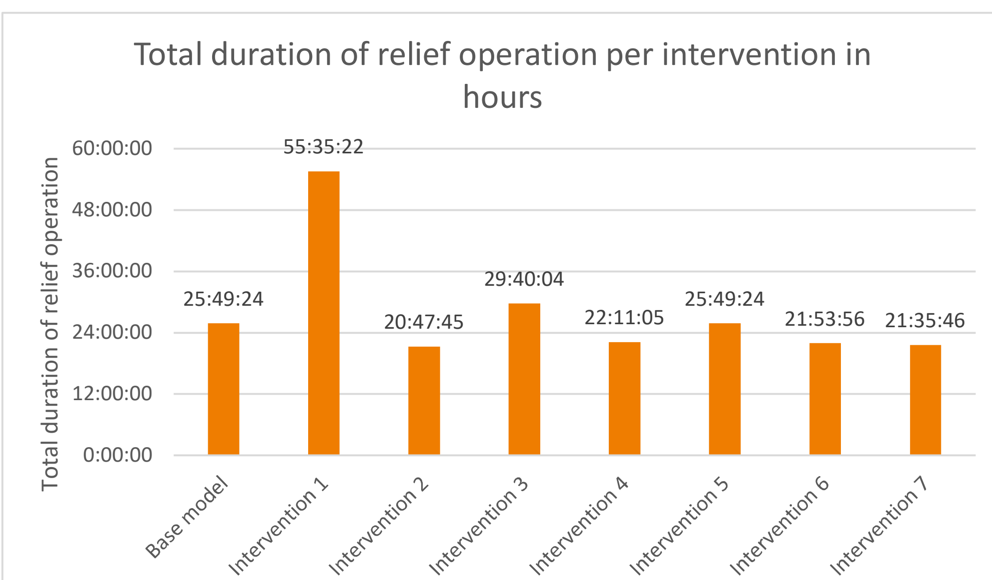


Figure 13: Graph of total duration of relief operation per intervention in hours.

4.4.2 Base model

Performing the base model experiment the simulation was run starting at 1953/02/01 00:00:00.0000, being the first moment the disaster effected the Netherlands in 1953. The timelapse developed by the University of Delft which simulated the course of the flood in 1953, comparably starts 1953/02/01 at midnight. The first dropping flight the plane performed ascended at 1953/02/01 11:00, due to the extreme weather and its limitations. Thereafter the plane satisfied all locations demands within approximately 26 hours, the last location was served at 1953/02/02 01:49:23. The operatable duration of the relief operation was 14:29:23. The total cost of the operation is €207.490, being the sum of all the costs for operating the plane from and to the different locations. As mentioned before, these results represent the performance benchmark of the relief operation after the flood to the numerous interventions.

4.4.3 Interventions

In this section the performance results of the interventions are being explained.

INTERVENTION 1

The first intervention delivers interesting performance results. The first UAV flight took off at 1953/02/02 02:00, due to the extreme weather and its limitations. The total relief operation including the inoperability of the UAVs due to weather condition took approximately 55,5 hours. This duration is remarkably higher then the relief operation solely performed by the plane. Compared to the performance results of base model, it took the UAVs 29:14:01 longer to satisfy all locations demands. The total cost of the relief operation add-up to a total of €346.762. When the experiment representing the sole use of UAVs is examined it can be acknowledged that certain locations have a sizeable demand, thereby requiring multiple UAVs flights with full capacity of 160kg to satisfy its demand. Resulting in high operational cost and increased duration of the relief operation. In addition these multiple UAV flights satisfying one locations demand result in numerous UAVs arriving at the location at the same time, causing chaos in the specific disaster area.

INTERVENTION 2 & 3

The performed experiments representing the interventions two and three delivered expected results. The weather condition is excluded from these interventions and both interventions deploy one of the two relief vehicles. The relief operations similarly start at 00:00:00 as both vehicles can immediately take-off when the first location is assigned to their route. The duration of the relief operation is the most important KPI analysing these interventions. Due to the early start of the operation of the plane in intervention 2 all locations demands are satisfied before 20:30, except for location 7. Location 7 is struck by the disaster at 1953/02/01 20:30 and therefore presents itself to the model at that time. The demand is satisfied by the plane which takes 00:17:45 hours, resulting in the last demand of location 7 that is satisfied being at 20:47:75. When the performance results of intervention 3 are considered it can be concluded that all locations demand are fully satisfied at 1953/02/02/ 05:40:04 which results in a total duration of the relief operation of 29:40:04 hours. Requiring the UAVs approximately 9 more hours to satisfy all locations demands with respect to the plane. The costs of the second intervention are somewhat cheaper with respect to the base model, this since routes can be planned more dynamic. This since locations consistently become visible to the model which results in different routes and therefore different operational costs. The capacity limitations of the UAVs lead to every UAV visiting one location whereafter it returns to the depot. This results in the UAVs having no planned route and therefore no differences appear in the operational costs of the relief operation.

INTERVENTION 4

The fourth interventions results can possibly deliver the most fundamental insights to this research. Due to the fact that the dominant weather limitation is excluded but both vehicles are included in the experiment. It includes a disaster situation that can be generalised to the largest amount of relief operation for future disasters with similar characteristics. The total costs of the relief operation sum up to a total of €192.698. This number can be split up into the two parts, the two different vehicles and their corresponding costs they separately add to the total. The plane was responsible for €175.833 of the total costs compared to the €16.865 of the UAVs. This division is made based upon numerous factors described in the logistical coordination mechanism section. The average characteristics of the locations assigned to the UAVs are analysed and compared to those of all the dropping locations. An overview of these average characteristics is given in Table 5. It shows the average distance between Airfield Valkenburg and every dropping location, being approximately the same as the average distance between Airfield Valkenburg and the locations satisfied by the UAVs. From this we can conclude that the remoteness of the location is not the most significant factor within the decision making. Comparing the average amount of relief goods over all dropping locations with the average amount over the locations assigned to the UAVs. It can be acknowledged that the locations assigned to the UAVs have significantly lower demands in relief goods. This can be substantiated by the fact that an UAV requires numerous dropping flights to satisfy a single locations demand in comparison to the plane.

Nevertheless, by including the UAVs in this operation the total costs of the relief operation decreased with €13.901 to the total costs of the second intervention where similar characteristics where in place. The operation is completed at 22:11:05 when the last locations demand is satisfied.

	UAV locations	**All locations**
Average distance from the hub to a location (KM)	68,4	65,5
Average demand in relief goods (KG)	1.124	2.608

Table 5: Locations characteristics

INTERVENTION 5

The combinational intervention 5, representing the most realistic relief operation after the flood of 1953 including humanitarian drones, produce interesting performance results. The total cost as well as the total duration of the entire relief operation are similar to the performance results of the base model. After extensive study of the operation, it can be concluded that the relief operation is completed in full by the robust Hercules c130 approximately 10 minutes before the humanitarian drones are able to take off. The last locations demand is fully satisfied by the cargo aircraft at 1953/02/02 01:49:23 compared to the first moment the UAVs are able to ascend at 1953/02/02 02:00:00. We can conclude that the weather condition is effecting the operational ability of the UAV in such a manner that they become redundant, since the 1 Hercules c130 aircraft can be deployed to execute the relief operation.

INTERVENTION 6

As the fourth intervention is most generalisable for future research, the characteristics of this intervention are included in the sixth and seventh intervention. Concluding to, no limiting weather condition and both vehicles are deployed to carry out the relief operation. Airport Rotterdam The Hague, is chosen as first humanitarian hub and all dropping flights within the relief operation now ascend from this airport. The performance results of intervention 6 are insightful, the total duration of the operation is based upon similar reasoning as to intervention 2 and 4 following from the distance of the last location to the hub. The last locations demand is satisfied at 1953/02/01 21:53:56, this being about 15 minutes quicker then the same operation performed from airfield Valkenburg. When the second KPI regarding the total costs of the operation is considered a significant decrease is acknowledged. The total cost of the relief operation is €155.088 which is €37.610 lower then the similar operation run from Naval Airfield Valkenburg. The location of the humanitarian hub being located to the dropping locations, thereby has an positive effect on the performance results of this relief operation.

INTERVENTION 7

For intervention 7 the same initial set up is used as for intervention 6, whereafter the location of the humanitarian hub is changed into the coordinates of Airbase Woensdrecht. The results of the experiment sum up to a total costs of the relief operation of €151.716 being even €3.372 cheaper then the lowest experiment run from Airport Rotterdam The Hague and €40.982 cheaper then Airfield Valkenburg 4. Concluding the operation from Airbase Woensdrecht, without including the take-off limitations and deploying both relief vehicles. The full demand of the last location is satisfied at 1953/02/01 21:35:46 resulting in this operation also being the shortest compared to intervention 4 and 6.

LOCATION ANALYSIS

To examine the impact changing the location of the humanitarian hub has on the performance results and the decision making process, the results of intervention 6 and 7 are closer investigated. When the performance logs of both interventions are examined, it shows that the division in locations assigned to either the UAVs or to the plane are effected by the location of the chosen airfield. In Figure 14, it shows that €13.820 of the total operational costs can be accounted to the UAVs in comparison to the €20.581 when airbase Woensdrecht is considered. Even though, the costs made by UAVs during intervention 7 is higher, the overall costs of the relief operation is lower.

When the location of the humanitarian hub is changed, the travel distances between the hub and all other dropping locations are effected as well. This does not only effect the costs for travelling with a certain vehicle type to the dropping location, it also effects the decision making of assigning a location to the certain relief vehicle. Therefore, the number of locations assigned to the different vehicle types are important. When all flights ascend from Rotterdam The Hague Airport, the demand of 21 locations out of 60, are assigned to be served by UAVs. Equivalently, when Airbase Woensdrecht is considered, 22 locations are served by the UAVs. Serving only 1 location more compared to the €6.761 higher costs, is remarkable. The locations served by the UAVs, per intervention is mapped in Figure 15 and 16. These figures clearly display the scattered difference of served locations within the two interventions. It can be seen that locations closer to the hub are served by the UAVs, when the hub is changed the locations served by the UAVs travel along.

By analysing the vehicle type costs, number of locations served and the positions of the locations, we can conclude that the location of the humanitarian hub has an impact on the decision making and thereby the performance results of the relief operation.

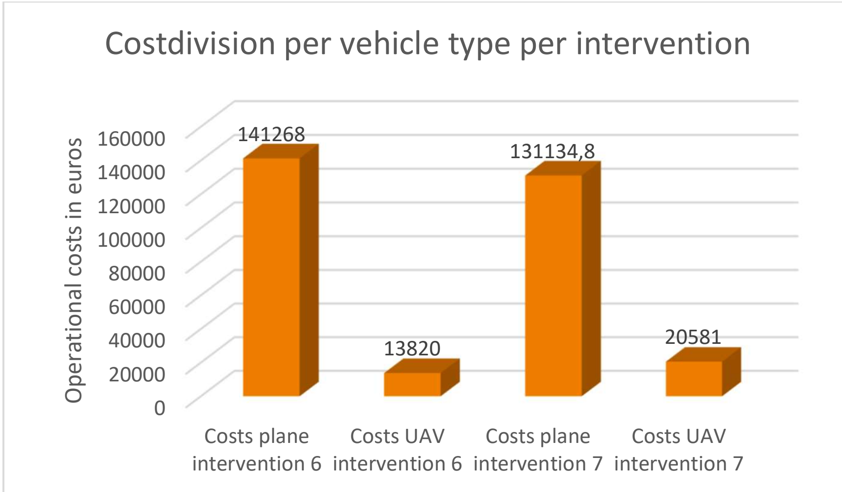


Figure 14: Costdivision per vehicle type intervention 6 & 7

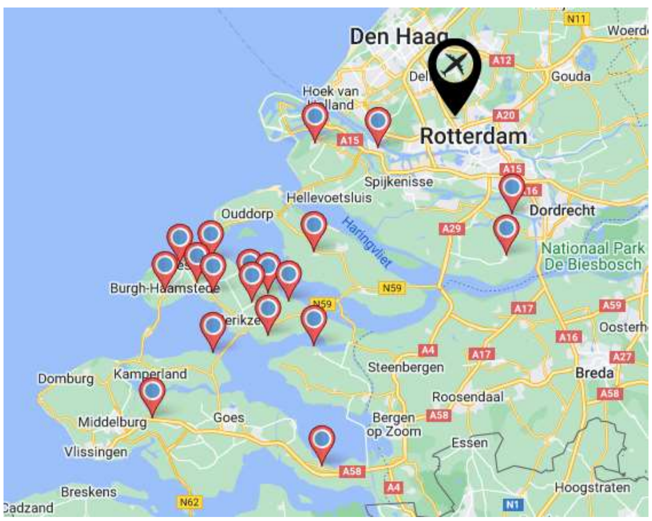


Figure 15: Locations served by UAVs with Rotterdam The Hague Airport as humanitarian hub.

Figure 16: Locations served by UAVs with Airbase Woensdrecht as humanitarian hub.

5. CONCLUSIONS

In this chapter we conclude our research and answer our main research question. In Section 5.1 the conclusions of the research are drawn, in Section 5.2 the limitations of the research are described and Section 5.3 contains future research proposals.

5.1 CONCLUSIONS

Before this research a knowledge gap existed regarding the potential impact humanitarian drones could have to a relief operation after a flood event. This research investigates using a constructed simulation model and performing numerous experiments the effects to answer the main research question being:

"What are the expected effects of using cargo drones in a relief operation after a disaster with the characteristics of the flood of the Netherlands in 1953?"

From the experiment results we conclude that drones can have a positive impact on the relief operation after a flooding event without the extreme weather conditions in 1953. In every intervention the deployment of drones along side the Hercules c130 was beneficial for the cost performance result of the relief operation. Adding the drones alongside the plane to the relief operation, without including the extreme windspeeds result in a decrease in total operational costs of 6.7%. Meanwhile, the total duration of the relief operation increases with 4.8% compared to the scenario where only the plane is deployed. Certain locations are chosen to be satisfied by cargo drones based upon costs perspective, but due to speed and capacity limitations require a longer time before the complete demand of the specific location is satisfied.

To extent this research, the effects of changing the location of the humanitarian hub is examined, resulting in two different airfields being included. By examining the performance results of these corresponding interventions we can conclude that, assigning a specific airfield as humanitarian hub has significant effects on the performance results of the relief operation. With choosing a different humanitarian hub then Naval Airfield Valkenburg the total cost of the relief operation shows a decrease of 19.5%-21.3% and the total duration of the relief operation decreases with 1.4%-2.8%. From extended analysis, we conclude that the locations with characteristics of having a smaller demand in relief goods and are located closer to the humanitarian hub are favourable to be served by cargo drones.

A trade-off occurs. When the relief operation is performed from Airbase Woensdrecht deploying both vehicles, the operation can be executed with the least amount of costs. Being 26.6% cheaper then the relief operation solely performed by the plane from Naval Airfield Valkenburg. With this saving in costs, would come an 47 minutes increase in total duration of the relief operation.

Additionally, from the experiment results we conclude that a relief operation after a disaster containing the same characteristics as the flood of the Netherlands in 1953, is not favourable to be performed by humanitarian drones only. This since only deploying drones results in the total cost of such a relief operation, being 129% higher then the cheapest relief operation which is included within this research. In addition, a remarkably longer duration time of the entire relief operation compared to other strategies was observed. Followed from the capacity limitations of the UAVs, requiring them to perform numerous flights in order of satisfying the total demand of a single location. Concluding that for operations with substantial demands such as the relief operation after the flood of the Netherlands in 1953, it is favourable to include relief vehicles with bigger capacities along side the UAVs.

At last, we can conclude that humanitarian drones during the relief operation after the flood of 1953 could not have been a large contribution. Due to the extreme weather limitation experienced by the UAVs with respect to those experienced by the Hercules c130 plane. This shows by the robust Hercules c130 plane satisfying all locations demands, thereby completing the entire relief operation, before the MiniFreighter drone is able to ascend at all. Subsequently, we can conclude that the limitation of the windspeed has a significant effect on the performance of the MiniFreighter during certain specific relief operations and should be improved if possible.

5.2 RESEARCH LIMITATIONS

Within this section, a discussion is made about the potential shortcomings of this research. In this simulation study an important translation between a disaster happened in 1953 and the effects modern humanitarian drone technology could have had on its relief operation was fundamental to be made. However, some shortcoming could arise when this research is either generalised for future disasters due to inclusions of the aspects related to 1953, or when the disaster of 1953 is researched and modern technology assumptions are unintentionally included.

By including the take-off limitation within this research it made the representation of the real-life situation more realistic. On the contrary, the speed reduction due to windspeeds within the travelled routes by the relief vehicles is not included in this research thereby possibly effecting the total duration of the relief operation.

Within this research the operation is assumed to be operational 24/7, resulting in no breaks and stops for maintenance for the relief vehicles or staff. Even though it is a relief operation and it is aspired to work around the clock to help the victims with the greatest urgency this could in practise be unworkable.

Another limitation of the research is the fact that the constructed dynamic heuristic is not reoptimizing the solution once a location is assigned to the route a vehicle. This could result in suboptimal results if locations that become visible to the model at a later point in time are a better match, but the route is already full.

5.3 FUTURE RESEARCH

The results of this research contribute to the relief operations containing humanitarian cargo drones of the future. During the validation of the simulation model the insight came that a lot of investments in cargo drones are currently made and will be made in the future. With that, the wide acceptance of cargo drones within multiple different supply chains throughout the world lies ahead. When these cargo drones and their infrastructure are widely accepted it could be beneficial to deploy these cargo drones normally used for last mile delivery of retail companies within the relief operation. Thereby significantly increasing the number of available drones that can simultaneously contribute to the operation. A suggestion for future research is to cover the inclusion of these additional drones and the nearest hubs they could use to load them with relief goods, thereby increasing the number of humanitarian hubs within the relief operation after a disaster. With these multiple humanitarian hubs they could all be assigned a subregion of the total disaster area which they can cover.

Additionally, future research regarding the robustness of the MiniFreighter is recommended. The take-off ability of the cargo drone experiencing cross wind, is rather low and greatly effects the performance results of the drone. If a similar storm as the one during the flood in 1953 presents itself, the drone cannot contribute to the relief operation. Even though events like this are rare, the endorsement of increasing the robustness such that it can take off with greater windspeeds should be made.

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APPENDIX A: INPUT DATA

A.1: Available airplanes

Table with available airplanes per day of the relief operation.

Available airplanes per day of the relief operation										
	a.	b.	c.	d.	e.	f.	g.	h.	i.	j.
1-2-1953	4	3	2	4	-	-	-	-	-	13
2-2-1953	5	3	2	4	-	-	-	-	-	14
3-2-1953	6	3	2	4	3	4	2	-	-	24
4-2-1953	6	4	2	4	4	4	4	-	-	28
5-2-1953	6	4	2	4	5	4	5	2	-	32
6-2-1953	6	4	2	3	4	-	3	1	2	25
7-2-1953	6	4	2	3	2	-	5	2	2	26
8-2-1953	6	4	1	3	-	-	6	1	1	22
9-2-1953	6	4	1	3	-	-	1	-	-	15
10-2-1953	6	4	1	3	-	-	-	-	-	14
11-2-1953	6	4	1	3	-	-	-	-	-	14
12-2-1953	6	4	1	3	-	-	-	-	-	14
13-2-1953	6	4	1	3	-	-	-	-	-	14
14-2-1953	6	4	1	3	-	-	-	-	-	14
15-2-1953	6	4	1	3	-	-	-	-	-	14
16-2-1953	6	4	1	3	-	-	-	-	-	14

Meaning Letters	
a.	Harpoons Squadron nr. 320 MLD.
b.	Mitchells Squadron nr. 8 MLD.
c.	Oxfords Squadron nr. 5 MLD.
d.	Dakota's Squadron Nr. 334 Airforce Netherlands.
e.	Dakota's K.L.M.
f.	Beecherafts R.L.S.
g.	C 119's U.S.A.F.
h.	Valetta's R.A.F.
i.	Deense Catalina's.
j.	Total per day

A.2: Flight assignments

Table with flight assignments per day of the relief operation.

Flight assignments per day of the relief operation																		
Date	Number of Flights	Flight hours	Sandbags	Rubber boats	Loafs of bread	Litres water	Rubber boots (Pairs)	Shovels	Straw/hay tons	Food tons	Clothes tons	Rubber suits	Rubber gloves	Medicines kg	Tarpaulins	Blankets	Mattresses	Cigarettes
1-2-1953	2	1:44	-	3	-	-	-	-	-	-	-	-	-	-	-	-	0	0
2-2-1953	46	91:13	9.000	39	5.575	1.000	-	-	-	4,10	-	-	-	150	-	-	0	0
3-2-1953	83	120:10	71.500	131	40.050	3.420	330	-	-	5,50	-	20	30	100	-	-	0	0
4-2-1953	91	119:32	149.000	84	17.330	3.360	850	-	3,0	0,50	0,3	-	-	-	-	38	0	0
5-2-1953	83	115:06	162.900	20	2.650	460	875	-	17,8	1,75	0,5	31	2.105	170	-	70	3	0
6-2-1953	47	66:29	94.200	-	7.600	3.000	998	150	-	1,10	0,1	50	350	100	40	230	18	4000
7-2-1953	48	81:29	126.000	2	250	1.500	1.577	266	-	-	0,3	-	150	410	-	-	0	0
8-2-1953	25	44:00	40.500	-	200	2.200	685	100	1,0	0,30	0,9	115	102	20	20	-	0	0
9-2-1953	8	14:42	5.000	-	200	-	120	150	-	-	-	-	4	20	-	-	0	0
10-2-1953	6	10:45	-	-	200	-	250	100	-	0,10	-	-	-	-	-	-	0	0
11-2-1953	9	14:25	-	-	190	-	500	60	-	0,20	-	-	-	20	-	-	0	11000
12-2-1953	4	5:10	15.000	-	-	-	191	-	-	-	-	-	-	-	-	-	0	0
13-2-1953	4	5:29	10.000	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
14-2-1953	3	4:38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
15-2-1953	2	8:05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
16-2-1953	3	3:47	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
Total	464	706:44	683.100	279	74.245	14.940	6.376	826	21,8	13,55	2,1	216	2.741	990	60	338	21	15.000
Kilo's per product			15	80	0,8	1	2	1,6				2	0,3		0,5	1,5	30	0,5
Total kilo's per product			10.246.500	22.320	59.396	14.940	12.752	1.322	21800	13550	2100	432	822	990	30	507	630	7.500
Total kilo's relief goods																		10.405.591
Excluding sandbags																		159.091

A.3: Dropping locations Operation WANO

Table containing the dropping locations and their populations during Operation WANO, Airfield Valkenburg (Defensie M. v., 1953-1955).

Dropping locations with their population during the relief operation from Naval Airfield Valkenburg											
Name	Population	Name	Population	Name	Population	Name	Population	Name	Population	Name	Population
Achthuizen	3585	Serooskerke Schouwen	512	Middelharnis	5062	Oud-Beierland	7218	Schuddebeurs	0	Stavenisse	1737
Breskens	3483	Goedereede	1195	Molendijk	0	Ouddorp	4034	Sloedam	0	Stellendam	1883
Brouwershaven	1196	Goes	13653	Moriaanshoofd	100	Oude Tonge	3088	Sommelsdijk	3699	Strijen	5102
Bruinisse	2317	Haamstede	1715	Nieuwe Tonge	2186	Ouwerkerk	565	Oost- en West-Souburg	6180	Suzannapolder	0
Burgh	732	Kamperland	2689	Nieuwerkerk	1858	Poortvliet	1705	St. Annaland	2680	Tiengemeten	5122
Colijnsplaat	1792	Kortgene	3748	Nieuwvliet	484	Puttershoek	2697	Sirjansland	512	Vlissingen	25402
Den Bommel	1993	Krabbendijke	2969	Noord-Gouwe	863	Renesse	830	St. Maartensdijk	2708	Wissekerke	3503
Dirksland	3018	Lage Zwaluwe	3585	Ooltgensplaat	3212	Rozenburg	3139	St. Philipsland	2136	Wolfaartsdijk	2560
Dreischor	1020	Melissant	2020	Oosterland	1819	Scharrendijke	512	Stad a/h Haringvliet	1327	Zierikzee	7129
Ellewoutsdijk	486	Middelburg	21817	Oostvoorne	4197	Scherpenisse	1352	Stad Tholen	3282	Zonnemaire	791

A.4: Vehicle characteristics

Table containing the characteristics of the aerial vehicles (Datasheet_MF001).

	MiniFreighter	**Lockheed C130 Hercules**
Modality	Air	Air
Speed	125	540
Range	500	3800
CapacityKG	160	19000
HourCosts	300	14000

APPENDIX B: SYSTEMATIC LITERATURE REVIEW

B.1: Key concepts

Key concepts	**Related terms/ synonyms**
Coordination mechanisms	Coordination method, (meta-) heuristic
Logistical heuristics	Planning, allocation method
(Heterogeneous) Vehicle routing problem	
Humanitarian logistics	Relief operations, supply chain
Dynamic systems	
Last mile logistics	Last mile delivery, urban logistcis

B.2: Search strings

Search String	**Scope**	**Date of search**	**Date range**	**Number of entries**	**Duplicates**
Scopus					
Humanitarian supply chain OR Humanitarian relief operation OR Humanitarian Logistics AND Last mile distribution AND Heuristics OR Coordination mechanism	Abstract, Keywords and Article Title	18-7-2022	1980-present	6	2
Humanitarian supply chain OR Humanitarian relief operation OR Humanitarian Logistics AND Heuristics OR Coordination mechanism AND Dynamic systems OR Heterogeneous fleet	Abstract, Keywords and Article Title	18-7-2022	1980-present	8	
Total				14	
Remove duplicates				-2	

Select based on exclusion and inclusion criteria				-4	
Not available for reading				-1	
Removed after scanning for relevance				-2	
Total selected for review				5	

B.3: Exclusion and inclusion criteria

Inclusion Criteria	**Motivation**	**Nr. included**
N.A.	N.A.	0
Exclusion Criteria	**Motivation**	**Nr. excluded**
Less then 10 citations	No peer-reviewed proof of quality.	4
Removed due to irrelevance	Main focus in the paper is on technology in camp management.	1
Removed due to irrelevance	Solely coordination between hubs instead of last mile distribution.	1

B.4: Findings systematic literature review

Article	**Keywords**	**Methodology**	**Key Findings**
Duhamel, C. S. (2016). Connecting a population dynamic model with a multi-period location-allocation problem for post-disaster relief operations. *Annals of Operations Research*, pp. 693-713.	Heuristics; Location-allocation; Logistics; Optimization; Post-disaster response; Resilience	Case study with a mathematical model and heuristics for solving a multi-period location-allocation problem in post-disaster operations.	For a humanitarian supply chain to function, resilience is required. PR^2; Preparedness, Response and Recovery R^4; Robustness, Resourcefulness, Redundancy and Rapidity.
Alem, D. C. (2016). Stochastic network models for logistics planning in disaster relief. *European Journal of Operational Research*, pp. 187-206.	Emergency logistics plannin g; Humanitarian logistics; OR in disaster relief; Risk-aversion; Two-stage stochastic programming	Paper developing a new two-stage stochastic network flow model to help decide how to rapidly supply humanitarian aid to victims.	Multiple stage programming in order of making the computational problem manageable.
Fikar, C. G. (2016). A decision support system for coordinated disaster relief distribution. *Expert Systems with Applications*, 104-116.	Coordination; Decision support system; Humanitarian logis tic; Last-mile distribution; Simulation optimization; Unman ned aerial vehicle	Paper including a simulation and optimization based DSS to facilitate disaster relief coordination.	Privat and relief organizations together have the perfect skill and supply set to battle a disaster. UAVs could potentially be a solution for cost-efficient coordination within relief operations.
Naji-Azimi, Z. R. (2012). A covering tour approach to the	Covering tour; Heuristics;	Article concerns the location of satellite	Relief distribution systems try to provide a fair, efficient

location of satellite distribution centers to supply humanitarian aid. *European Journal of Operational Research*, pp. 596-605.	Mathematical model; Vehicle routing	distribution centers to supply humanitarian aid.	distribution of aid. By introducing SDC (Satellite Distribution Center) the total diaster area which is served by the central depot is split up into multiple subareas served by the single SDCs.
Ferrer, J. O. (2016). A GRASP metaheuristic for humanitarian aid distribution. *Journal of Heuristics*, pp. 55-87.	GRASP; Humanitarian logist ics; Metaheuristic; Multi-criteria decision making	Paper addressing a last-mile distribution problem in disaster relief operations.	Implementable plans can be constructed when important information such as movements of vehicles and load-in time is included in the planning. When metaheuristics are used the complexity of the algorithm is not increased significantly, this leads to more accurate measures that can be utilized.

APPENDIX C: ALGORITHMIC STRUCTURE/ PSEUDOCODE HEURISTIC

```
WHILE there are sites that still have demand
    Initialization; Set start values
    IF Both vehicles can take-off
        FOR i = 1 to Nr of UAVs
            FOR j = 1 to Length of vehicle route
                Determine amount of KG dropped at location
                Calculate relative cost of UAV satisfying total demand of location
                Save cheapest UAV option
                Calculate when UAV is available to perform dropping
                Check if cheapest UAV is first available UAV
                Select best option as BestCalculationUAV
            NEXT j

        NEXT i

        FOR i = 1 to Nr of Plane
            FOR j = 1 to Length of vehicle route
                Check location of plane
                If located at the hub
                 Determine amount of KG dropped at location
                 Calculate relative cost of plane satisfying total demand of location
                 Save as cheapest plane option
                If not located at the hub
                 Calculate all distances between locations in route of plane
                 Determine amount of KG dropped at location
                 Calculate relative cost of plane satisfying total demand of location
                 Save cheapest location to insert as cheapest plane option

            NEXT j
        NEXT i

        IF BestCalculationPlane < BestCalcuationUAV

            Add location at the cheapest place to the route of the plane
```

```
                IF remaining capacity of plane = 0
                        Plan route to hub
                        Increase number of trips with 1
                        Reset capacity of plane to initial value
                END

        ELSE

                Add location in the last place to the route of the cheapest UAV
                Plan route to hub
                Reset capacity of UAV to initial value

        END

ELSEIF Only the plane can take-off
        FOR i = 1 to Nr of Planes
                FOR j = 1 to Length of vehicle route
                        Check location of plane
                        If located at the hub
                         Determine amount of KG dropped at location
                         Calculate relative cost of plane satisfying total demand of location
                         Save as cheapest plane option
                        If not located at the hub
                         Calculate all distances between locations in route of plane
                         Determine amount of KG dropped at location
                         Calculate relative cost of plane satisfying total demand of location
                         Save cheapest location to insert as cheapest plane option

                NEXT j
        NEXT i

        Add location at the cheapest place to the route of the plane

        IF remaining capacity of plane = 0
                Plan route to hub
                Increase number of trips with 1
                Reset capacity of plane to initial value
        END

ELSEIF Only the UAV can take-off
        FOR i = 1 to Nr of UAVs
                FOR j = 1 to Length of vehicle route
                        Determine amount of KG dropped at location
                        Calculate relative cost of UAV satisfying total demand of location
                        Save cheapest UAV option
                        Calculate when UAV is available to perform dropping
                        Check if cheapest UAV is first available UAV
                        Select best option as BestCalculationUAV
                NEXT j
        NEXT i

        Add location in the last place to the route of the cheapest UAV
        Plan route to hub
        Reset capacity of UAV to initial value
```

ELSE

Exit Loop

END

END

APPENDIX D: HEURISTIC CODE

```
-- .Models.GUI.LogisticsPlanningControl.HeuristicXander2
param Vehicle1, Vehicle2: string
var BestVehicleNr, BestVehicleNrUAV, InsertionRow, i, j, x, y, z, Delivery, TripNr, TripStartRow, LastRow, q, r, l, k: integer
var CapacityRemainingUAV, CapacityRemainingPlane: integer[100]
var BestCalculation, BestCalculationUAV: real
var Calculation, t: real
var TimeResult, FirstTime, TotalTimePlane: datetime

TripNr := 1 --Set initial TripNr to 1
BestCalculation := 9999999999 -- High initial value
FirstTime := EventController.AbsSimTime + 365*24*3600 -- High initial value
CapacityRemainingUAV[100] := 160 -- Starting capacity value UAV
CapacityRemainingPlane[100] := 19000 -- Starting capacity value Plane
TotalTimePlane := root.Settings.DisasterDate + 11*3600 --Set the initial begin time of plane operation at 1953/02/01 11:00.00.0000

for i := 1 to 100 -- Loop over all available vehicles
    CapacityRemainingUAV[i] := 160 -- Giving all UAVs a starting capacity of 160
    CapacityRemainingPlane[i] := 19000 -- Giving all Planes a starting capacity of 19000
next

if VehicleData["Data", Vehicle2]["Route", 1].yDim /= 0
    TripNr := VehicleData["Data", Vehicle2]["Route", 1]["TripNr", VehicleData["Data", Vehicle2]["Route", 1].yDim]
    VehicleData["Data", Vehicle2]["Route", 1].setCursor("TripNr",1) --Set search arrow in at the first row in the TripNr collum
    VehicleData["Data", Vehicle2]["Route", 1].find({"TripNr",*}, TripNr) -- Find TripNr value in this collum
    TripStartRow := VehicleData["Data", Vehicle2]["Route", 1].CursorY -- Assign the rownumber to TripStartRow

    for i := TripstartRow to VehicleData["Data", Vehicle2]["Route", 1].yDim
        k := VehicleData["Data", Vehicle2]["Route", 1]["AmountKG", i]
        CapacityRemainingPlane[1] -= k
    next
end

--Determine Vehicle
while root.PeopleDemand.RequestsOpen.yDim > 0 --When there are still sites to visit, choose the first site to assign a vehicle to
    z := root.PeopleDemand.RequestsOpen["Location", 1] --Choosing z as the first location on the RequestOpen list

BestCalculation := 9999999999 -- Reset initial value for BestCalculation
FirstTime := EventController.AbsSimTime + 365*24*3600 -- Reset initial time
```

```
    If root.PeopleDemand.Windspeed["TakeoffAbilityDrones", root.settings.Windperiod] = "1" AND
root.PeopleDemand.Windspeed["TakeoffAbilityPlane", root.settings.Windperiod] = "1" --Both vehicles can take off with respect to
the wind limitations

        For i := 1 to root.VehiclesUAVs.Vehicles["Limit", Vehicle1] --Loop over all UAV's
                Delivery := min(CapacityRemainingUAV[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the amount
of KG dropped at the location
                Calculation := CalculateCosts("UAV", 1, 1, z, Delivery) -- Calculate insertion costs
                TimeResult := EventController.AbsSimTime + CalculateTime("UAV", 1, 1, z, Delivery, i) -- Calculate expected
return time to depot
                if Calculation < BestCalculation then -- Check if new option is the best one yet
                    BestCalculation := Calculation -- If its true, then save new option as best one yet
                    BestVehicleNrUAV := i -- If its true, then save this vehicle as best vehicle
                    FirstTime := TimeResult -- If its true, then save this expected return time to depot as first time
                elseif  Calculation = BestCalculation and -- Check if new option is the same as the best one yet
                    TimeResult < FirstTime -- Check if expected return time to depot is smaller then first time
                    BestVehicleNrUAV := i -- If both are true, save this vehicle as best vehicle
                    FirstTime := TimeResult -- If both are true, then save this expected return time to depot as first time
                end
                BestCalculationUAV := BestCalculation -- Save best cost for UAV option
        next

        For i := 1 to root.VehiclesUAVs.Vehicles["Limit", Vehicle2] --Loop over all planes
            if VehicleData["Data", Vehicle2]["Route", i].yDim = 0 then-- No route, vehicle is on hub
                x := 1 -- X location of the hub
                y := 1 -- Y location of the hub
                Delivery := min(CapacityRemainingPlane[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the amount
of KG dropped at the location
                Calculation := CalculateCosts("Plane", x, y, z, Delivery) --Calculate insertion costs for a plane
                if Calculation < BestCalculation then -- Check if new option is better then best option yet
                    BestCalculation := Calculation -- If its true, save new option as best option yet
                    BestVehicleNr := i -- If its true, save vehicle as best vehicle yet
                    InsertionRow := 1 -- Insert the location in the first row
                end
            else

            TripNr := VehicleData["Data", Vehicle2]["Route", i]["TripNr", VehicleData["Data", Vehicle2]["Route", i].yDim]
            BestVehicleNr := 1
```

```
            VehicleData["Data", Vehicle2]["Route", BestVehicleNr].setCursor("TripNr",1) --Set search arrow in at the first row in
the TripNr collum
            VehicleData["Data", Vehicle2]["Route", BestVehicleNr].find({"TripNr",*}, TripNr) -- Find TripNr value in this collum
            TripStartRow := VehicleData["Data", Vehicle2]["Route", BestVehicleNr].CursorY -- Assign the rownumber to TripStartRow

            l := VehicleData["Data", Vehicle2]["Route", i].yDim

            if z = 7
                l := VehicleData["Data", Vehicle2]["Route", i].yDim - 1
            end

                For j := TripstartRow to l --Loop over all route distances between locations in the route of a plane
                    --Set x and y: where to insert
                    if j = VehicleData["Data", Vehicle2]["Route", i].yDim --From last site to hub
                        x := VehicleData["Data", Vehicle2]["Route", i]["Location", j] -- Location of last site
                        y := 1 -- Location of the hub
                    else --From site A to site B
                        x := VehicleData["Data", Vehicle2]["Route", i]["Location", j] -- Location of site A
                        y := VehicleData["Data", Vehicle2]["Route", i]["Location", j+1] -- Location of site B
                    end
                    Delivery := min(CapacityRemainingPlane[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the
amount of KG dropped at the location
                    Calculation := CalculateCostsPlane("Plane", x, y, z, Delivery) --Calculate insertion costs
                    if Calculation < BestCalculation then -- check if new option is better then best one yet
                        BestCalculation := Calculation -- if its true, save new option as best option yet
                        BestVehicleNr := i -- if its true, save new vehicl as best vehicle yet
                        InsertionRow := j+1 -- if its true, save place where to insert the location into the route of the plane
                    end
                next
            end
        next

        if root.VehiclesUAVs.Vehicles["Limit", Vehicle1] = 0
            BestCalculationUAV := 9999999999
        end

        If BestCalculation < BestCalculationUAV -- Check if best option from the plane is cheaper then best option from the UAV
            --if its true, insert location in route of the plane
            Delivery := min(CapacityRemainingPlane[BestVehicleNr], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Amount of KG
dropped at the location
```

```
            InsertSite(Vehicle2, BestVehicleNr, InsertionRow, Delivery, 1, TripNr) --Fill the characteristics of the location at
the right spot within the route of the plane
            --Update capacity remaining
            CapacityRemainingPlane[BestVehicleNr] -= Delivery -- Subtract the amount of KG that needs to be dropped at the

            if CapacityRemainingPlane[BestVehicleNr] = 0 -- Check if remaining capacity of the plane is 0
                TripNr += 1 -- increase tripnumber with one when hub is visited
                For j := TripStartRow to VehicleData["Data", Vehicle2]["Route", BestVehicleNr].yDim + 1
                    if VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j] = void then
                        VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j] := 1
                        VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["TripNr", j] := TripNr
                    end
                next
                CapacityRemainingPlane[BestVehicleNr] := 19000
            end

            if z = 7 and root.VehiclesUAVs.Vehicles["Limit", Vehicle2] = 1 then
                --TripNr := VehicleData["Data", Vehicle2]["Route", 1]["TripNr", VehicleData["Data", Vehicle2]["Route", 1].yDim]
                InsertionRow := VehicleData["Data", Vehicle2]["Route", 1].yDim + 1 -- row to insert the location of the hub
                VehicleData["Data", Vehicle2]["Route", 1]["Location", InsertionRow] := 1 -- insert the next location as hub
                VehicleData["Data", Vehicle2]["Route", 1]["TripNr", InsertionRow] := TripNr -- set the tripnumber of the trip to
the hub to 1
                VehicleData["Data", Vehicle2]["Route", 1]["AmountKG", InsertionRow] := 9000 -- increase amount of KG in trip such
that it reaches its capacity limitation
            end

        Else -- Best option from UAV is either cheaper or the same as the best option from the plane
            InsertionRow := VehicleData["Data", Vehicle1]["Route", BestVehicleNrUAV].yDim + 1  -- Insert location in the first
row of the vehicle route
            Delivery := min(CapacityRemainingUAV[BestVehicleNrUAV], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine
the amount of kilo dropped at the location by the best vehicle
            InsertSite(Vehicle1, BestVehicleNrUAV, InsertionRow, Delivery, 1, 1) -- Fill the characteristics of the location at
the right spot within the route of the plane

            --Plan route from last site to Logistics Hub (SiteNr 1)
            InsertionRow := VehicleData["Data", Vehicle1]["Route", BestVehicleNrUAV].yDim + 1 -- Select 1 row lower then the last
planned location as insertion row
            VehicleData["Data", Vehicle1]["Route", BestVehicleNrUAV]["Location", InsertionRow] := 1 -- Insert hub as next
location
            VehicleData["Data", Vehicle1]["Route", BestVehicleNrUAV]["TripNr", InsertionRow] := 1 -- Reset Tripnr to 1, since you
```

```
visited the hub
            CapacityRemainingUAV[BestVehicleNrUAV] := 160 -- once visited the hub reset remaining capacity of chosen vehicle to
initial value
        End

    Elseif root.PeopleDemand.Windspeed["TakeoffAbilityDrones", root.settings.Windperiod] = "0" AND
root.PeopleDemand.Windspeed["TakeoffAbilityPlane", root.settings.Windperiod] = "1" -- Only the plane can take off with respect to
the wind limitations

        if z = 7 then
            TripNr := VehicleData["Data", Vehicle2]["Route", 1]["TripNr", VehicleData["Data", Vehicle2]["Route", 1].yDim]
            InsertionRow := VehicleData["Data", Vehicle2]["Route", 1].yDim + 1 -- row to insert the location of the hub
            VehicleData["Data", Vehicle2]["Route", 1]["Location", InsertionRow] := 1 -- insert the next location as hub
            VehicleData["Data", Vehicle2]["Route", 1]["TripNr", InsertionRow] := TripNr -- set the tripnumber of the trip to the
hub to 1
            VehicleData["Data", Vehicle2]["Route", 1]["AmountKG", InsertionRow] := 5000 -- increase amount of KG in trip such
that it reaches its capacity limitation
        end

        For i := 1 to root.VehiclesUAVs.Vehicles["Limit", Vehicle2] -- Loop over all planes
            if VehicleData["Data", Vehicle2]["Route", i].yDim = 0 then-- No route, vehicle is on hub
                x := 1 -- X location of the hub
                y := 1 -- Y location of the hub
                Delivery := min(CapacityRemainingPlane[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the amount
of KG dropped at the location
                Calculation := CalculateCosts("Plane", x, y, z, Delivery) --Calculate insertion costs
                if Calculation < BestCalculation -- Check if next option is cheaper then best option yet
                    BestCalculation := Calculation -- if its true, save the next option as best option yet
                    BestVehicleNr := i -- if its true, save the vehicle as best vehicle  yet
                    InsertionRow := 1 -- Insert the location in the first row
                end
            else

            TripNr := VehicleData["Data", Vehicle2]["Route", i]["TripNr", VehicleData["Data", Vehicle2]["Route", i].yDim]
            BestVehicleNr := 1

            VehicleData["Data", Vehicle2]["Route", BestVehicleNr].setCursor("TripNr",1) --Set search arrow in at the first row in
the TripNr collum
            VehicleData["Data", Vehicle2]["Route", BestVehicleNr].find({"TripNr",*}, TripNr) -- Find TripNr value in this collum
            TripStartRow := VehicleData["Data", Vehicle2]["Route", BestVehicleNr].CursorY -- Assign the rownumber to TripStartRow
```

```
            l := VehicleData["Data", Vehicle2]["Route", i].yDim

            if z = 7
                l := VehicleData["Data", Vehicle2]["Route", i].yDim - 1
            end

                For j := TripStartRow to l --Loop over all route sections
                    --Set x and y: where to insert
                    --if j = TripStartRow --From hub to first site
                        --x := 1 -- Location of the hub
                        --y := VehicleData["Data", Vehicle2]["Route", i]["Location", j] -- Location of the first site
                    if j = VehicleData["Data", Vehicle2]["Route", i].yDim --From last site to hub
                        x := VehicleData["Data", Vehicle2]["Route", i]["Location", j] -- Location of the last site
                        y := 1 -- Location of the hub
                    else --From site A to site B
                        x := VehicleData["Data", Vehicle2]["Route", i]["Location", j] -- Location of site A
                        y := VehicleData["Data", Vehicle2]["Route", i]["Location", j+1] -- Location of site B
                    end
                    Delivery := min(CapacityRemainingPlane[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the
amount of KG dropped at the location
                    Calculation := CalculateCostsPlane("Plane", x, y, z, Delivery) -- Calculate insertion costs
                    if Calculation < BestCalculation then -- Check if next option is better then best option yet
                        BestCalculation := Calculation -- If its true, save next option as best option yet
                        BestVehicleNr := i -- if its true, save next vehicle as best vehicle yet
                        InsertionRow := j+1 -- The row where the location should be inserted within the route
                    end
                next
            end
        next

        If BestVehicleNr /= 0 -- Check if there is a best vehicle
            Delivery := min(CapacityRemainingPlane[BestVehicleNr], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine
the amount of KG dropped at the location
            InsertSite(Vehicle2, BestVehicleNr, InsertionRow, Delivery, 1, TripNr) -- Fill the characteristics of the location in
the right spot of the route of the plane
            --Update capacity remaining
            CapacityRemainingPlane[BestVehicleNr] -= Delivery --Subtract the delivery from the capacity remaining of the plane
            for j := 1 to VehicleData["Data", Vehicle2]["Route", BestVehicleNr].yDim - 1-- loop over al locations in route of
plane
```

```
                t := VehicleData["Times", Vehicle2][VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j],
VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j+1]] -- calculate travel time between location j and j+1
                TotalTimePlane += t -- add travel time between location j and j+1 to total time of the route
            next

            if TotalTimePlane > root.PeopleDemand.WindSpeed["DateTimeRevealed", 10] --check if total time of the route is larger
then the 10th cell of the windspeeds
                root.PeopleDemand.Windspeed["TakeoffAbilityDrones", root.settings.Windperiod] := "1" --if thats the case then set
takeoff ability of UAVs to 1
            else
                TotalTimePlane := root.Settings.DisasterDate + 11*3600
            end

            if CapacityRemainingPlane[BestVehicleNr] = 0 then
                TripNr += 1
                For j := TripStartRow to VehicleData["Data", Vehicle2]["Route", BestVehicleNr].yDim + 1
                    if VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j] = void then
                        VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["Location", j] := 1
                        VehicleData["Data", Vehicle2]["Route", BestVehicleNr]["TripNr", j] := TripNr
                    end
                next
                CapacityRemainingPlane[BestVehicleNr] := 19000
            end
        Else
            Exitloop -- No Vehicle is found
        End

    elseif root.PeopleDemand.Windspeed["TakeoffAbilityDrones", root.settings.Windperiod] = "1" AND
root.PeopleDemand.Windspeed["TakeoffAbilityPlane", root.settings.Windperiod] = "0" -- Only the UAV can take off with respect to
the wind limitations
        For i := 1 to root.VehiclesUAVs.Vehicles["Limit", Vehicle1] -- Loop over all UAVs
                Delivery := min(CapacityRemainingUAV[i], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the amount
of KG dropped at the location
                Calculation := CalculateCosts("UAV", 1, 1, z, Delivery) -- Calculate insertion costs
                TimeResult := EventController.AbsSimTime + CalculateTime("UAV", 1, 1, z, Delivery, i) -- Calculate the expected
return time to the depot
                if Calculation < BestCalculation -- Check if next option is better then best option yet
                    BestCalculation := Calculation -- if thats true, save next option as best option yet
                    BestVehicleNr := i -- if thats true, save vehicle as best vehicle yet
                    FirstTime := TimeResult -- if thats true, save the return time as first time
```

```
                elseif  Calculation = BestCalculation and -- check if next option is better then best option
                    TimeResult < FirstTime -- check if expected return time for this vehicle is sooner then first time
                        BestVehicleNr := i -- if thats true, save vehicle as best vehicle yet
                        FirstTime := TimeResult -- if thats true, save return time as first time
                end
        next

        If BestVehicleNr /= 0 -- If there is a best vehicle found
            --Insert site into route of vehicle1
            InsertionRow := 1 -- Row to insert the location in the route of the UAV
            Delivery := min(CapacityRemainingUAV[BestVehicleNr], root.PeopleDemand.RequestsOpen["AmountKG", 1]) -- Determine the
amount of KG dropped at the location
            InsertSite(Vehicle1, BestVehicleNr, InsertionRow, Delivery, 1, 1) -- Fill in the characteristics of the location in
the right spot of the routeplanning

            --Plan route from last site to Logistics Hub (SiteNr 1)
            InsertionRow := VehicleData["Data", Vehicle1]["Route", BestVehicleNr].yDim + 1 -- row to insert the location of the
hub
            VehicleData["Data", Vehicle1]["Route", BestVehicleNr]["Location", InsertionRow] := 1 -- insert the next location as
hub
            VehicleData["Data", Vehicle1]["Route", BestVehicleNr]["TripNr", InsertionRow] := 1 -- set the tripnumber of the trip
to the hub to 1

            CapacityRemainingUAV[BestVehicleNr] := 160 -- reset the capacity of the drone when the hub is visited to 160
        Else
            Exitloop -- No Vehicle is found
        End
    else
        exitloop
    end
end --while requests open
```