The last airmile

Using strategic and operational policies to reduce the constraints of bottlenecks on the airport relief chain

Dave Grund

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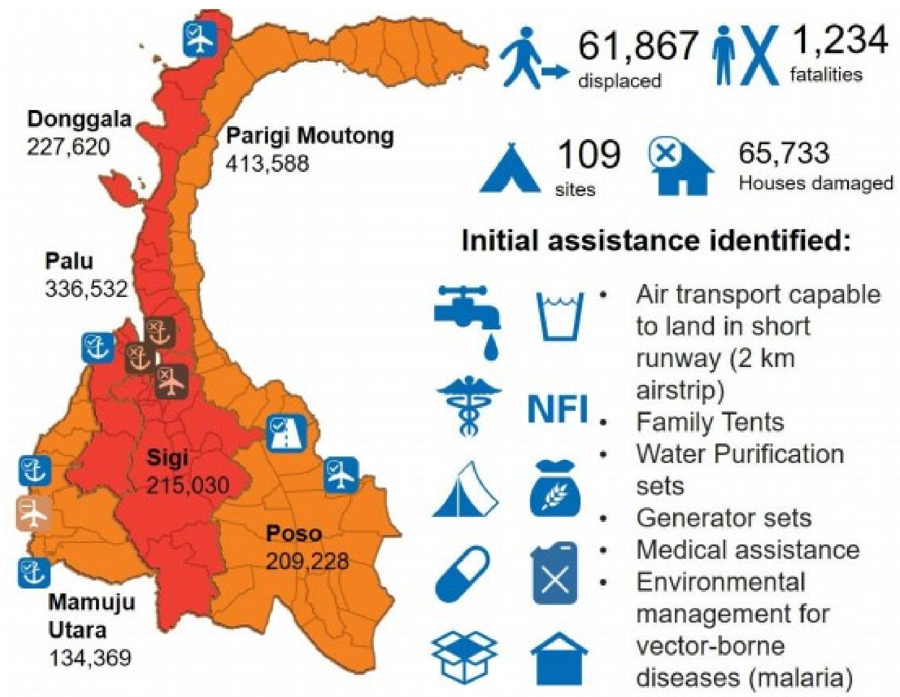

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Using strategic and operational policies to reduce the constraints of bottlenecks on the airport relief chain

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preface

This master thesis is the conclusion of my master Engineering and Policy Analysis, the last hurdle to overcome before applying the acquired skills in real world situations. This hurdle was a valuable experience, which showed me the importance of a clear problem definition and the value of a research question to the process of a study. Once the research question and subquestions were clearly identified the process become increasingly smooth and structured.

Hereby, I want to thank my committee for the feedback and the help with structurin the process. Their feedback was of great help together with the opportunity provided by the Humtech lab at the TU Delft, to join the HNPW in Geneva. At the HNPW many interesting participators from the field of humanitarian aid were present sharing both their passion and knowledge. From the conference I would like to give special thanks to Chris Weeks for providing both insights and aiding in the face validation process.

Lastly I would like to thank my good friends Robert Smits and Mark in 't Veld for their support in aligning the text and pre-reading the master thesis. They were of great help in the process of finalizing the thesis.

Executive Summary

The frequency of occurrence and the size of natural disaster is increasing, with more people to be affected in the coming years. The impact is huge, with major infrastructures being damaged and access to basic needs cut off for the disaster struck regions. The affected regions and communities are dependent on the delivery of disaster relief aid, by governments and non-governmental organizations. The delivery can be difficult, while airports, harbours and other infrastructure is often damaged from the disaster.

The timely delivery of relief aid to the affected communities is a major challenge of today. The airports used for the distribution of relief items are often unable to handle the shear size of the influx of these items. The resources are damaged and personnel might not be able to show up for work. In order to reduce the overexertion of the local airport, an airbridge can be made with a regional airport. The regional airport can then be used as a buffer, for bundling and storing relief aid, until it can be delivered to the local airport. The system in which the regional airport receives the international contribution of relief items and sends them in a moderated flow to the local airport is called the airport relief chain.

The relief chain is subject to several bottlenecks, but due to scarcity in research, the influence on airport relief chains had not been identified previously. Reducing these bottlenecks and improving the relief chain can be achieved by improving the processes on individual airports, as well as by altering the structure of the relief chain itself. The research question is consequently: *How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief chain system, considering both the airport operations and network design?*.

To be able to confirm the bottlenecks and investigate possible solutions, a simulation model was built for the airport relief chain system. To obtain relevant outcomes, data of a real world case study was applied to the simulation model. The case study of choice is the earthquake followed by a tsunami in september 2018, that struck the island of Palu, Indonesia. In this disaster, an airport relief chain system was created, in which the delivery to Mutiara on Palu, serving as the local airport, was provided through Sepinggan airport on Kalimantan, serving as the regional buffer airport.

To this end three bottlenecks were identified for the airport relief chain. namely: (1) The aircraft arrival process at the regional airport, (2) The cargo handling after unloading of the aircraft at the regional airport, and (3) the airbridge connection between the local and regional airport. The bottleneck at the airbridge is the most stressing, absorbing most of the cargo. Even when the other bottlenecks are resolved, without improvement in the airbridge the performance will eventually be limited.

With the airbridge as a major constraint in the airport relief chain system, the delivery of relief items can not be larger than the throughput of the airbridge. The bottlenecks identified at the aircraft arrival and the regional airport processes reduce the flow of relief items even further. The policies investigated are meant to maximize the performance up to the airbridge, creating maximal performance within the constraints of the system.

The performance was measured through two sets of performance indicators, timely delivery and

resilience. Timely delivery is divided into *total delivery* and the *share of priority demand delivered*. The resilience is measured as the *processed cargo*, *idle cargo* and *throughput time*. The timely delivery performance indicators represent the total performance of the system, while resilience is used to identify bottlenecks and the impact of bottlenecks on the system.

The individual policies were ineffective to truly improve the airport relief chain as a whole. Several policies proved to be quite effective at reducing bottlenecks, thus improving the resilience. However, only small improvements were seen in the timely delivery, especially on the *total delivery* measure. The *share of priority demand* alone could be raised effectively through prioritization policy. Those policies would not provide further system improvements, making their use even more case specific.

In order to improve on the timely delivery indicators, which includes the total delivery, combinations of strategic and operational policies were examined. Based on the individual performances *destination prioritization* and *arrival gates* were chosen as the strategic policies and *additional workers* as the operational policy. The combinations approached optimal system performance, given the constraint imposed by the airbridge.

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1 Introduction

Natural disasters are in an upward trend, creating distress in increasing frequency. The Economist (2017), reported the largest number of natural disaster to have occurred in the period between 1995-2015. The tides do not seem to have turned, with more disasters over the last few years causing major humanitarian crises. The hurricanes Harvey and Irma in 2017 were responsible for major upset around the Americas, while earthquakes shook the Indonesian archipelago in late 2018. These are a few large scale examples, but were few of many in this period. One reason for this increase in the frequency of disasters is global warming, and the correlated rise and warming of the oceans. Even as long back as 2007, the rise of Water based disasters was already forecasted (Diaz, 2007).

The impact of these natural disasters is huge, with disasters shaping public opinion and the political agendas long after the event had happened. The crisis caused by hurricane Irma on the Saint Martin remained a topic of debate in the political agenda for months (Knops, 2018). This is often related to the difficulty of providing adequate delivery of relief aid to the disaster struck region.

This adequate delivery has seen a rise in importance, but is difficult to achieve in the early stages of the disaster relief operations. The situation after a disaster is highly complex, enforcing a time constraint on the relief workers, while information is often scarce or unfiltered and organizations are forced to collaborate. In order to fulfill the high demand for resources in the short response window, the operations have to align as much as possible.

The delivery of relief items is generally managed through local airports, at which operation alignment is very difficult. The airport itself has insufficient space and is often damaged by the disasters. This causes two major problems. Firstly, a reduction of the capacity to deal with the influx of relief items. Secondly, the untimely delivery of relief items throughout the humanitarian supply chain. It was found by Veatch and Goentzel (2018), that the unloading capacity of the airport was lacking, both in terms of availability of gates and quantity of professional workers. Their paper was aptly named feeding the bottleneck, highlighting the inefficient practice of overstocking small airports ill equipped to handle the influx of relief aid.

In order to reduce the influx at the local airports, a regional airport can be assigned as buffer, prioritizing and limiting the flow of relief items to the local airports. Additionally, the regional airport then serves as a hub, connecting the airports in the affected areas (Chandes & Pache, 2010). This approach circumvents the bottleneck defined by Veatch and Goentzel (2018) at the local airport, making more effective allocation of resources achievable. The connection between the regional and local airport make an airbridge system, which will for future reference be called, **the airport relief chain**. In this study the focus will be on this airport relief chain, in which the intermediate storage of goods is included. The airport relief chain is represented in figure 1.

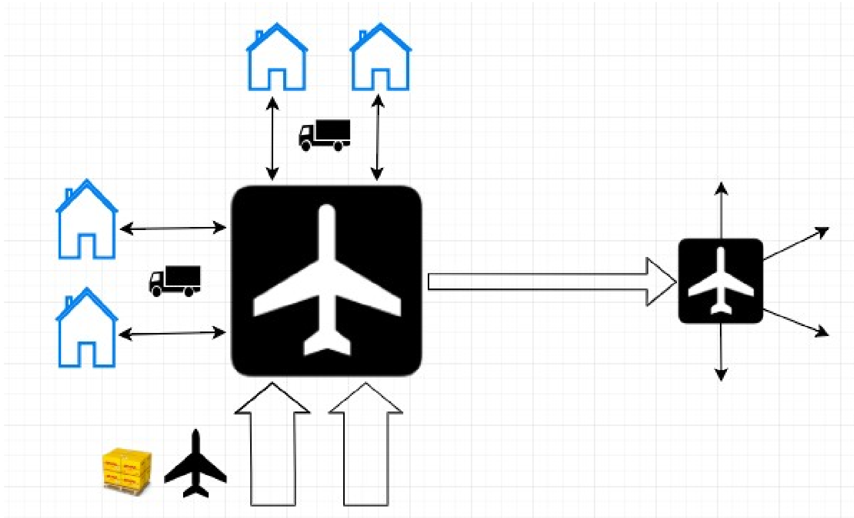

Figure 1: airport relief chain

The time it takes to provide the relief effort to the disaster struck region is sought to be minimized. In a relief chain, this is determined by the performance of the weakest link. As such, improvements on the individual airports can benefit the throughput time of the chain and create additional value on the system's level (Kovacs & Spens, 2007). The performance of the airports is an absolute necessity, to create a sustainable and smooth flow of relief items through the airport relief chain.

The airport performance is measured in terms of resilience. A resilient airport is seen as an airport that can recover not only to the pre-disaster performance in a short period of time, but also increase capacity to deal with the influx of relief items. This is difficult to accomplish for a single airport serving the disaster region, but for an airport relief chain system, it is significantly easier. In this system, the regional airport does not have to face the reduced capacity from damage, and has better resources available to deal with the influx of relief items.

Research goals

This research aims at improving the resilience for both the local and regional airport to create a significant level of performance, before optimizing the airbridge. It further takes into account the interplay of the various system components, and how these components are affected by prioritization rules used in practice as described in the work of Gralla and Goentzel (2018). Aside from operational changes to the system which the work of Gralla and Goentzel (2018) is concerned with, various network design changes could improve the airport relief chain as well. The interplay of the various system components could change by means of strategic policy, improving the relation between the two considered airports.

With the previous system changes in mind the question this research aims to answer is: ***How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief***

chain system, considering both the airport operations and network design?

Research design

The research design is set up to provide a grounding in literature to study the airport relief chain first, then to set up the research methodology, before incrementally answering the research question. This resulted in the following structure: Firstly section two addresses the research gaps. Secondly, the third section is used to provide a layout of the research design. In order to fill the gaps found in literature, the research question is separated into four subquestions as described in this methodology section. The fourth section includes the conceptual models for the airport relief chain and the prioritization rules, which is concluded with the performance indicators for the airport relief chain system. The fifth section discusses the simulation tool and the choice for the simulation paradigm.

After section five, the design of the airport relief chain is concluded. The design of the relief chain is done by means of a case study, focusing on an airport relief chain with one regional hub airport and one local airport. In this airport relief chain, both the local and regional airport are described by the discrete event model as proposed by Feil (2018). The proposed model is generic and on a mesoscopic level, which means it has to be altered to represent the specified airports, while maintaining the level of detail. This scale was chosen by Feil (2018) as it is easier to tailor a simplified higher level model towards a specific case than a very detailed model, regarding a wide set of input variables. For the airport relief chain the mesoscopic scale is suited as well, whereas the model connections require not an immensely detailed representation, but verified commonalities and relations where in practice interactions would be observed. With a more detailed representation, a large extent of the detail will be lost in the connections between the components in the model.

After the design of the case study and the airport relief chain model, the design of the policies and the analyses are performed. The influence of the policies is described in section six, with the design of the scenarios presented in section seven. The results of the policies on the different scenarios are described in section eight. The results are followed by section nine considering the validation and verification of the model. The outcomes of the validation and verification are discussed in section ten, before conclusions are drawn in section eleven.

2 Literature review

This sections aims at analyzing the current state of the art in resilience of air transportation networks, the organization of humanitarian logistics and the modelling practices. These three parts of the literature review each represent a knowledge gap, in which this research will contribute. The research aims to fill these voids by combining the three knowledge gaps into a single knowledge gap formulation spanning the three, at the end of the literature review.

2.1 Resilience of the last airmile network

The airport relief chain as described in the introduction is a construction seen in disasters to reduce the immediate strain on the facilitating airport. The smaller disrupted airports cannot deliver the required capacity within a short period of time, making the system dependent on the local availability of resources. A larger airport serving as a hub to the affected regions could improve the delivery of relief items, through the bundling of relief efforts. The larger airport is for example less prone to the bottleneck defined by (Veatch & Goentzel, 2018) at the aircraft handling. It does however, become dependent on the airport operations of both the local and regional airport, with lastly the performance of the airbridge connecting the two as a final possible bottleneck.

The ability of the airport relief chain to improve the delivery of relief items is dependent on the resilience of both airports in the system, as well as the network or chain resilience. In this section the term resilience in this research is addressed first, followed by the resilience of airports. Once the resilience of airports in literature is clarified the literature on relief chains is reviewed.

2.1.1 Resilience

Resilience has various definitions depending on the field in which it is used, which creates importance on defining resilience in a study, before using it. In the fields of ecology, physics and engineering the term has long been popular after introduction as early as the 1940's (Manyena, 2006). In the field of ecology, the term resilience is seen as the amount of disturbance a system can withstand until it can no longer bounce back to the original state. This is far more narrow than the definition used in the field of engineering, where resilience is the reduction of chance of a shock, the improvement of absorption of a shock and the time it takes to recover from a shock (Bruneau & Reinhorn, 2006). The definitions of resilience always refer to recovery of the system, yet in engineering the focus is on taking action to assure system performance.

2.1.2 Resilience of airports

The hub function of the airport in the relief chain makes the throughput of the humanitarian aid dependent on the airport resilience. Balcik, Beamon, and Smilowitz (2008) stress the role of the airport in humanitarian logistics as one of the most necessary elements. With the increased threat of natural disasters, disaster management is as important as ever. This has led to new initiatives like the DHL Getting Airport Ready for Disaster (GARD) program, in which regional airports are prepared for disasters. Paradoxically to the fact that disaster management has become very important, the implementation of these programs only progresses slowly.

The definition of resilience in engineering and ecology is insufficient considering the role of airports in disaster regions. Both the DHL GARD program and Balcik et al. (2008), stress the urgency of the airport and the ability to perform under a higher standard than the original state. Recovery to the performance before the disaster will not deal with the influx of relief goods, making the airport a bottleneck in the airport relief chain as was restated by Balcik, Beamon, Krejci, Muramatsu, and Ramirez (2009) and Van Wassenhove (2006a).

The description of Johansson and Hassel (2010) is adequate for his situation. They describe resilience as a combination of two components, the coping capacity and a part of learning. This learning represents what was described by Feil (2018) as ramp up capacity of which his work is now one of very few examples. The utilization of this definition of resilience is only seen in single airport studies, making it understudied for larger systems. The importance of the resilience of the airport to the humanitarian relief chain is unknown, while it could significantly impact the delivery of relief items to disaster struck regions.

2.1.3 Resilience of relief chains

The airport relief chain utilizes a multitude of airports, each presenting a possible bottleneck if capacity comes short of the ramp up capacity. Network systems such as described by Dunn and Wilkinson (2016); Janic (2015), regard the resilience of network systems only on a high aggregation level. The airports are nodes in the network, for which disconnection and connection is considered. In these studies the resilience is seen as the ability to minimize the impact of shock, which is meant to be improved. The airport relief chain is on a far smaller scope, unable to replace airports for the last airmile.

In contrast to relief networks, the moment a bottleneck is identified, the inherent weakness of the system comes to surface. The system has very few alternatives within the chain. Due to the lack of redundancy, conservation tactics have to be considered, as was proposed by Cox, Prager, and Rose (2011). This amounts to reducing the number of flights and amount of cargo to relieve the strain on the system. This adversely affects the performance of the relief chain even though it has to be done shortly. According to Janic (2015) airports in earthquake prone areas have usually short down times, making the use of such conservation tactics only necessary in the early phase of disaster response.

2.1.4 Knowledge gap for the last airmile network

Resilience in ecology and engineering studies considers the return to the stable pre-disaster situation, and (Janic, 2015) considers minimization of impact. Their definitions of resilience do not suffice for research considering an airport relief chain. The airports in these relief chains cannot mitigate the shock or the correlated damage. Returning to pre-disaster situations would lead the airport to under perform. A new adequate definition is neccessary.

This more adaptive definition for resilience was proposed by Johansson and Hassel (2010), which was further adapted by Feil (2018). The work of Feil (2018) as such is one of very few examples using the new definition of resilience. The narrow application of this changed definition of resilience is worrying, while more fields would do well to adopt a more agile approach to resilience. Resilience of networks being the first designated in this study to benefit from the new definition.

The resilience in relief chains is usually approached as resilience of the total network. The scope is rarely on the resilience of the airport in the network system, while the airports are considered as interchangeable nodes in the network. When the airports are studied as unchangeable nodes, the improvement of resilience is seen as the goal which conservation tactics are meant to achieve.

The adaptive definition for the resilience as introduced for airports is rarely studied, while relief chains with airports as necessary components in the chain is widely understudied as well. The knowledge gap for the last airmile network considers both the resilience of airports and the unchangeable position of airports in the network structure. This knowledge gap is formulated as: *"The academic literature is lacking with regard to the influence of the airport resilience on the airport relief chain"*.

2.2 Humanitarian logistics

The humanitarian logistics account for around 80 percent of the total cost of relief operations (Balcik et al., 2009; Van Wassenhove, 2006b). This can be partly explained by the difference in objectives between what could be called commercial and humanitarian logistics. The commercial logistics tend to be forced into a more optimal system, for the maximiation of profit. These systems tend to be far more fine tuned than humanitarian logistics systems in which delivery is favoured over cost effectiveness. The cost of underutilized equipment is seen as economic loss from excess cost (Stevenson, 2005). According to Weeks (2019) this disconnect is part of the problem concerning wrong and poor delivery through humanitarian supply chains. The humanitarian logistics should be optimized with regard to cost, whereas it would reduce lost storage capacity and the strain on the relief chain as a whole. A system describing the additional storage capacity of the airport is presented in figure 2.

2.2.1 Inventory management

The state of the art in inventory management (IM) tends to have two commonalities throughout the literature. Firstly, the focus of IM is on cost effective operations Das and Hanaoka (2014); Davis, Samanlioglu, Qu, and Root (2013). This aligns with the need for optimizing the relief logistics, yet is mostly on storage cost and transportation cost in network systems. The second commonality is the use of two-stage stochastic programming models to optimize the size of warehouses and the location for minimal transportation cost Balcik, Bozkir, and Kundakcioglu (2016); Davis et al. (2013). These two commonalities would each suffice in network systems, with alternatives for the hub nodes in the system. This study however, focuses on intermediate storage of relief goods with regard to priority setting. For such a system the state of the art in IM does not inherently suffice and alternatives have to be found.

The intermediate stock approach does not regard optimal cost, as intermediate stock with transportation is never optimal. The focus on time effective allocation of relief goods, which is impossible if the airport is severely constrained. Providing sufficient supplies was studied by for example Holguin-Veras, Jaller, van Wassenhove, Perez, and Wachtendorf (2012), whom stated that the majority of response-based instead of population needs. Estimating the real population needs is difficult, which is intensified by the timely requirements for delivery. According to Balcik (2010) the

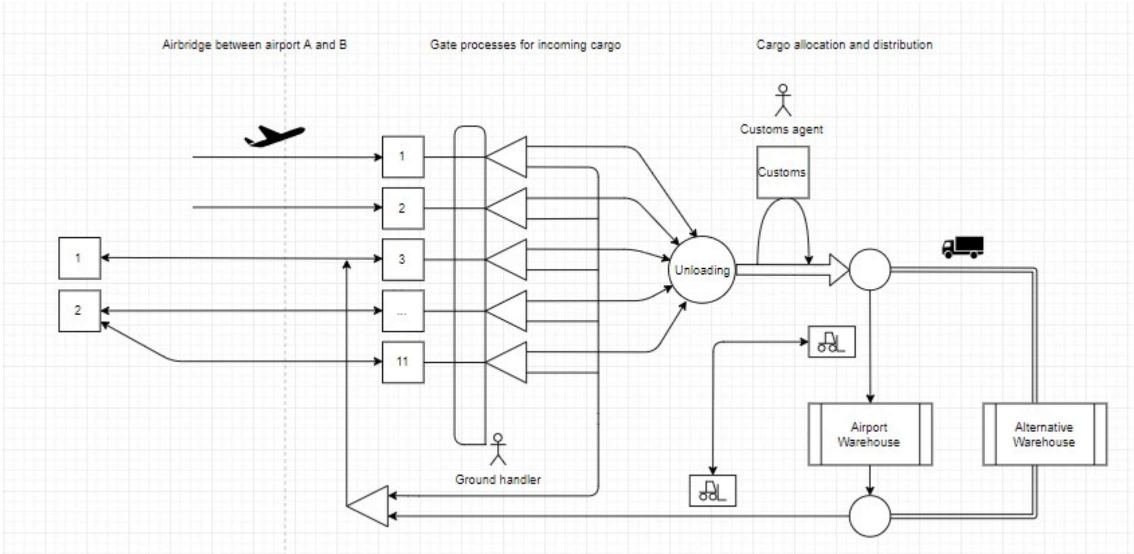

Figure 2: Sepinggan-Mutiara airbridge with satellite warehouse usage at Sepinggan airport

lead-times tend to be shorter for local provision, yet for inflated cost. This validates the approach of warehousing within the chain.

2.2.2 Knowledge gap logistics

In the literature on humanitarian logistics the difference between logistics supply chains is discussed, with humanitarian logistics suffering from a lack of chain optimization. Excess supplies should be minimized, by streamlining the throughput of the different processes in the humanitarian relief chain. The approaches in IM focus on this streamlining process, yet do not regard intermediate storing of supplies. The use of warehouses in IM is for creating cost effective operations and minimizing cost of transportation instead of making timely deliveries. The literature in humanitarian logistics does not regard the full spectrum of the focus of this study, leading to the following knowledge gap: *"The literature on inventory management in the humanitarian logistics does not take into account the intermediate storage of supplies for on-time delivery."*

2.3 Airport and transportation planning modelling

This section regards the modelling state of the art with regard to airports in disasters and transportation planning through network models. The combination of the two topics is rarely studied, while the role of the airport is of significant importance in the airport relief chain. In order to study this combination, the modelling of the separate topics are discussed first in this section.

2.3.1 Airport modelling

The airport modelling was usually approached from a cost and operations perspective, contrary to the shift in recent years towards airport resilience and airports as critical infrastructure. The modelling of airports is generally done in three levels of detail, as micro, meso and macro level. These levels indicate the precision of the processes and the lens through which airport operations are seen. The state of the art in airport modelling currently focuses on the microscopic level with many similar models, answering similar questions (Manataki & Zografos, 2009; Verbraeck & Valentin, 2002). (Manataki & Zografos, 2009; Verbraeck & Valentin, 2002) suggest in their work a change to the current state of the art with the use of higher level and more generic models. This approach is meant to lead to the re-use of previous models instead of constructing the same models over and over again.

The sharing and re-use of models within humanitarian literature seems very limited. An example of this is the lack of mesoscopic and macroscopic models in humanitarian aid literature. Caunhye, Xiaofeng, and Shaligram (2012) describe this as a fractured approach in the humanitarian field, which according to them is a problematic phenomenon. The connection on a higher level should as such be made to maintain a knowledge transfer in the field, instead of retaking previously ventured steps. Harding (1997) further stipulates the need for higher level models by claiming that grand challenges become too large and complex to work with microscopic or atomic models.

The introduction of bottlenecks and impact of bottlenecks on the humanitarian relief chain is often disregarded as part of a grand challenge, while the majority of airport modelling studies have a very narrow focus with respect to bottlenecks and queues (Verbraeck & Valentin, 2002). Even within marcoscopic models using system dynamics, the focus is on particular operations at the airport like with the research of Miller and Clarke (2007). The work of Veatch and Goentzel (2018) is a very strong example of this specific focus, while using discrete models. Their findings present both a bottleneck and opportunity in the arrival process, yet is scoped to only include the aircraft parking and unloading. Such a scope neglects the work of (Goldratt, 1990) on the shifting of bottlenecks completely, making it difficult relate to the airport as an overarching system.

The question remains how other parts of the system would be influenced by possible improvements in the identified bottleneck. This influence on the remainder of the system is especially interesting given the role of the airport as a hub in the network system. The relief chain is dependent on the ability of the airport to distribute the relief aid appropriately (Kovacs & Spens, 2007).

2.3.2 Transportation planning modelling

The transportation planning in networks can be modelled through graph theory (Dunn & Wilkinson, 2016) and multi-modal flow models (Balcik et al., 2008; Haghani & Oh, 1996). The latter studies consider a variety of demand rules and distinguish multiple item types and priorities. This could be bridged to airport models, if these airport models are built on a high level of aggregation. The high level aggregation is rarely studied in airport modelling, making the generic flows in network models often incompatible with the airport models.

The modelling of the flow in humanitarian networks not utilizing only graph theory is often done with linear programming, to optimize allocation in the end node. The optimization in last-mile humanitarian aid delivery includes examples of Barzinpour and Esmaeili (2014), Balcik et al. (2008) and Haghani and Oh (1996), which focus on various modalities and the capacity of these modalities to provide the connection from the hub to the disaster areas.

The last-mile allocation does not include constraints in the hub, with the focus on modalities. The constraints includes are on the means to transport goods from A to B. The role of the airport in the scheduling is as such disregarded, while it is regarded as a stock in the network. The means of transportation are rarely connected to detailed time-based delay, with at best a fixed time cost as punishment on the route for which delay is expected. The level of detail for these studies can be described as macro-level modelling, with little detail on the actual transportation flow between two nodes.

2.3.3 Knowledge gap modelling

The airport and network models in humanitarian aid present a disconnect in literature with the very specific and narrow scope of airport models on the one hand, and the disregard of airport importance in the scheduling of relief processes in a network on the other hand. The disconnect leaves a gap in literature on the mesoscopic level in which network models and detailed airport models are connected.

The impact of bottlenecks in the airport models should in this proposed connection be calculated through the entire network, with a far larger scope regarding relief flows. This would require more detailed delay-times than usually included in relief network models. The adjustment of the level of detail to include the network and the importance of the airport in the distribution of relief aid is the most predominant gap found in the relief modelling literature. The gap is formulated as: *"The academic literature has mismatching scopes between airports and relief chain models, without clear interdependence, leaving the system-wide impact of bottlenecks understudied."*

2.4 Knowledge gaps

The literature review highlighted three knowledge gaps in academic literature, in the fields of resilience, humanitarian logistics and modelling. These have to be connected to specify the contribution of this research to the literature. The knowledge gaps are reiterated below, before a connection between the three gaps is made. These are done in different order to specify the similarity in unexplored directions in literature, before connecting the three into a single research gap.

The resilience literature is lacking with respect to the impact the airport resilience has on the airport relief chain. This accounts resilience a little different with resilience being both the ability to recover and to handle increased demand after the disaster. This gap is mostly considering a disconnection in resilience literature between airports and relief chains. This is directly in line with the findings in the modelling section.

The modelling of humanitarian relief chains and airports are widely separated with the initial scope and level of detail in the models. The impact of bottlenecks throughout the humanitarian relief chain is hard to measure through this disconnect, given the often underappreciated role of the airport in relief network models. The distribution of relief aid from the airport is generally seen as stock to demand allocation with multiple connected nodes receiving relief aid, instead of the preparation on a high level of detail to represent constraints in such network system.

Lastly the humanitarian logistics literature is similar to the airport modelling literature, with respect to the narrow and similar scoping. Any additional capacity is only regarded when performing a bundling function or final distribution. Any additional capacity to cope with increased stress is unstudied, leaving intermediate storage as a possible solution for timely delivery as an unstudied direction within humanitarian logistics literature.

The contribution of this research aims at providing the connection between network model and airport model, while doing justice to the important function of the airport within the network. This means the model implements a connecting scope, to study the impact of resilience and bottlenecks at the airports within the system, on the totality of the defined system. In this system the intermediate storage of relief aid is considered to provide timely delivery instead of storage for cost effective operations.

3 Methodology

This section aims at providing an approach to filling the knowledge gap found in the previous section, by providing an exemplary case study on the prioritization of relief aid, while taking into account the systems perspective.

The research revolves around the question ***"How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief chain system, considering both the airport operations and network design?"***. This question aims at providing a better understanding for decision makers into the impact of various decision rules on the delivery of relief aid through and airbridge system.

This question is answered through a set of subquestions, as part of an incremental process for the development and the analysis of the system model. The subquestions are represented in the table below, and more extensively described in the following section. This section clarifies the subquestions before linking them together to describe the research design with regard to answering the main question. The section ends with a description of the case study, which is used to provide exemplary work for the approach in a real world application situation.

1. How can the prioritization of relief aid and the airport system network design be conceptualized?
2. How can the performance of an airport relief system be evaluated?
3. How can the airport relief chain system be modelled in discrete event simulation?
4. What policies could decrease the impact of bottlenecks on the airport relief chain system?

3.1 Subquestions

The prioritization of relief aid could considerably improve the effectiveness of relief operations. The provision of the most urgent goods however, has to be studied as a logistics system, instead of a single component in the network. The design of this logistic system with airports as intermediary nodes needs to be conceptualized to provide insight into the occurrence of bottlenecks. The relief item prioritization of humanitarian organizations has not been studied within the context of such a logistic system, which as a result has to be done in the first subquestion.

1. How can the prioritization of relief aid and the airport system network design be conceptualized?

Once the airport system and the prioritization of relief aid are conceptualized, performance measures have to be introduced suitable for assessing the impact of bottlenecks on the system. These measurements aim at assessing both the timely provision of urgent relief items as well as the reduction of bottlenecks. This all relates to measuring influence on the system, or also known as performance measures. The questions regarding these measures is formulated as:

2. How can the performance of an airport relief system be evaluated?

After the output variables, or performance measures, and conceptualization are finished, the translation from conceptual model to simulation model has to be made. The simulation tool considered for the airport relief chain model is a discrete event simulation model which regard the queueing of the relief aid through the relief chain. The subquestion regarding the simulation tool and the translation choices from the conceptual model to a simlution model is described below in subquestion 3.

3. How can the airport relief chain system be modelled in discrete event simulation?

The system conceptualization, output variables and the simluation model are eventually all made for the policy testing, to provide a policy advice as the result of this research. The policies that are tested in this research have to be formulated and described and various combinations are explored, all combined in subquestion 4. These policies focus on the bottlenecks found in the queueing model of subquestion 3.

4. What policies could decrease the impact of bottlenecks on the airport relief chain system?

3.2 Case study selection

The subquestions progressively build a model for policy testing in an airport relief chain system. In order to provide a proof of concept, the research involves a case study with a specific airport relief chain system. For this question the use of a case study is very relevant. Especially as it is hard to test policy influence on bottlenecks in real life applications. A relevant case for which the impacts can be quantified can provide the necessary means to deliver new insights. In the humanitarian logistics surrounding the airports in distress small shifts in performance can have far reaching impact on the disaster relieve at hand.

The airport relief chain system for this case study was selected on three criteria. The criteria it had to fulfil are, (1) the disaster had to be recent, (2) the application of an airbridge relief system in practice and (3) the modes of transport had to be limited in number and diversity.

The first criterion was selected to ensure the availability of experts and their expert knowledge as well as to provide for an interesting case which people have recently heard of. Aside from these two reasons, it is also more likely that policy effectiveness can be accepted. The tangibility on a known case makes it more relevant to practitioners. The field of disaster management has taken many leaps in recent years and the state of the disaster management regarding a specific case can be of importance to the willingness of responsible agencies to take the research into account as well.

The second criterion regarding the application of an airport relief chain was selected to provide possibilities for historic validation and cross validation of the airport relief chain model. It furthermore provides an ideal case if just one regional and one local airport were used in the airport relief chain, as the in case existing one-on-one relationship inherently narrows the scope in comparison to a multi airport disaster relief network with multiple local hub airports. This approach can generally be seen in disasters in archipelagos or mountainous regions, with few airports serving large regions and local airports being the only connection for smaller communities. Countries such as Indonesia, Malaysia and Nepal fit the bill really well as such countries tend to have limited air traffic infrastructure, which is dependent on nearby large hub airports and small regional airports for last-mile distribution.

The third criterion was closely in line with the previously explained criterion, as this regards the narrowing of the scope of the case. The airport relief chain system has to be bounded in terms of possible modes of transportation supplying relief goods, to keep the case manageable within the time horizon of this research. Island systems are most suitable, especially when the harbours can not be used. In case the harbours are inaccessible for the majority of the disaster struck region, the only possible means of transportation of relief aid would be air transportation. As such all other modalities for the main flow of resources could be disregarded in the conceptualization of the model.

3.3 Case study

The case found to check all the boxes was the earthquake in Sulawesi, Indonesia. The island of Sulawesi and it's capital Palu were struck by a tsunami, which offset all disaster response by boat to the Palu harbour for the first weeks (OCHA, 2019). It is part of the island system of Indonesia and the airports on Sulawesi tend to be small and serve specific areas of the island. The relief aid was set up from the nearby island of Kalimantan from where an airbridge was set up to the airport nearest to Palu, named Mutiara.

On the 28th of September 2018, an earthquake with a magnitude of 7.6 on Richter's scale occurred near the coast of Palu, the capital of Sulawesi. This earthquake caused a tsunami to sweep over the area of Palu, ravaging the infrastructure. According to Hadi (2018), over 190.000 people were in need for humanitarian aid, the majority located in the region of Central Sulawesi. On the first of October the first request for international aid was issued by the Indonesian government. The disaster response organization was logged on reliefweb, a project of the United Nations for the coordination of humanitarian affairs, also known as OCHA. The response was organized by means of an airbridge, as the Mutiara airport was too small to function as a hub for humanitarian relief (Weeks, 2019).

As such the response was organized from the Sepinggan airport in Balikpapan, which is across the other side of the Street of Makassar from Palu. The large NGO's as well as the representatives of country teams set up shop on Sepinggan airport and had to communicate in meetings in which slot their resources could be shipped for the next day. The shipments were than sent by plane to Mutiara from where the goods were unloaded and distributed over the network. The organization of storage and forwarding was done by allocating a lean chain being controlled by the capacity of Mutiara. As such the resources and manpower were shipped to Sepinggan if possible only a day before, stored in the designated warehouse to be shipped the next day. This will be generalized in the case study for simplicity purposes to have the transport prepared for the next day or scenario wise in shorter time frames.

In this case study the resilience of both airports is crucial for the performance of the system as a whole, with the additional performance of the airbridge being a decisive factor for the throughput time and total delivery. The case study is therefore split into three segments, the separate airports as segments 1 and 2, and segment 3 being the airbridge. The resilience of the airports without the connection should follow the resilience framework set up by Feil (2018), further broadened by the addition of capacity within the network. Once these airports have a base case and a policy option for resilient performance, the connection can be made. This connection can than be tested for both the base case and policy settings.

4 Conceptualization of relief aid prioritization and the airport relief chain system

In order to study the performance of relief aid transportation over airbridge systems in disaster situations, this chapter outlines the design of the model and the choices made for representing the real world system in a bounded reality. These choices include the implementation of prioritization rules, the selection of destinations and the quantity of the relief aid. The section starts with a description of the processes and the process logic, followed by an overview of the relations between objects in the system. This object overview will closely represent the model implementation which has to be able to incorporate the processes. Lastly the prioritization of both relief items and destinations within the scope of this study is described. These individual subsections are then used to answer the question "How can the prioritization of relief aid and the airport system network design be conceptualized?".

4.1 Process diagram

An important step in the specification of a system is the mapping of the business processes according to Hengst-Bruggeling et al. (2019). This process description regards on an aggregate level the processes needed to move the relief items through the airport relief chain as described in the introduction. These processes consist of various sub-processes, making the aggregate processes models on their own. This hierarchical representation from high level aggregation to low level process description is done using the IDEF0 technique. This format is very strict and specifically useful for multi-level presentation in a process diagram NIST (1993).

4.1.1 IDEF0 technique

The IDEF0 technique, also known as Structured Analysis and Design Technique (SADT) is used to break down the business functions into functions of a smaller granularity, until these functions closely align with operational processes, or activities as described in the technique (Weske, 2012). The IDEF0 technique defines activities as one of five primary elements facilitating this approach. The other four primary elements are the input, output, mechanism (and call) and control.

Once the functions are translated to operational processes, the technique forces a modeller to structurally think about the influence of the process on the system, as it translates input to output. This transition has to be controlled and always utilizes a mechanism. Furthermore, output is always needed, as an activity always has to deliver a change. Without the output no change would have occurred and the activity in itself would have been useless from the standpoint of a modeller. The activities are presented in the technique by a square box, with the other primary elements being arrows connecting to the box. The input arrives on the left hand side, the output leaves on the right hand side, the control comes in from the top and lastly mechanism enters the box from the bottom. One activity can have one or more of each element, with the addition that no input or call has to be present. The representation of an activity with these arrows is presented in figure 2.
The hierarchical structure is done through a level design with a decomposition inheriting part of the name from the parent activity. The highest level of aggregation is called level A-0, with only one activity A0, making it the final aggregation and making it the only level not following the name inheriting rule. This is then divided into sub activities, named A1, A2, etc. on the A-1 level. The

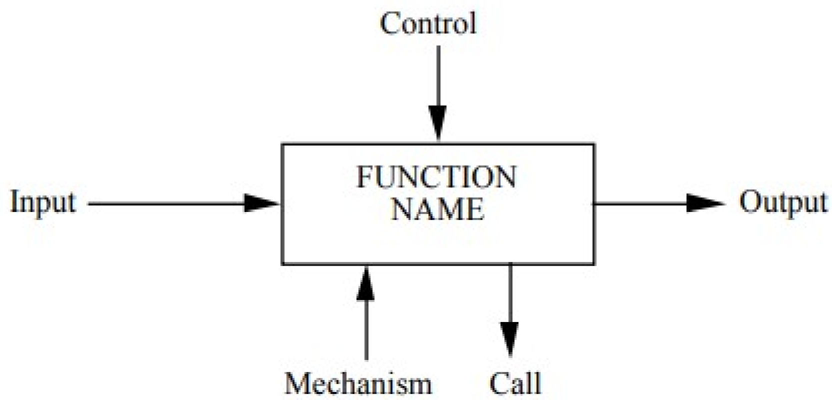

Figure 3: Representation of an activity with all primary elements as from NIST (1993)

decomposition of these processes adds a numeric after the parent activity. An example would be the decomposition of activity A1, into three sub activities which would be named, A11, A12 and A13.

4.1.2 Process model

The function of the system is defined as to move relief aid from point A to point B through a chain of airports in the least amount of time, considering the demand for the different types of relief items. The activities found of importance for the airport relief chain were the arrival of relief aid, the processing of relief aid to the regional airport, the processing of relief aid at the local airport and the transportation and storage between the regional and local airport. These four were translated to activities for the level-1 description of figure 3

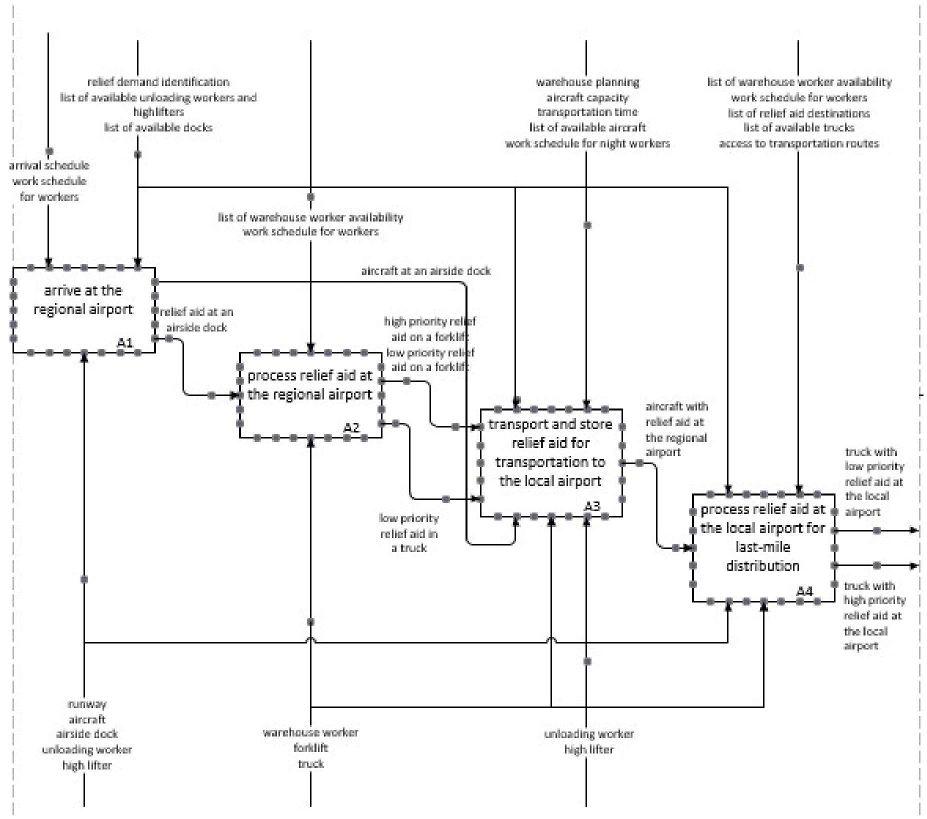

Figure 4: IDEF-1 presentation of the airport relief chain

Arrive at the regional airport

The airport relief chain system acts as a linearly progressing chain with feedback from the warehouses and the humanitarian sites in the disaster region. The feedback system, from the humanitarian sites, has to directly affect the arrival of relief aid into the chain. This is to counteract when overshoot of a specific relief type is imminent. As such the fulfilled relief is taken into account when shipments are sent to the regional airport. The process of these arrivals can be seen in figure 4, which is a simplified representation of the decomposition of the arrive at the regional airport activity from figure 3. This arrival procedure consists of the actual landing on the runway, routing to the airside docks and unloading of the aircraft. The arrival as such encompasses all activities outside the airport's interior, before the cargo is unpacked and prepared for further transportation. The main focus is on the cargo, which can be seen as the main unit within the stream through the simplified representation.

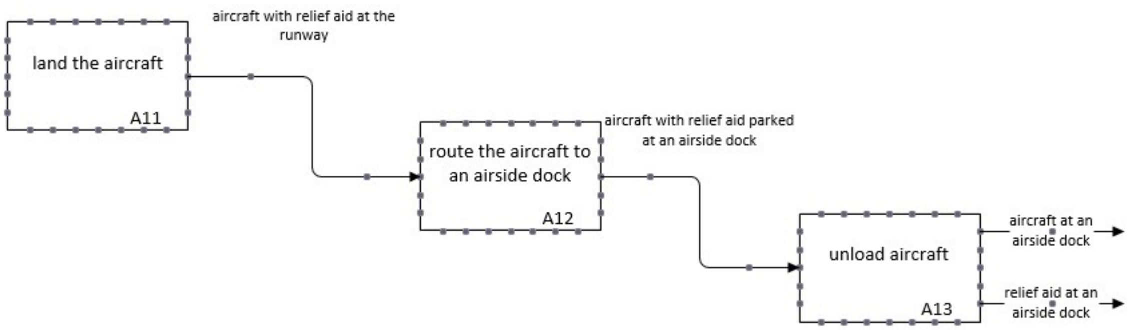

Figure 5: Simplified representation of the arrival at the regional airport activity

Process relief aid at the regional airport

The relief aid at the regional airport after unloading has to be processed either to be placed in storage or to be send to the airbridge. The cargo processing consists of division into relief types, out of the unloaded cargo, and the prioritization at the airport for further processing. Lastly when all relief items are prepared for further routing, the transportation to the storage facilities commences. The flow of cargo through these three activities can be seen in figure 5.

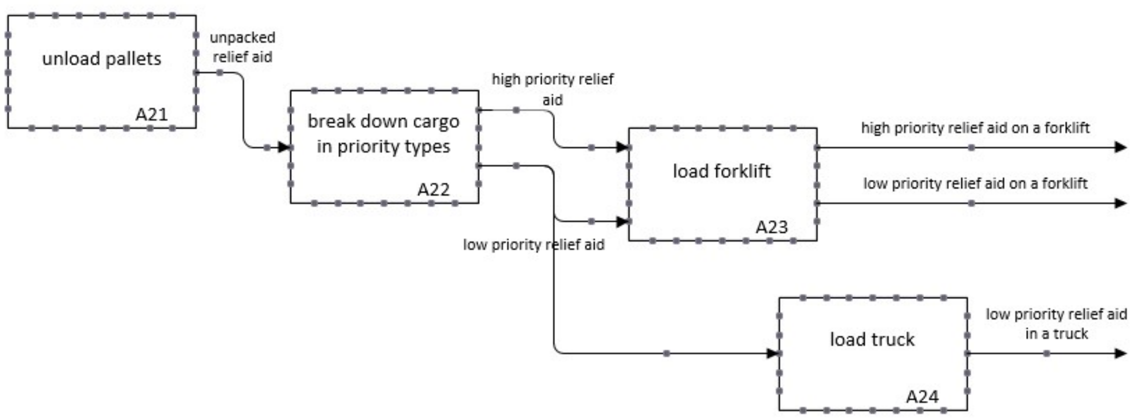

Figure 6: Simplified representation of the regional airport processes

The selection of relief items and proper relocation to storage locations is one of the expected bottlenecks in the system, with mostly the break down activity constraining the system. According to the director of humanitarian affairs at DHL (appendix F) the assignment of relief items to storage locations is problematic in most disasters, even when a limited flow of relief aid is transported through the regional airport. In appendix H the cargo breakdown process is the longest among the normal processes. It is therefore expected to determine the system performance of the regional airport.

transport and store relief aid for transportation to the local airport

The processes at the regional airport provide an inflow through forklifts and trucks into storage space where the relief items are to be stored for transportation from the airbridge. The activities in which the cargo is stored and forwarded to the airbridge are displayed in figure 6, as the activities store, transport, prioritize and load. The cargo is seemingly put together after it leaves storage, yet the physical bundling would at the earliest convene at the load activity. This is however unlikely as dock selection is determined by priority, likewise to the selection of storage.

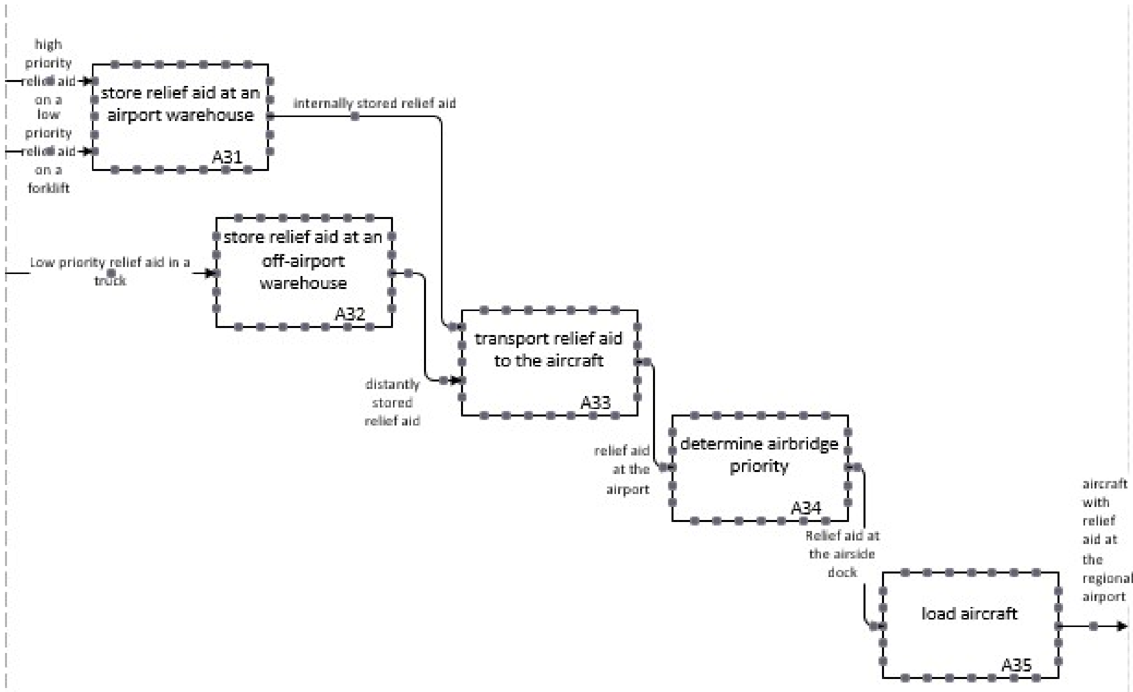

Figure 7: Simplified representation of the storage of relief aid and transportation to the local airport

This part of the activities is of most interest when considering possible network related options for policy implementation, as it is ideal for capacity improvement and priority setting by means of physical structures. The modes of transport with separate inflows in the activities already facilitates this option with the outlook on the policy section in section 6, in which both operational and strategic policies are considered.

process relief aid at the local airport for last-mile distribution

This activity is separated into subactivities mostly present at the regional airport already, yet with different connections. The local airport combines arrival activities with airport processing activities, before adding the outflow to the relief chain system, which can be seen in figure 7. This alternative coupling is chosen as the arrival procedure is together with the prioritization principles mostly directed at the regional airport. The influx of relief aid is meant to be designed towards the ability of the local airport to handle the relief aid.

The only decision rules present in the relief chain system at the local airport are the allocation rules for the disaster sites to which the relief aid has to be transported. This final routing of the relief aid is not primarily in the focus of this research, but added in to provide for more diverse application of the proposed model in future work.

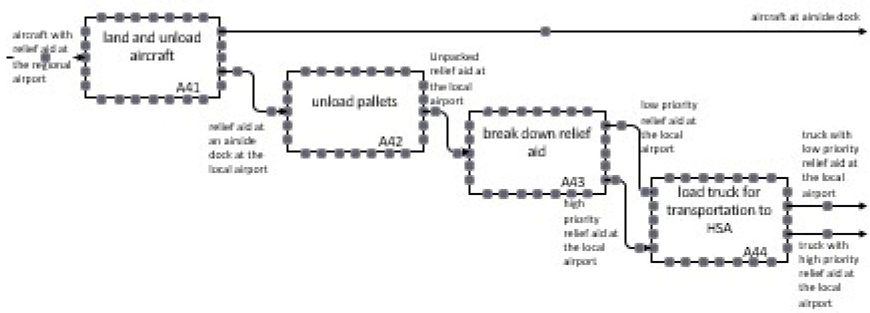

Figure 8: Simplified representation of the processing of relief aid at the local airport

4.2 Network diagram

In this subsection an initial conceptual model is identified with all included components of the airport relief chain in the conceptual models. It is named network diagram, even though it represents more of a chain diagram. The variability in routes is limited in comparison to a network, yet the name network diagram is used as the system with the satellite warehouses included, resembles a network structure. In this subsection boundaries of the system are chosen first by the physical system boundaries shown in the actual network diagram and secondly by the simplifications in the system components, represented in the class diagram. The latter is a representation of the relief chain as a network diagram as well, but provides a more in depth overview of the relations between system components, with inclusion of the mechanism element from the process diagram.

The boundaries are structured following the general cargo chain of the process diagram in section 4.1, yet expanding the conceptualization to the actual physical components in the system. As such the network model in figure 5 has the arrival of the aircraft at the gate and the airbridge connection from gate to gate centered between the regional and local airport. The regional airport is connected at the top to the possible storage units, while the local airport at the bottom represents a hub function for further distribution.

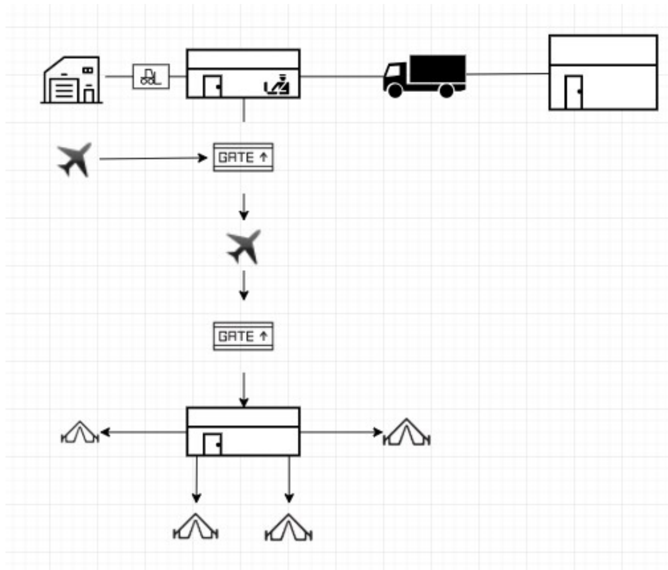

Figure 9: Network Model

The interrelations within the the system can be seen in figure 8, which is a class diagram following the Unified Modelling Language, better known as UML. This modelling language for class diagrams is meant for the design and implementation of complex systems (Hengst-Bruggeling et al., 2019; Lucidchart, 2018).The system in figure 9 shows overarching relations of components in both airports. Both subsystems have a similar process within the airport, while utilizing the same resources. This is the reason the coupling of the resources in the UML are made the same with the distinction in airport falling on the mode of transportation.

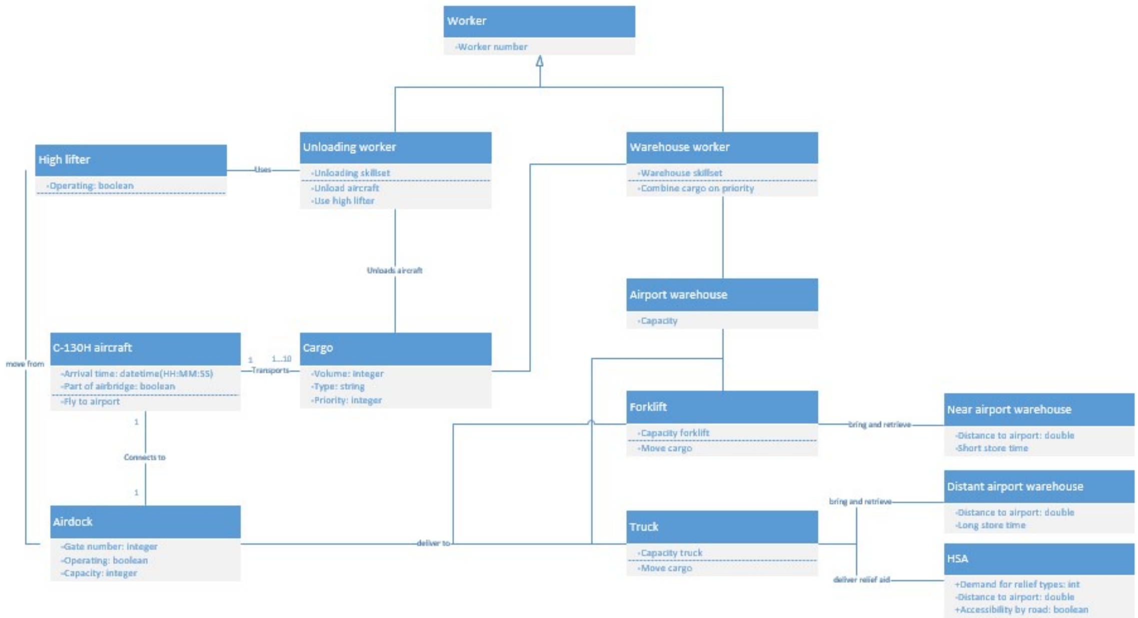

Figure 10: UML model for the airport relief chain

Airside docks

The airside docks or gates are the connection point for the terminal and the plane. The initial handling of the plane and unloading processes of the cargo take place here. Regarding the airside docks, two major processes were defined, being the selection of the docks for the aircraft and the unloading of the aircraft by cargo handlers. The selection of docks is dependent on the availability at the airport, as well as the state of the runway. The unloading of the aircraft is influenced by the availability and capacity of personnel, as well as the availability of support equipment like high loaders.

Regional airport

The regional terminal is seen as the place where all initial distribution processes happen. As such after unloading, the cargo is split, prioritized, recombined on priority and sent to a storage facility. The splitting of cargo and recombination of cargo based on priority helps with in time delivery of necessary resources. As stated by the director of humanitarian affairs of DHL the processing of relief items can be improved when dealt with a uniform flow of relief aid. The allocation of the cargo packages to storage facilities is then based on the priority of the package at the local airport.

The priority of multiple goods can make them suited together as packages, as non-governmental organizations prefer at times combinations for their on-site project. For example, shelter and sanitation are combined to provide all required initial aid to a family. This is meant to prevent unbalanced and insufficient delivery to disaster sites (Nirody & Lacy-Hall, 2018).

The regional terminal is in the UML as physical component represented by the regional airport cargo hall. This area is connected to the warehouse workers whom are part of the process relief aid at the regional airport activity from section 5.1. The output from this activity is in connection with the other relations of the regional airport cargo hall, namely the forklift and truck components.

Warehouse

The warehouses have the function to store either the packages or cargo pieces until they are required. This is planned in advance to maintain in time delivery. As such the warehouse receives an order, before the cargo is prepared for transport. The preparation for transport means it is to be delivered by truck or forklift back to the runway from where the aircraft is rerouted to the local airport from the regional airport.

Local airport

The local terminal receives the prioritized cargo packages after the order was sent, after which similar processes take place as in the regional terminal. Namely, unloading and unpacking. In the local terminal the cargo is also prepared for transport to the regions in need of the resources. The difference with the regional terminal is that unpacking is not always necessary, and that the cargo can be directly transported to the end station. The humanitarian sites distributing the relief aid are processed as soon as possible, making intermediate storage unnecessary, with the only exception being the damaged infrastructure. It is assumed that when the roads are damaged the airport storage locations are as well, leaving out the storage component in this part of the system.

4.3 Prioritization of relief aid

The prioritization of relief aid is often done in the early stages of humanitarian aid, as part of the enquiry of the damage in the region. It is disaster dependent, which relief items have the highest priority. Such priority assessments can be based on the cluster approach. This cluster approach provides a method for coordination and responsibility for specific requirements in the process of providing humanitarian aid (*What is the cluster approach*, n.d.).

It is difficult to research all cluster, for which quantification would be needed. In order to reduce the diversity, a focus is put on the most stressing relief types. The method used for filtering these clusters to a workable number is the selection by priority value in the case study, and the influence on individuals as direct aid. This approach is presented in appendix E.

The selected clusters are: Shelter, food, health and water, sanitation and hygiene. These come directly from the response plan of (Nirody & Lacy-Hall, 2018). The size of the relief aid demand is based on the values presented in the three month response plan for validity purposes. In similar disasters, these cluster would reasonably pertain a major share of the relief aid, with experts in appendix F pointing towards these clusters as well. The addition of the group other in the model is done to preserve some level of detail on the other groups as well as to provide a means to test for material convergence at the hub airport in future studies, but does not have any significance in the scope of this research. As such the other group is left out of the conceptualization.

The relief aid flow on which the case study focused only contains the international relief aid, since domestic relief aid is only scarcely documented. Aside from creating more complexity, the addition of domestic relief aid is undesirable, since it would create unmatched flows with the relief types not fully overlapping.

4.4 Key performance indicators

The previous subsections positioned the boundaries on the level of detail this research aims to provide, with a description of the processes and an overview of the relations between resources and components. These sections provide the building blocks for the airport operations and network design in which the bottlenecks are analyzed. In order to answer the question "How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief chain system, considering both the airport operations and network design?" the only part still missing in the airport relief chain system is the measurements to report the decrease in impact from the analyzed bottlenecks. This section revolves around the key performance indicators (KPI's) for which the system is evaluated.

The system distinguishes two kinds of KPI's, which are evaluated separately. The first set of KPI's is named timely delivery, the second set can be grouped under the name resilience. The first set focuses on the delivery within the assigned period of time, which is a 20 day period. The total performance is on the other hand an indication of the existence of bottlenecks, yet provides little insight into the problems at hand. The second group of measurements distinguishes both location and size of bottlenecks, providing understanding and context to the system performance.

4.4.1 Timely delivery

The first set is specifically tailored towards total system performance, and purposeful delivery of relief aid. The timely delivery is separated into two measurements, the first being the sum of all relief aid processed within the time boundaries in the airport relief chain system in tons. The second is in close relation to the clusters as addressed in section 4.3 which assigned different priorities following the responseplan of Nirody and Lacy-Hall (2018). The second measurement of total delivery is the percentage of priority demand delivered to the demand locations.

Policies providing an improvement in priority item allocation to demand regions could be preferred over policy improving the total size of delivery. This trade-off might occur within the timely delivery performance measures, which are policy wise addressed in the results section. Especially item priority and destination priority policies are subject to these trade-offs, given the fact that differences in the flow size and flow routing could prefer one measure over the other. These trade-offs were observed as well in the work of Gralla and Goentzel (2018).

Measuring total system performance compared to various measurements is a frequently used design for relief aid or aid delivery, independent of the trade-off measurements nature.Examples of models measuring total performance as part of their trade-off design are Jun, Jacobsen, and Swisher (1999) and Gormez, Koksalan, and Salman (2011), which focus on different systems in which throughput or demand satisfaction reflect part of the trade-offs in their respective systems. The decision for representation of priority delivery by percentage is to provide an accessible measurement for comparison for the specific policies tailored towards specific improvement in priority aid delivery.

4.4.2 Resilience

The resilience measures are directly based on the work of Feil (2018), whom introduced an new resilience framework tailored towards the handling of the influx of relief aid. The total system performance of timely delivery is decided by the resilience of the subsystems in the airport relief chain, with the resilience measures both identify and provide a small scale review of the bottlenecks in the chain. An improvement in resilience in one of the system components with a defined bottleneck would relieve not only the bottleneck, but provide additional buffer capacity as well.

The measures provide a methodological approach to reviewing the time in which a bottleneck occurs and whether the theory of constraints has to be accounted for. This can be seen in connected components when a bottleneck is resolved, resulting in spillover effects into the downstream components. The simplicity for reviewing the bottlenecks through these measures come from the approach in the framework to measure over time.

The framework identifies periods at which behaviour can be classified to fulfill specific needs of the system. The most important periods for the study into system bottlenecks are the time of disaster, and the time of final absorption. These two periods provide the influx and the moment at which the system can overcome the strain of the influx, slowly depleting the bottleneck over time. Lastly the framework utilized averages for the measures over the time window for disaster response. These are inter-comparable to the same measures for different system settings, providing an independent measure for system performance other than the total delivery.

The measures of resilience are the processed cargo in tons/hour, idle cargo in tons and the throughput time in hours. These three have close relations to one another, yet utilizing average as a measure, the correlation can diversify the results as the components face different levels of relief aid in the system. The system components are individually evaluated (arrival, regional airport, warehouse and local airport) to observe differences in behaviour with regard to the resilience of each individual subsystem and change in the correlation between the measures.

5 Model design and description

The conceptual models have to be actualized in a simulation environment, in order to advance to policy testing for the reduction of bottlenecks. The modelling approach taken as well as the tool will be described first with the reasons why these choices are suited for the modelling of the airport relief chain. This section ends with a brief description of the modelling decisions made, while translating the conceptual models into a discrete event model.

5.1 Discrete event modelling

Discrete event modelling uses a state space as a function of a discrete set, in which the states are only permitted to change at discrete points in time. The usefulness of change only being permitted at discrete points is the simplicity it provides to the modeller on both visualization of the system and the implementation of logic (Cassandros & Lafortune, 2008).

Discrete event modelling is often used for the modelling of the warehouse systems, in which the object of interest is subject to change over the course of time. A warehouse capacity system for example is empty on initialization, then is filled on arrival of products, before the products are moved again from storage. The mathematical representation of this function is shown in figure 10. The changes in the system can be called the State Transition System Specification *Simulation Masterclass* (2019).

$$x(t^+) = \begin{cases} x(t)+1 & \text{if } (u_1(t)=1,\, u_2(t)=0) \\ x(t)-1 & \text{if } (u_1(t)=0,\, u_2(t)=1, x(t)>0) \\ x(t) & \text{otherwise} \end{cases}$$

Figure 11: Mathematical representation of the relief items in a warehouse, source: Cassandros and Lafortune (2008)

The interesting features of discrete event modelling for the modelling of an airbridge system come from resemblance with the previously described warehouse system. It is particularly easy to analyse capacity and queuing in the system. The warehouse from the above example can be described according to the IDEF0 technique which closely resembles discrete event modelling. This process description as such can easily be translated from concept to model. The activities in section 4.1 transform the input into output. The input can be seen as the cargo flowing into the warehouse, changing, even if only in time, before being transported outside the warehouse. This is controlled by the control element, and utilizes the mechanism element to perform the transformation. When the transformation takes more time to occur for the input than the input arrives, the system becomes crowded and queues starts to form. This can occur at any activity for which the activity is larger than the inter arrival time, compensated for the number of parallel activities. This is described in figure 11, without compensation for the parallel processing of activities.
The analysis of queues and capacity is required to evaluate policy on the bottlenecks occurring in the airbridge system, which is done to answer the first part of the main question, namely the decrease of impact of the bottlenecks. The bottlenecks are a function of the input and output over time with the input significantly outmatching the output. The change of x(t) is significantly positive, without interference, approaching unsolvable proportions.

$$\lim_{t \to \infty} x(t) = \infty$$

Figure 12: Mathematical function of a bottleneck without distinction in capacity

The last positive feature of discrete event modelling making it ideal for the study of complex airport relief chain systems is the ability to perform what-if scenarios within the model settings, allowing the modeller to implement uncertainty into the model (Jun et al., 1999). The uncertainty will be part of the experiment design in section 7.3.

5.2 Modelling environment

The use of discrete event simulation is effective at the analysis of capacity and queuing in systems, in this instance an airport relief chain system. The airport relief chain system however has to be constructed in a modelling environment suitable to represent both airports as well as the airbridge connection between the airports. The modelling tool selected for the application of discrete event simulation is called Simio, the successor of Arena and among market leaders in the simulation field. Simio is based on processes, that are comprised of individual process steps (*Simulation Masterclass*, 2019). The tool supports events, objects and processes, seamlessly connected to one another. The objects can all be exactly explained as activities, for which in the process view the process logic can be integrated.

The Simio models consist of servers for the activities, sources for the input into the airport relief model and sinks as output from the system *Simulation Masterclass* (2019). These three components process the cargo which is an entity in the system. The entities are the flow unit through the processes. An overview is given in figure 12 of a simple source, server and sink model with one entity. The process logic initiation can be seen in figure 13, in which a simple decide assign process is displayed.

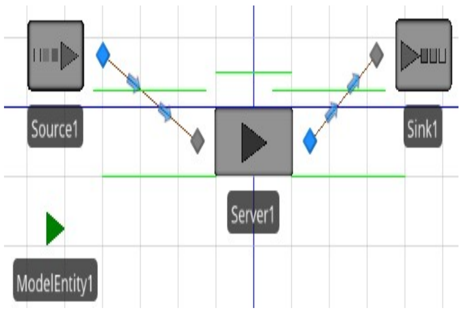

Figure 13: Simio source, server and sink model with a model entity

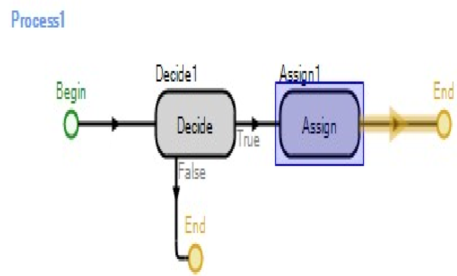

Figure 14: Simio process outlook example

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6 Policies

A set of policies is introduced to improve both KPI's (namely, resilience of the airport relief chain, and timely delivery) by changing components and parameters in the system. These changes are made both on the prioritization rules, and the network design. This is an interplay between the operational and strategic level at the airport. The policies are separated into the two levels, into the strategic decision making level on the availability of physical resources, and the operational decision making regarding the prioritization of relief items and personnel.

The strategic policies are based on the policies of Feil (2018) whom focused on high level decision making for mesoscopic airport models in disaster situations. These are combined with the policies of Gralla and Goentzel (2018) which are based on the experience of logistics officers from the field, which are both on an operational and strategic level. The combination of these policies should provide a more coherent approach in disaster situations taking into account both decision makers from the government and the practitioners in the field.

6.1 Strategic policy levers

The strategic policies relate to the policy makers ability to change the system, regarding for example system design. The strategic policies regard high level changes with longer-term effects, such as the placement of new facilities. These changes take time before they can come into effect, which means a time cost is involved.

Operating off-airport storage
The warehouse capacity at the airport tends to be very limited and relief items get stuck a critical system components at the airport hindering the performance of the airport relief chain. In order to reduce the strain of relief items on these system components, temporary warehouse space away from the airport could be considered. The use of temporary warehouses at the local airport is fairly common as the facilities are often damaged, however common storage space at the regional airport is usually only limited to present warehouses, which are at the time in use. This policy in essence re-utilizes a state-of-the-art policy method to provide intermediary relief of the system. The system is inherently changed to a more network like structure with a feedback loop from the regional airport into the warehouses, back into the airport for further transportation.

The structural changes create an alternative routing with a modelled fixed delay to provide insight into the effects of the alternative routing and possible strain reduction of personnel. This approach is modelled by providing three off-airport storage locations. In the simplistic process diagram of figure 14, it is visible how the delay occurs for the modelling of the alternative warehouse system and the difference in resources used for the transportation of the relief aid. The process of warehouse storing at the off-airport storage is a timed delay compared to internal storage and transportation times way in too. This is a trade-off both between speed and capacity, because the internal storage has limited capacity, and cannot process more than 100 items per hour.

The priority rules for the selection of the internal warehouse over the off-airport warehouse and for different off-airport warehouses is arranged according to two separately analyzed policies with regard to the destination prioritization of the off-airport storages. The first is the priority for nearby

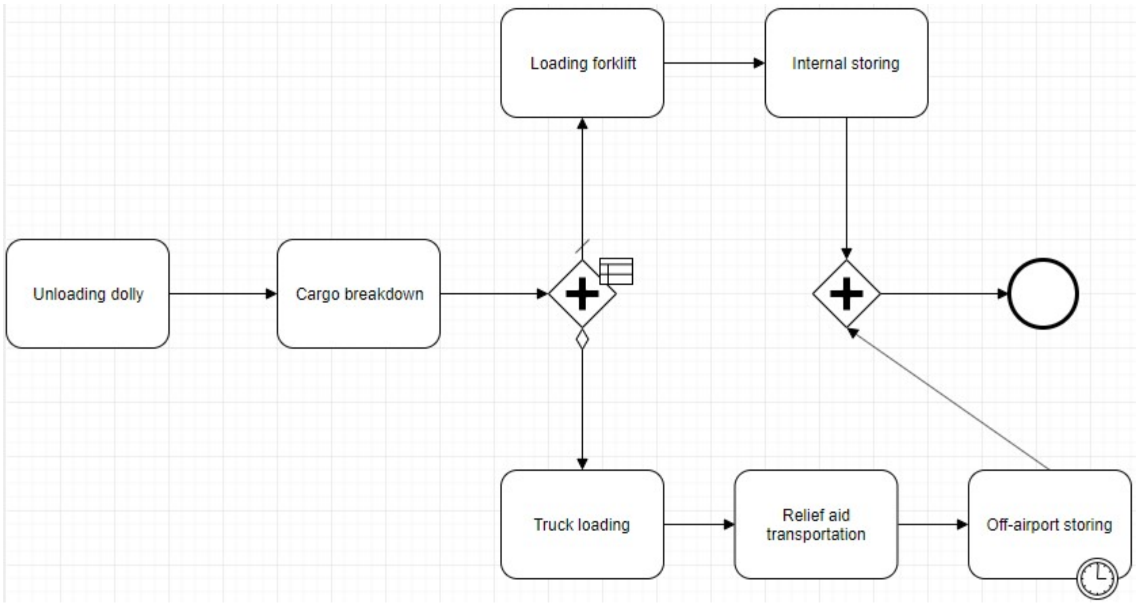

Figure 15: Process chain for relief aid storage at the regional airport

allocation, with the majority of the resources still send through the internal storage, only when capacity runs out the off-airport storage is utilized. This policy is known as **dP-1**

The second priority setting revolves around pro-active allocation of relief aid at the off-airport storage decreasing the speed of the stream into the airbridge, creating stock. In this policy 70 percent of the relief aid is send to the off-airport storage, a value taken from the work of (Gralla & Goentzel, 2018). This policy is called **dP-2**.

For both policies the relief aid allocation is done by trucks when sending to the off-airport storages, compared to the internal process of using forklifts. The difference is here aside from the distant the capacity of the vehicle, with the truck being assigned two times the capacity of a forklift, however at the cost of just over three times the loading cost. This loading inherently takes away more space from the warehouse personnel possible conflicting with the freeing of personnel. This is the case if time cost for truck loading outweighs the benefit of a larger outflow of relief items.

Location	Resources	Time cost (number of resources)
Internal warehouse	Forklift, 2 workers	3 minutes (2 items)
Off-airport warehouse	Truck, 2 workers	10 minutes (4 items)

Table 1: Off-airport storage versus internal storage

Additional gates for international aid

The number of gates is important for the arrival process into the airport relief chain system, as well as the airbridge connection between the airports. These two parts of the airport relief chain service the incoming aircraft and outflow of relief aid, both probably constraining the system as a bottleneck. In the work of Gralla and Goentzel (2018) the arrival of aircraft is identified as such a bottleneck with the potential to improve the system significantly. To do so the aircraft have to be scheduled greedily, to maximize the utilization of the arrival processes.

The gates have to service both the arrival of aircraft and the airbridge connection, for which both gates and resources are shared. The distinction between the arrival and the departure gates is not made in the model, but instead assumed as a process constrained by the availability of the workers at the gates, with creative parking assumed. The implications of these assumptions are that whenever the worker capacity is increased, a larger number of gates becomes the optimal number. This will always hold, until alternative bottlenecks constrain the system, which would eventually be the airbridge itself, constrained by the number of gates available to the local airport.

The arrival of aircraft and the airbridge connection can only be improved in relation to the number of workers. The unloading of aircraft is done by eight workers which does not change however large the pool of unloading workers is. As such the total number of unloading workers has to match the gates made available for international relief aid. The availability of these gates can increase and relieve stress on the airport by determining the inflow of relief items. This only concerns the arrival gates, yet the departure gates receive more dedicated personnel when the number of arrival gates decreases. At the original state of the system, these do not fully match, with only 24 initial unloading workers. This leaves room for improvement by coupling the additional resources to differing numbers of gates.

The total number of gates at the Sepinggan airport for the case study was eleven gates, yet there was reason to believe around half of the incoming relief aid would be domestic. This lead to the assumption that between 4 and 6 gates would be available for the airport relief chain considering international relief aid. In this policy the system is studied with 4 and 5 gates on the influence of a reduction in gates at the arrival site.

6.2 Operational policy levers

The operational policy levers are based on the ability of a logistic operator to change the behaviour in the system. The prioritization of relief items can be influenced by the operator, by addressing specific types of items first, or allocating relief items differently. Aside from item prioritization, the deployment of specific personnel is an operational policy lever as well.

Prioritizing the most stressing relief type first
The cluster design as described in section 4.3, is used by governments and policy makers to identify the needs of the population in disaster struck areas. The prioritization of the most needed relief type is one of the policies most commonly used by logistics officers as was found by Gralla and Goentzel (2018). This approach ensures timely delivery of the most needed items, yet disregards to some extent the total delivery of relief aid. As such the policy regarding this prioritization takes into account a more uniform influx of relief items, as well as the prioritization of airport storage capacity for these items. This policy is named iP-1 as well for further reference.

The policy assumes a prioritization rule setting before the arrival of relief aid in the airport relief chain, which is operational policy, yet has to be implemented on a very high level of aggregation, which would best be done by governments as was suggested by an expert in appendix F. The arrival could for the policy be disregarded, yet would have less polarized impact, meaning the influence is more case dependent.

After the arrival processes are changed through this policy, further action has to be taken with respect to the storage of priority relief items. The internal storage is in all cases reserved for priority items, yet with this policy, the only items that should go to internal storage should be the priority items if possible. Especially when considering the strategic policies this could improve the flow of priority items through the airport relief chain. At the airport these policies have to be implemented by operators on site.

The last change in the system is at the loading of the aircraft again with the relief items. The volume of priority items present at the airbridge is made as high as possible, providing a constant inflow if possible. This would mean at the airbridge these items should receive priority treatment as well, with a separate gate for priority items at the airbridge. This means the flow is fully separated for testing from the relief items with lower priority values. This might cause additional waiting time at the dedicated gate over the priority assignment of the items to the other two available gates.

Prioritizing the relief type with the smallest demand
The logistics officers turned out to apply a fast delivery policy at times, in which nearest destinations and smallest quantities are done first. In the model this policy translates to prioritizing the relief items with the smallest quantity, to assure more uniform delivery. This uniformity becomes increasingly more desired within the field of humanitarian aid, with the ASEAN countries demanding uniform aircraft types for handling as well as more standardized cargo, which was discussed in appendix F. This policy is also called iP-2.

The arrival of aircraft is similarly altered to the case with prioritization of the most stressing relief items to favour the relief type the policy is effectively maximizing the arrival and throughput of. Likewise, this policy will have to be implemented on two levels. The first on a high level like the government controlling the relief items flow to the airport, and second, the operational differentiation between relief items for the regional airport and airbridge processes.

The clear distinction in the on site prioritization of relief items between the prioritization of the most stressing relief items and the smallest demand items, is that in the latter, all relief items are routed as before, except for the relief items with the same or more urgency than the smallest demand items. Those are processed in this policy the same way the highest priority items are being processed in the regional airport. For the airbridge system, the influx is only shifted to a different gate, yet is operated the same.

Additional workers
The unloading processes are among the most constrained processes in the logistics process of relief aid through airports. A more aggressive arrival approach is suggested by (Veatch & Goentzel, 2018) as the unloading was not only seen as a constraint, but at times also underutilized. To assess this notion, the number of unloading workers is set to the minimal number to operate all arrival gates simultaneously. This comes down to 48 workers in total, meaning the policy provides a total of 24 unloading workers to the system.

The intermediary storage and processing of relief aid at the regional airport is one of the most pressing operations to provide sustainable airbridge operations, which can be seen in appendix H. In appendix H the critical path analysis is shown, in which these processes take the longest within their respective chain. The warehouse processes require specified workforce dedication, with the majority of the processes taking up two workers to execute. The capacity of the processes is herein determining for the maximum potential of the warehouse system performance, with the time cost determining the majority of the capacity allocation.

For the warehouse processes regarding the internal facilities, no constraint on the handling capacity was set at the regional airport, as it typically provides a hub function in the area already, meaning operational space should not be the limiting factor in this instance. A similar approach was used in terms of allocation resources available at the airport, meaning the number of trucks and forklifts were not limited. The loading of the trucks is limited neither, as it provides great outflow and can be done outside the confinements of the airport. The capacity for forklift loading however, was considering the short loading time set to one, to consider the limited movement space between sections of the airport.

The policy settings for the warehouse require the baseline 8 warehouse workers, which would receive another 16 workers in parametrization 1, and 32 workers in parametrization 2. This is presented in table 2. In this same table the setting for the arrival time is presented as well. All additional workers from this policy arrive after 9 days, coming from both the work of (Feil, 2018) and an estimation based on (Andersen & Semaan, 2018d). It is rather common to provide additional resources after a start-up period, yet the exact time at which this happens might differ between various disasters.

Variable	Parametrization1	Parametrization2
Warehouse workers	8 workers	8 workers
Additional workers	16 workers	32 workers
Arrival time	9 days	

Table 2: System settings for the warehouse worker policy

7 Experiment design

In order to test the policies in the model environment an experiment design is chosen which answers the question how prioritization and network design influence the output variables. This section starts with the reasoning behind the design, and the scenarios based on this reasoning. Hereafter, the output values are described in which the connection is made with the prioritization of relief aid and the network design of the airport relief system.

7.1 experiment design choices

The design of the experiments is focused on the two airport system in which both airports have independent processes. The scenario's are impacting firstly the chain in the regional hub airport, with the accumulation of relief aid at the airbridge and secondly the end distribution with possible congestion at the local airport. The focus on the network system elements in the relief chain resembles the case study of Gralla and Goentzel (2018), whom researched the decision making process of relief transportation planners, yet disregards the network design with multiple hubs.

The scenario's are based on this decision making process proposed by Gralla and Goentzel, but is tailored towards a system chain, more than a network. The scenario's of Gralla and Goentzel (2018) focus on three system aspects, namely item priority, destination priority and last-mile distribution. The latter is disregarded, as the last-mile distribution is mostly outside the scope of this research. The item prioritization and destination prioritization were taken as the variables of interest for the scenario design. The priority values are implemented in the model as iP-number for item priority and dP-number as destination priority.

7.2 Base case parametrization for the Sulawesi disaster

Aside from the priority values, the scenario's are designed to have 30 replications, with a run length of 20 days for all policy testing. The policies are tested for what is called the base case scenario. The run length is based on the recovery time proposed by Feil (2018). The base case scenario is a combination of parametrization from the Sulawesi disaster, appendix A, and the design of Feil (2018). The arrival schedule used is called SulawesiDisaster1stScenario. The arrivals are handled by six gates, as explained in section 6.1. Other important parameter settings are the scheduling of 24 and 8 unloading and warehouse workers respectively. The last two important parameter are the airbridge and highlifters which are set to 10 and 3 respectively.

The design of the policies based on the work of Gralla utilizing the Base case scenario is presented in table 3. These policies have specific experiment parametrization alongside the slight change in policy. The policies like additional workers value the extra worker value based on the number of workers are expected to arrive after a set number of days. With the policies based on Gralla, this is slightly different. The influx of cargo is alternated as well, with for example 70 percent of the assigned cargo being priority items when iP-1 policy is active.

scenario name	item prioritization	destination prioritization
Baseline	none	none
Priority items	iP-1	none
Smallest demand items	iP-4	none
Priority destinations nearby	none	dP-1
Limited capacity	none	dP-2

Table 3: Adapted scenario list from the study of Gralla and Goentzel, 2018

Baseline

The baseline case is self explanatory in the sense that it represents the base case. The base case of the airport relief chain however, disregards any prioritization, which is unlikely in real world application. This approach straying a bit from reality is taken as the exact level of priority in real world application is hard to measure, and the differences between baseline and priority scenarios become more apparent. The gap between the baseline and the priority scenario is not meant to represent what is now and what it should be, but rather what the potential of a certain strategy is.

Priority items

The priority items scenario has a fixed preference on the highest priority items. The items with priority iP-1 are assigned 70 percent of the total demand for relief item arrivals, and are assigned the full capacity of the nearest warehouse facilities. This scenario aims for completing the demand for priority items as fast as possible, without completely disregarding other relief items.

The shear influx in particularly priority items, will cause the arrivals to fulfill the demand of relief items in the system within the time frame of 20 days, meaning further arrivals with similar shares or even any of the priority item would only cause overflow in the airport relief chain. The feedback mechanism as described in ... would interfere when this situation occurs, stopping further arrival of priority items and dividing the cargo capacity of incoming aircraft over the remaining relief types for which the demand is not yet to be fulfilled by the airport relief chain.

Smallest demand items

An alternative for item prioritization is to strife for fulfilling any demand as fast as possible, which optimizes on unification of relief items. This scenario closely resembles the priority items scenario, but sets the 70 percent demand to the items with the smallest quantity in the demand request.

The smallest demand is most easily satisfied, especially given the 70 percent share in the arrivals. Whenever the demand for the smallest demand priority items can be fulfilled by the amount of cargo present in the airport relief chain, the future arrivals will divide the capacity of incoming aircraft over the remaining relief types, for which this is not yet fulfilled.

Priority destinations nearby

This scenario focuses on the network design instead of the item prioritization. The prioritization of shortest supply chains is modelled as the addition of capacity in the warehouses at the airport, and transporting all relief aid through the airport warehouses. This approach tries to minimize storage time and aid transportation.

Limited capacity
The destination priority is set to provide very limited storage capacity near the airport, whereas the majority of relief aid has to be stored at distant warehouses. This policy ignores specific item priority, but divides the flow in a 70-30 flow in favour of the off-airport storages. The item prioritization can be included by deciding the size of priority influx in this policy.

7.3 Alternation for a more generic case

The experiment set is altered for the uncertain dichotomous parameters of Feil (2018). These together with the suggested change in arrival schedule, which is seen as a dichotomous parameter as well, the total number of alternative scenarios for the combined policies is 8. These eight scenarios are only evaluated and compared to one another for the promising policy combinations in order to keep the total number of required evaluations small. In order to assess all possible combinations, these eight alternatives have to be evaluated for a total of 16 possible policy combinations requiring 128 total alternative scenarios to be compared.

Instead of evaluating such a large number of policies, only two promising policies were selected. The performance of the most promising operational policy, combined with the two most promising strategic policies. The two most promising policy combinations are lastly weighted on their ability to improve the airport relief chain system, in order to provide recommendations.

8 Results

The policies defined in section six and the process of evaluating the policies as described in section seven have led to a wide range of results from the model. This section focuses on the evaluation of the results with regard to the key performance indicators, that are most likely changed by the analyzed policies. This section starts with an analysis of the base case scenario in which the closest representation of a non-policy system is provided. This representation was used for the detection of bottlenecks which the policies are meant to resolve. The ability of each individual policy to resolve these bottlenecks is discussed, with their implication on the system. At the end of the strategic and operational policies sections a comparison between the policies in each of the sections is made. From this comparison the most promising policies are filtered, to be tested in combination with the other type of policies. The combinations are not only evaluated then for the Sulawesi base case scenario, but also for the general case described in section 7. This last dual testing of the combinations have led to general conclusions on the effectiveness and airport relief chain system properties.

8.1 Results evaluation process

The base case for the airport relief chain model was described in section 7.1. The results from the 30 replications for the base case are averaged for to provide a clear indication of the performance of the system on the key performance indicators. The timely delivery performance indicators are reported over time, while the policies are compared for the total average delivery on the two measures at the end of the 20 day run period. These same initial settings are used for all policies, only to be altered for inclusion of the policy.

The resilience measures behave slightly different, while the measures are based on system components. The activities are split into the subactivities where necessary and evaluated as the added total performance of the system component. The regional airport processes for example are evaluated for the unloading of dollies plus the breakdown performance.

The calculation of the resilience measures differs as well. Once the averages are obtained, the values for the processed cargo are divided by 160, for the number of operational hours given the work schedule of the workers. The throughput time and idle cargo are directly taken as the reported totals for each of the system components.

8.2 Bottlenecks

In the base case scenario all five performance measures are of importance; the first two comprising timely delivery, the second three representing the resilience. The total delivery and priority relief delivery are presented first, as the main measures of performance, for the airport relief chain system. This is then broadened to performance of the system components, by assessing the components on the resilience metric. The system components follow the outline of the process diagram, with each of the process components on the IDEF-1 level representing a system component for which resilience is tested. This can be seen in section 4.1. as well, where the main distinction in subsystems is clarified.

The results of the baseline are presented in figure 16 with representation of the policy settings next to it in table 4. In addition table 5 provides the numerical performance of the resilience metrics for the system components. The values in each table for resilience follows the standards of table 5 with cargo processed and throughput time rounded to one digit, while idle cargo is rounded to numerals. When the idle cargo values are near .5 the values are rounded up, even though sometimes the value would under normal circumstances be rounded down. An idle cargo component should naturally be a natural number, in which rounding up makes more sense than the omission of a piece of the cargo.

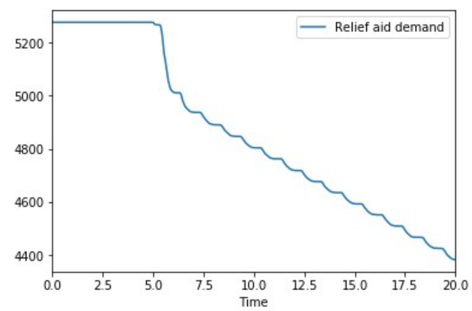

Figure 16: Baseline delivery of cargo in tonnes

strategic policy	
Off-airport destination priority	none
International Gates	six
operational policy	
Warehouse workers	8, 0
Item priority	none
Timely delivery	
Total delivery	893
Percentage priority aid	11,9

Table 4: Baseline setting and delivery result

Subsystem	Processed cargo	Idle cargo	Throughput time
Aircraft arrival	21,2	747	25,1
Regional airport operations	10,6	442	38,1
Warehouse storage	10,5	16	148,2
Local airport handling	1,4	246	118,0

Table 5: Baseline average performance on the resilience measures

The base case scenario or the baseline scenario as described in section 7.1 regards low settings for the parameters, inherited from the work of Feil (2018). Airport performance was insufficient to handle the influx of relief aid. With the inclusion of the regional airport to deal with the influx of relief aid, the performance was still sub par, though the supply of the local airport became manageable. The constraints in the regional airports seem to impact the total system performance, even though the local airport received the dampened influx of relief aid.

The bottlenecks found in the system are the dock selection at aircraft arrival, the regional airport processes at cargo breakdown, and the airbridge aircraft loading performance. The strain at these three locations all show large numbers for the idle cargo criterion, as well as poor throughput times (table 5). Especially after the aircraft arrival operations the processing of cargo is insufficient to handle the influx with a downward trend on the ability to handle the incoming cargo.

The decreasing trend for processed cargo is an indication for behaviour in the system related to the theory of constraints. It is based on these results likely that when performance in the arrivals or in the regional airport processes that the airbridge will be restrained even more.

The poor throughput times are reflected as well in the warehouse storage and the local warehouse, these however have alternative reasons for the poor performance. The warehouse storage has an internal delay for the cargo, meaning the focus is on delaying the cargo significantly even though the represented times are poorer than expected. The local airport faces downtime on the delivery network from storage or handling to the disaster sites.

8.3 Strategic policy

The strategic policies regard the interventions meant for long-term improvement of the system, by means of structural or design changes to the system. The policies described in section 6.1. are meant to alleviate the pressure on the system components at which bottlenecks occur with these long-term improvements. The policies analyzed in this section are the use of additional storage locations and the assignment of international gates to the transportation of international relief aid. These two main policy directions are studied in on their change in performance compared to the baseline scenario, regarding the total demand delivered from the timely delivery KPI, and the resilience KPI as a whole.

8.3.1 Off-airport storage

The storage of cargo is limited within the confines of the airport, with in the case study only one warehouse made available. This was at that point sufficient for one airbridge day, without running into significant issues. This is supplemented by additional storage capacity as part of the strategic policy set in the vicinity of the airport. The policy consists of two destination priority settings, or dP-numbers as described in section 6.1. The first is only the addition of Off-airport storage with the storage being used mostly as additional capacity to back up the airport storage, whereas the second treats the airport storage as limited capacity and moves most relief items through the newly dedicated off-airport storage locations. These are evaluated separately for the relief transportation, whereas the resilience is presented in a side-by-side tables, supporting direct comparison.

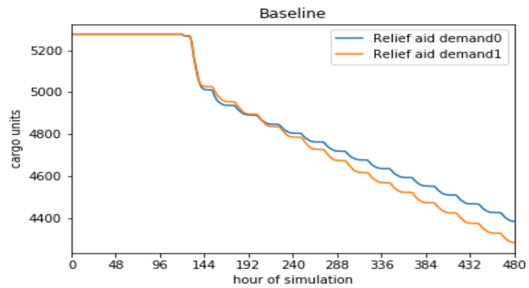

Figure 17: Baseline compared to dP-1 delivery

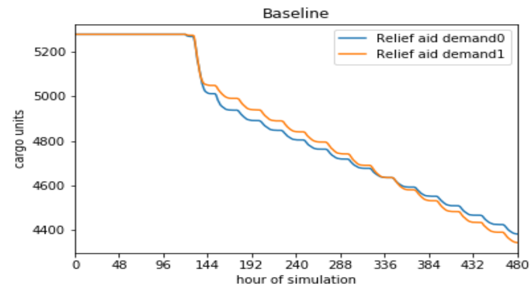

Figure 18: Baseline compared to dP-2 delivery

The figures 17 and 18 show the decrease in relief aid demand over the period of twenty days considering the base case scenario with the parameter for off-airport storage alternated, with dP-1 for the internal storage prioritization and dP-2 for off-airport storage prioritization. The differences in the total delivery is small, with both alternatives only marginally improving on the performance indicator.

destination priority setting	subsystem	Processed cargo	Idle cargo	Throughput time
dP-1	Aircraft arrival	30,3	448	35,3
	Regional airport operations	8,3	958	35,0
	Warehouse storage	8,2	14	152,6
	Local airport handling	1,6	50	134,9
dP-2	Aircraft arrival	33,9	348	38,9
	Regional airport operations	7,4	1105	32,3
	Warehouse storage	7,3	13	131,1
	Local airport handling	1,5	32	129,5

Table 6: Destination priority performance on the resilience metrics

The policies both show an improvement over the baseline, with decreased constraint in the bottleneck at the arrival of aircraft and the airbridge performance, which are correlated to some extent. The improvements are significant in both components when considering the idle cargo numbers. The amount of unprocessed cargo has seen a rise in the regional airport processes, becoming the main source of delay in the system. The idle cargo on average more than doubles for the regional processes compared to the baseline scenario. This can be seen in table 6, with the clearly red color indicating lower performance in the policies than in the baseline scenario.

The idle cargo at the regional airport for the two destination prioritization policies as well as the baseline is shown in figures 19 and 20, showing the dolly unloading and cargo breakdown respectively. The blue line represents the baseline case, with the orange line displaying the dP-1 and

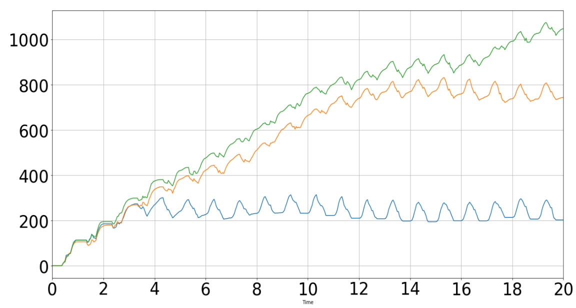

Figure 19: Regional airport idle cargo comparison at dolly unloading

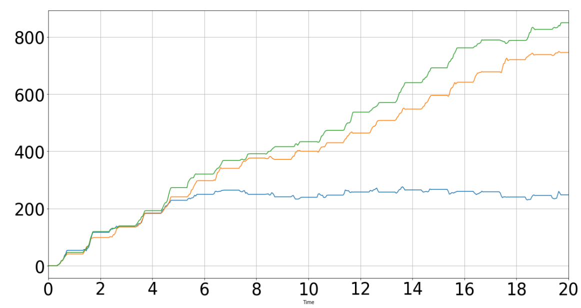

Figure 20: Regional airport idle cargo comparison at cargo breakdown

the green line representing dP-2.
The addition of warehouses improves the system, but is constrained in effectiveness by under performance in the regional airport processes. In comparison to one another dP-2 almost completely dominates the performance of dP-1 on the resilience metric, yet performs worse on the total demand delivered from the timely delivery performance indicator. This is likely due to even larger impact of the bottleneck found in the regional airport performance.

8.3.2 Additional gates for international relief aid

In section 8.1 it was found that without significant increase in the number of unloading workers the airside docks were highly constrained. The regional airport has to deal with a tremendous increase in the number of aircraft arriving at her gates, while dealing with both the international and domestic relief aid. The international relief aid throughput at the airside docks logically improves when the number of available gates is shifted, yet this number has to be kept as low as possible to maintain the domestic relief chain. This trade-off makes the policy difficult to implement, as discussed in section 6.1. In this same section it was noted that the performance of the airbridge and the arrival gates have a correlation, creating a possible opportunity space for systems utilizing a smaller number of gates.

The airside docks made available to international relief aid is varied between four and six gates. The performance of the system is presented below with a comparison of the fulfilled relief demand, and the resilience of the airport chain throughout the system for determining the ideal number of gates in the case study.

The comparison on the ability to provide relief aid to the final destinations is made in figures 21 and 22, where the blue line represents the baseline, and the orange line the system with an altered number of gates dedicated to international relief aid. The comparison shows as can be seen below that over the period of twenty days the systems with less docks output a larger number of relief aid, than the baseline scenario. This is counter-intuitive whereas a larger number of processed cargo at the arrival of the regional airport would likely provide a larger number of processed cargo in the end. It can be noticed that the overall output of relief aid in the system with only four docks is slightly larger than the system with five docks.

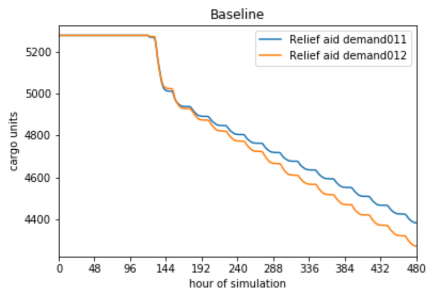

Figure 21: Baseline compared to a system with 5 docks

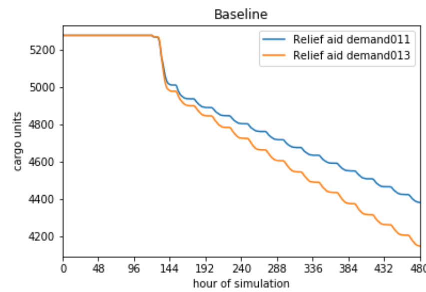

Figure 22: Baseline compared to a system with 4 docks

The table below presents the resilience metrics, which were compared to the resilience metrics of the baseline case. The performance of the aircraft arrival has significant reductions when utilizing a smaller number of gates, with a drop from around 21 tons/hour to below twenty in both cases. This leads to crowding of the runways with the idle cargo increasing as well. The throughput of the subsystem improves however, as the taxi process increases in time, yet the unloading practices decreases from an inverse relationship. The unloading is less crowded slightly improving the average unloading time, compensating for the crowding at the gates. This does not compensate however for the decrease in performance on the other two metrics which means for both the 5 docks system and the 4 docks system, the resilience of the aircraft arrival decreases. The bottleneck as such only constraints the system more.

The performance in the other system components shows significant similarity with the baseline case as can be seen in table 7, with downstream improved performance from the early constraints being watered down, providing more even distribution to the rest of the airport relief chain.

Number of docks for international relief aid	subsystem	Processed cargo	Idle cargo	Throughput time
5	Aircraft arrival	18,2	821	23,5
	Regional airport operations	10,6	274	37,8
	Warehouse storage	10,5	16	47,0
	Local airport handling	1,6	210	135,7
4	Aircraft arrival	16,8	858	22,7
	Regional airport operations	10,1	256	35,6
	Warehouse storage	10,0	15	42,7
	Local airport handling	1,8	145	154,2

Table 7: Comparison tables for the resilience of the system components with 4 and 5 international relief docks

The number of international docks given the slight improvement in both timely delivery and downstream resilience could be scaled down. The performance of the 4 and 5 docks system are very comparable making the lower setting likely preferred if no other bottlenecks are resolved. Even considering the small improvements between the alternatives, the policies with fewer international aid docks require fewer resources and provide more opportunities to dedicate docks separately for the airbridge system.

The limitations of this policy closely align with the conclusion above. The performance remains similar and even improves slightly with the decrease in international gates, but is caused by spill-over effects with multiple bottlenecks restraining performance. The system would benefit from more policies reducing the bottlenecks which might in turn warrant a higher number of international gates.

8.3.3 The performance comparison of the strategic policies

The strategic policies have all shown improvement over the baseline scenario even if only to some extent. It is evident, however that the individual performance of the policies is not significant enough to resolve all three bottlenecks simultaneously. The best results in the system on timely delivery were observed in the smallest number of international relief aid, even though the difference over the entire relief chain was no more than two hundred tonnes of cargo. This was achieved by small reduction in the bottlenecks at arrival and the airbridge, while maintaining performance in the regional airport bottleneck.

The improvements in the bottlenecks found in the destination priority policies was significantly larger than the performance change in the four gates system, yet with the downside of increased constraints in the regional airport processes. This trade-off makes it difficult to universally decide on a single best performing policy. The second destination priority policy does however show larger improvements in the resilience metrics than that of the similar dP-1 policy, making it for combined policy the preferred option.

With dP-2 and 4 international gates as most promising policies, the strategic policies section for the comparison to the baseline case is concluded. The two policies will be combined with the promising policies of the operational policies section in 8.3. The table the conclusions for the performance comparison of the strategic policies is based on is table 8, which distinguishes the policies on timely delivery and resilience.

policy	timely delivery	resilience
dP-1	small improvement	reduced two bottlenecks, regional airport bottleneck remained
dP-2	small improvement	reduced two bottlenecks, regional airport bottleneck remained
5 gates	small improvement	reduced regional airport bottleneck, other bottlenecks remained
4 gates	medium improvement	reduced both regional airport bottleneck and airbridge bottleneck

Table 8: Conclusion on the strategic policies considering the timely delivery and resilience

The results compared on the resilience metrics for the promising policies dP-2 and 4 international gates. The presented results below are for the individual components of the airport relief chain in which the policy outperforms both the baseline with the bottleneck and the other promising policy. These are respectively the arrival procedure for the dP-2 policy and the regional airport operations for the policy with four gates for international relief aid. After the comparisons are made with the other promising policy in figures 23 and 24, the performance improvement of both on the airbridge bottleneck is presented in figure 25. These are all compared on the idle cargo criterion as this most promisingly shows the reduction in the bottleneck present in the simulation systems. The legend for the three figures is the same and can be found in table 9.

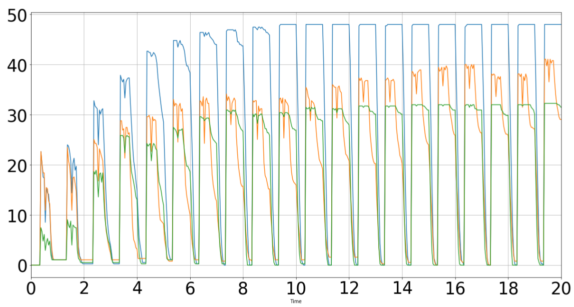

Figure 23: Baseline compared to dP-2 and 4 gates for cargo at docks

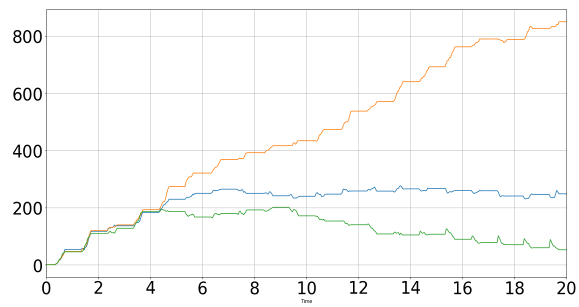

Figure 24: Baseline compared to dP-2 and 4 gates for cargo at breakdown

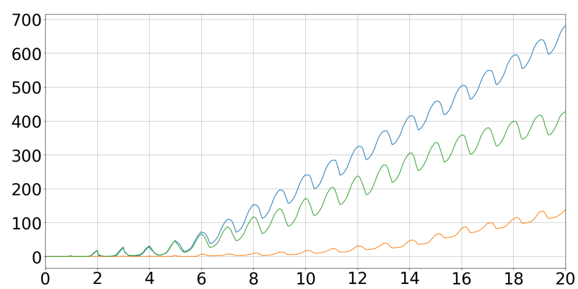

Figure 25: Baseline compared to dP-2 and 4 gates for the airbridge performance

policy	color
baseline	blue
dP-2	orange
4 gates	green

Table 9: Legend for figures 23, 24 and 25

8.4 Operational policy

The operational policies are meant as day-to-day changes that can be made within short periods of time. The operational policies analyzed in this section are the item priority policies, and the deployment of additional work force in the arrival of aircraft and regional airport operations. These two main policy directions are studied in on their change in performance compared to the baseline scenario, regarding the timely delivery and the resilience.

8.4.1 Item prioritization

The item priority policies are vastly different in what the priority items represent, yet both fall under a form of item prioritization. The item priority policies are furthermore, based on the work of Gralla and Goentzel (2018), whom refer to the policies as: iP-1 and iP-2. The item priority policy is for this reason taken together with two subsections for the individual policies, and a last section comparing the two on the resilience metric with the clearest change and a 40 day period performance comparison to the baseline.

Priority on the most stressing relief type

The prioritization on the most stressing relief aid is presented in figure 26 with the provided number of relief items and the percent of priority relief aid delivered to the shelter locations on the right side in table 10. The policy should most effectively contribute to the latter, by assigning a large share of the influx of relief aid to the priority relief type, as well as to dedicate the shortest routes when alternatives are available to this group. This policy is regarded as the iP-1 policy, with respect to the policy in Gralla and Goentzel (2018), where this reflects a similar policy.

The performance of the relief chain was similar in total delivery to the baseline over the period of twenty days, yet showed an improvement of a near 15 percent on priority relief delivered. The minor increase in total relief aid delivered with an almost insignificant difference can be seen as an indication that within the normal airport relief chain system uniformity of items does not necessarily lead to better delivery numbers.

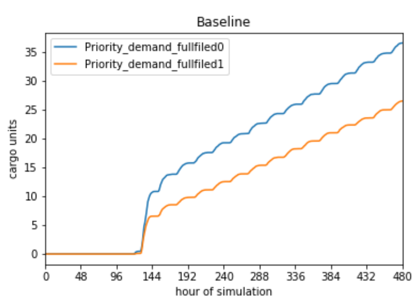

Figure 26: Comparison between the baseline and the priority on the most stressing relief aid

Variable	Baseline	iP-1
Total delivery	893	943
Percentage priority aid	11,9	26,6

Table 10: Baseline compared to the IP-1 policy

The uniformity and priority of the highest priority relief can be seen in table 11 with a positive influence on the aircraft arrival with more than 50 percent less idle cargo and over 70 percent better processed cargo. The positive influence is undone however by the bottleneck in the regional airport operations. The policy as such is good for priority demand delivery, without actually solving the bottlenecks by means of uniformity.

Subsystem	Processed cargo	Idle cargo	Throughput time
Aircraft arrival	36,2	346	56,7
Regional airport operations	10,1	1056	37,2
Warehouse storage	10	15	87,0
Local airport handling	1,5	264	132,1

Table 11: Resilience metric values for the highest priority items prioritization

Priority on the smallest quantity relief type

The prioritization on the smallest quantity relief type aims at provision of uniform relief type, by providing the majority of resources to the smallest stream. The stream with the smallest quantity is set as the iP-2 policy, yet is in the simulation iP-4. For further reference iP-2 will be used as the policy resembles the prioritization policy of Gralla and Goentzel (2018).

The iP-2 policy performs significantly better on the provision of the lowest demand relief items, with nearly all of these items delivered within the twenty day period. It should be noted that the base delivery of the smallest quantity relief items was already at 36,7 percent for the baseline scenario. This uniform delivery provides the expected performance, with a shift in relief items earlier in the system already. The true influence of the uniform delivery is limited within the scope of the experiments, which do not yet show improvement in the total delivery. In figure 27 the orange line represents the provision of relief items for the iP-2 policy, whereas the blue line is again the baseline, with in table 12 the values for the timely delivery KPI.

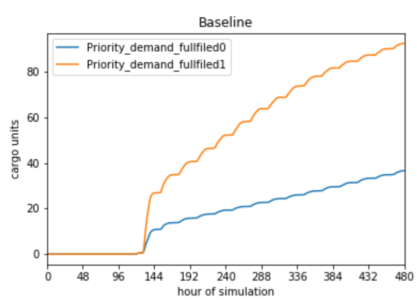

Figure 27: Comparison between the baseline and the priority on the smallest quantity relief type

Variable	Baseline	iP-2
Total delivery	893	982
Percentage priority aid	36,7	92,6

Table 12: delivery result and priority delivery for baseline case and iP-2 policy

The resilience of the system with the iP-2 prioritization policy in place shows moderate improvements with regard to the arrival of relief aid and the initial processing thereof. The constraints on the taxilane decrease, leading to less cargo at the runway and docks. The amount of idle cargo reduced by around 15 percent. The regional airport however sees an influx in idle cargo, as can be seen in table 13. The warehouse and the local airport both perform similarly on the resilience metrics compared to the baseline case. The difference for the local airport as seen in the table is the shift in idle cargo and throughput time of the local airport. These are changed inverse of each other, meaning a dampened change in the resilience of the local airport.

Subsystem	Processed cargo	Idle cargo	Throughput time
Aircraft arrival	25,0	633	35,6
Regional airport operations	10,4	642	37,8
Warehouse storage	10,3	15	143,4
Local airport handling	1,5	216	132,8

Table 13: Resilience metric values for the smallest quantity prioritization

The improvements in the system mostly come from the interdependence of the gate availability at the regional airport, where the arrival of aircraft and the airbridge performance depend on the same workers. These workers finish their job before shifting from arrival to departure and the other way around, to represent in simplified form the constraints of airside docks being used for both arrivals and departures. This dependency is utilized most efficiently when the cargo of the same types are moved in larger quantities together, freeing more workers for the arrival processes.

Item priority policy change to resilience

The resilience metrics for both item priority policies improve the aircraft arrival process. This is likely in relation to the dedication of an increased number of personnel to the arrival gates, with fewer airbridge dedication for the lower priority items. This improvement in the arrival bottleneck on the other hand has an inverse effect in the regional airport processes making the bottleneck only larger and having little impact on the total delivery from the timely delivery metric. The policies on the other hand boast significant improvement in delivery of the dedicated priority items. The inverse relation is presented in figures 28 and 29 below, with a decrease in 28, below the blue line, and increase in 29.

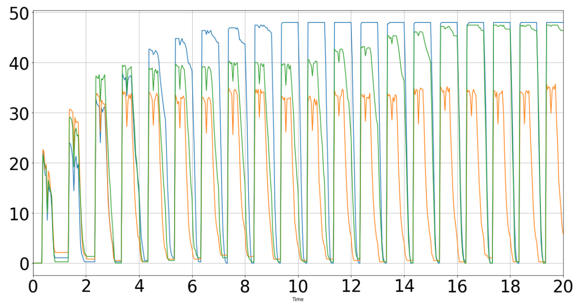

Figure 28: Baseline compared to iP-1 and iP-2 cargo at docks

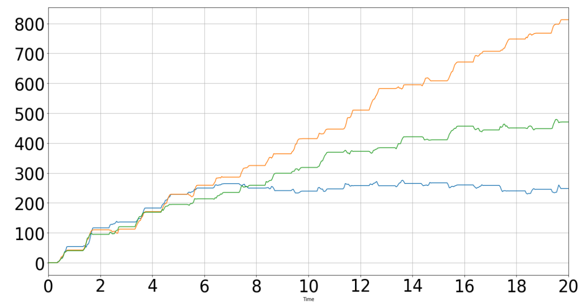

Figure 29: Baseline compared to iP-1 and iP-2 cargo at breakdown

Item priority policies for a 40 day period

The uniform flow of relief items was the main reason to do item prioritization with the iP-2 policy, while iP-1 would maximize the priority relief delivery through the same assumption. The real performance improvement for the longer period would preferably be in both timely delivery measures, while in the short period policies the measure for priority relief would be the only one really changing.

In the longer time period, the change in the system was still arguably small, providing hardly any change in total delivery. The lines follow the same shape and provide very similar behaviour, meaning extended run lengths would hardly provide any more credit to the policies for implementation. The only reason to implement the policies as such would be to provide increased delivery of a specific type of relief items, by decreasing the delivery of the other types of relief items. Policy iP-1 would be most favourable as such, but would only be useful when certain levels of a specific demand have to be met before a specific time, while other types could be disregarded.

8.4.2 Additional workers

The introduction of additional workers provides an improvement on both the unloading of the aircraft, as well as the processes at the regional airport. The impact of providing additional resources on both ends, means significant change is to be expected in comparison to the baseline case. The impact of the addition of different levels of workers is tested in the sensitivity analysis, while in this section the unloading workers are set to maximum deployment and warehouse workers is varied on two levels. These levels are as described in section 6.2, an additional 16 and 32 warehouse workers.

The policies improve the delivery of relief aid, with over 400 tonnes of relief aid delivered additionally for both policies, which is presented in figure 30. The policies compared to one another differ very little on average with respect to the timely delivery measures. The behaviour of the relief aid delivery of the policies are closely matching with only at the last several days a minor

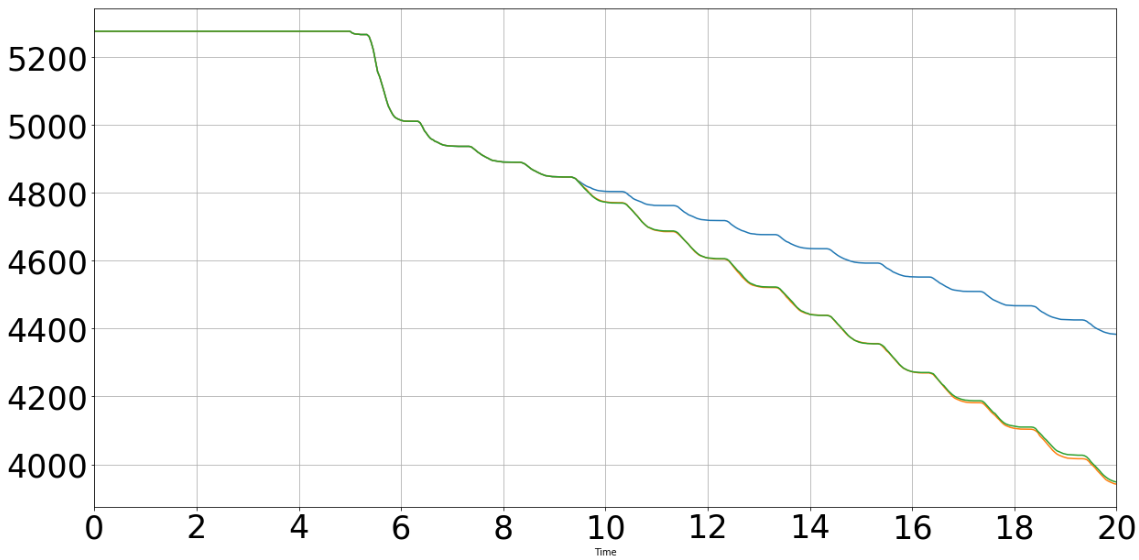

Figure 30: Relief aid demand for the comparison between the baseline and the two levels of additional workers

change.
The additional workers in this section are compared on the individual performance between the evaluated alternatives and the extent to which large increases in resources lead to large increases in the performance measures. In table 14 the number of unloading workers and warehouse workers are presented similar to the variations in destination priority, with the resilience metrics evaluated for each of the two levels.

The main difference with the results for the additional workers policy is the comparison to the baseline, which is harder to make. The difference from the policy is expected to show more significant change in the system. For this reason the policies are compared to each other and on the ability to resolve the bottlenecks for which the policies were analyzed. For this reason the color coding is left out of the table.

The settings for the additional worker policies are the same as for the baseline, with the logical exception of the quantities of workers. The performance measures are calculated through the same rules as the base case, making the systems similar and comparable in the end. The comparison is still made in the operational policy comparison to decide on the promising policies.

Warehouse and Unloading workers	Subsystem	Processed cargo	Idle cargo	Throughput time
16, 24	Aircraft arrival	40,3	434	58,3
	Regional airport operations	22,4	454	39,9
	Warehouse storage	22,2	33	134,7
	Local airport handling	2,1	607	199,1
32, 24	Aircraft arrival	40,3	431	58,7
	Regional airport processes	25,2	255	39,2
	Warehouse storage	25,0	37	140,9
	Local airport handling	2,1	799	197,9

Table 14: Resilience metric values for the variation in unloading and warehouse workers

The bottlenecks at the aircraft arrival and regional airport operations seem significantly reduced, with improvements on the processed cargo and for aircraft arrival also on idle cargo. The throughput time of both subsystems remains high however, making it difficult to say whether the bottleneck has truly been resolved. The idle cargo displays a clear recovery of the subsystems with the additional deployment of 16 warehouse workers proving sufficient to resolve the bottleneck at arrival, while 32 additional warehouse workers resolve the bottleneck at the regional airport processes as well.This is displayed in figures 31 and 32.

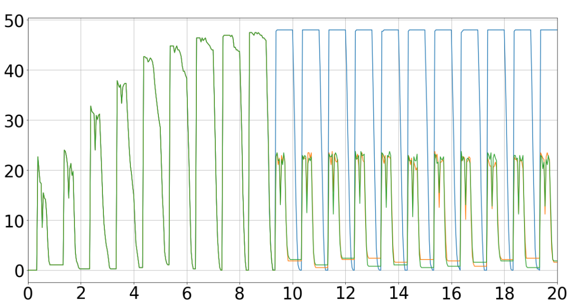

Figure 31: Stabilization of the additional workers policy at the arrival of aircraft, presented in tonnes/hour

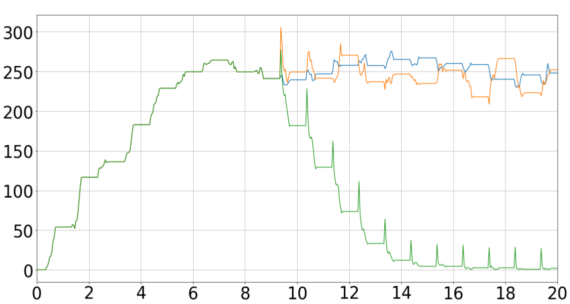

Figure 32: Stabilization of the additional workers policy at the regional airport processes in tonnes at cargo breakdown

The similarity in output on the timely delivery performance metric discussed above is in stark contrast to the expected improvement of the additional work force. This is an indication that the improvements in the arrival of aircraft and the regional airport processes still face a bottleneck in the system before delivery at the disaster sites. The bottleneck at the airbridge would considerably delay the system processes in the end with the idle cargo at the airbridge increasing, even though the amount of relief aid stored in warehouses improves alongside the absolving of the other two bottlenecks.

8.4.3 The performance comparison of the operational policies

The item priority policies provide really promising results when considering the priority relief aid measure, but fail to produce results on the resilience of the airport and to some extent on total delivery as well. The only notable improvement on the system resilience can be seen at the aircraft arrival, which is the earliest bottleneck found in the airport relief chain system. This would mean any improvement would lead to little to no change to the total delivery through the system without significant improvement in both the regional airport processing and the airbridge component.

The deployment of staff after a nine day period proved to be effective at dealing with the bottlenecks in the system bringing the system back to a steady mode for the resilience metrics. The improvement on timely delivery of relief aid was leveled out after 16 workers were added to the regional airport processing operations, yet did not provide true stability in the system component. This was achieved with double the number of additional workers. To this end a larger additional deployment is warranted, if the airbridge bottleneck could be reduced.

In table 15, the conclusions on the two sets of KPI's are presented. The power of the additional worker double policy to resolve two bottlenecks makes it a very promising policy for policy combination testing. The iP policies could be taken into consideration when specific requirements for the system demand levels of specific item delivery. Nonetheless, the additional worker double policy is taken into account for the combined policy section, beating out the other operational policies on especially the resilience metrics.

policy	timely delivery	resilience
iP-1	improvement in priority item delivery	little change in arrival with inverse effect in the regional airport processes
iP-2	barely any change	little change in arrival with inverse effect in the regional airport processes
Additional worker	medium increase in delivery	resolves the first bottlenecks, reduces the second, yet faces increased strain at the airbridge
Additional worker double	medium increase in delivery	resolves the first two occurring bottlenecks, yet faces increased strain at the airbridge

Table 15: Conclusion on the operational policies considering the timely delivery and resilience

8.5 Combined policies

In this section combinations of strategic and operational policies are explored, in an attempt to improve the system more significantly by connecting different levels of policy implementation. The policies explored in this section are combinations made from the promising policies in the performance comparison subsections. The analysis is done similarly to the other policy evaluations, with regard to both resilience and the timely delivery. This means either one or both key performance indicators were improved, while no significant decrease in the other was observed.

The policies applicable in this section are two from the strategic policy list, and one from the operational policy list. The strategic policies are dP-2 and four gates for international relief aid processing. The dP-2 policy was inapt at providing a large improvement on timely delivery measures. It does improve, however, the performance in the arrival of aircraft and at the airbridge. The 4 gates policy did provide a larger improvement to the timely delivery measures, while reducing the regional airport processes bottleneck and airbridge bottleneck.

The operational policy to study in the combined policies is the additional worker double. This was the superior policy to the normal additional worker policy, however any improvement in the quantity of personnel would influence the airport relief chain positively considering the bottlenecks at the aircraft arrival and the regional airport processes.

8.5.1 Strategic policy dP-2 with operational policy double worker

The additional off-airport storage aims at relieving the stress on the processes at the regional airport for throughput to the local airport. In this combination the additional personnel can more quickly prioritize cargo and allocate faster at both the unloading processes at the aircraft as well as the regional airport processes. This combination is regarded as one of the most promising combinations.

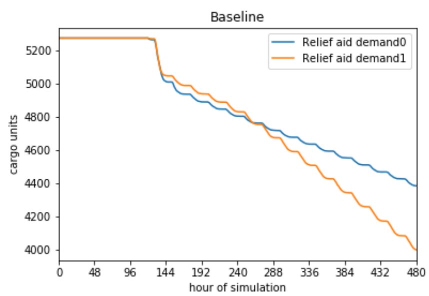

Figure 33: Timely delivery comparison between the baseline and combination dP-2/double worker

strategic policy	
Off-airport destination priority	dP-2
International Gates	six
operational policy	
Warehouse workers	8, 32
Item priority	none
Timely delivery	
Total delivery	1280
Percentage priority aid	15,9

Table 16: Baseline setting and delivery result

The policy combination utilizing additional storage space in off-airport storage is combined with the additional worker policy, supplying 32 additional workers after a period of nine days. The dP-2 policy showed improvements in aircraft arrival and the airbridge processing. The double worker policy provides improvement on the arrival of aircraft as well, by completely mitigating the bottleneck within the investigated experimental settings. The policy further mitigates the bottleneck found at the regional airport processes.

The two policies separately either resolved or reduced two bottlenecks, combining to impact all three the bottlenecks analyzed in the airport relief chain model. The combination provided a raised performance for the timely delivery measures, with the delivery increasing similar to the double worker policy.

Subsystem	Processed cargo	Idle cargo	Throughput time
Aircraft arrival	45,1	167	49,8
Regional airport operations	28,3	527	29,9
Warehouse storage	28,0	52	85,7
Local airport handling	2,0	851	196,4

Table 17: Resilience metric values for the policy combination of dP-2 and double worker

The combined policy performed better for the resilience metrics as well, absolving all bottlenecks except for the bottleneck at the airbridge. The airbridge is still significantly under performing compared to the other subsystems. The airport relief chain significantly outperforms the base case system throughout the regional airport, yet is more constrained at the last bottleneck, losing all potential from the early system improvements. It does on the other hand have the idle cargo at more ideal locations in the airport, making it favourable when compared to only the double worker policy.

8.5.2 Strategic policy 4 docks with operational policy double worker

The decrease in airside gates is meant to reduce the strain on the bottlenecks, similar to how the deployment of additional personnel provides capacity in the constrained system components. The combination aims at maintaining adequate capacity, with slowed influx of the relief items.

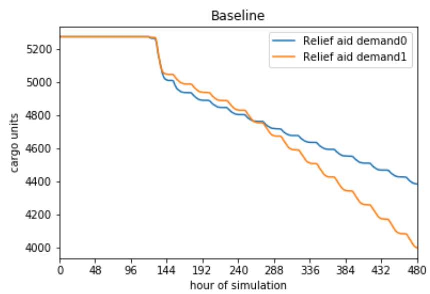

Figure 34: Timely delivery comparison between the baseline and combination dP-2/double worker

strategic policy	
Off-airport destination priority	none
International Gates	four
operational policy	
Warehouse workers	8, 32
Item priority	none
Timely delivery	
Total delivery	1378
Percentage priority aid	18,4

Table 18: Scenario setting and delivery result for dP-2/double worker

The timely delivery measure is improved significantly, with both priority relief delivery and total delivery improving within the twenty day period. This is shown in figure 34, with table 18 presenting the table settings. The policy combination provided on average an improvement of nearly 300 tonnes of relief items for the model settings. The additional cargo delivered sustains nearly over 15 percent of the total demand for priority relief items.

The policy combination presented in table 19, shows promising results on specifically the bottlenecks for the aircraft arrival and the regional airport operations. The airbridge processes still suffer from the bottleneck with the aircraft and docks capacity. It does, contrary to other policies and policy combinations, not negate as large a proportion of the improvements made in the system from reduction in the bottlenecks in the airport relief chain.

Subsystem	Processed cargo	Idle cargo	Throughput time
Aircraft arrival	35,3	581	60,6
Regional airport operations	22,2	188	38,7
Warehouse storage	22,0	33	134,2
Local airport handling	2,2	620	200,2

Table 19: Resilience metric values for the policy combination of 4 docks and double worker

8.6 Conclusions on combined policy for general implementation

The combination of the policies provided both improvements to the system, but the policy combination of 4 docks and double worker deployment outperformed the dP-2/double worker combination on both timely delivery measures. Furthermore, it proved to be the more effective policy downstream, providing better system performance at the airbridge and local airport. By providing a smaller reduction in the aircraft arrival bottleneck the system managed the influx better, showing decreased numbers of idle cargo. The contradictory performance here shows that the turtle can beat the hare, with worse values on both processed cargo and throughput time for the 4docks/double worker policy.

In order to make a true comparison for the policy combinations, this section reviews the combinations for different scenario settings. The results have all been tailored towards the case study, with a single set for the base parameters. In order to provide a more generic conclusion for this research the airport relief chain is reviewed under random demand for the relief types, and different arrival settings. The parameter setting for the general cases is presented in table 20.

System parameter	alternative values
Arrival schedule	two SulawesiDisaster1stScenario AggressiveApproach
Relief aid demand	one Normal distribution, 1000; 200
No show workers	two 0 percent 30 percent

Table 20: General airport relief chain setting

The policy combinations are compared in two separate sections with each section representing one of the arrival schedules. The first schedule is the same as the base case scenario, with then alternated parameter values on relief aid demand and the no show of workers. The second is using aggressive scheduling with double the number of incoming flights. This aggressive scheduling is based on the conclusion of Veatch and Goentzel (2018), in which they state that additional arrivals of aircraft with creative parking would provide better results even though the already constrained gates would be pressured even more.

The comparison in the tables is done by presenting the values for the policy combinations side by side. This means the three values for the processed cargo, idle cargo and throughput time are doubled with two inputs per resilience measure. The combinations for the policies are called in the table dP2 and 4Dock, for the different policy per combination.

8.6.1 Variation on demand for the various levels of worker no show

In this section the impact of workers not showing up to the disaster struck airport is investigated on the airport relief chain system for the relief types, with an assigned similar demand. The similarity in demand makes the systems more comparable for generic situations, with no assumption on the specific relation between the different relief types. The outcome values will in this instance only be compared to one another and the same policies tested for the Sulawesi disaster. In order to show the uncertainty in this process the no show of workers is taken into account. The implications of the comparisons with the variation in demand and the implications of the no show of workers are discussed at the end of the paragraphs considering the specific comparisons.

The system performs significantly better for the smaller quantities of relief aid, which is shown by an improvement in both sets of key performance indicators. In the timely delivery indicator, the total deliveries were compared between for the policy combinations with and without randomized demand. The resilience was compared on the three components for resilience.

Total delivery
The delivery of the relief items averaged over the experiments around 1280 tonnes and 1378 tonnes for the dP-2 and 4 docks policies in combination with the double worker policy respectively. These numbers are very similar to the delivery numbers of the same policy combinations for the alternative scenario setting. These were 1252 and 1394 respectively.

Resilience
Aside from the stable delivery of relief items for the airport relief chain systems with and without the variation in demand, the lower quantities of idle cargo and lower throughput times show a reduction in the strain of the airport processes. The decrease in idle cargo and throughput time do on the other hand result in lower numbers of processed cargo, which is taken as the differences between tables 21 and 22. This decrease compared with the similar delivery present the impact of the bottlenecks, clearly showing the limited effectiveness of higher numbers of processed cargo early in the airport relief chain system.

No show of workers
The difference between the number of workers present at the local airport in the airport relief chain is fairly limited, even considering the smoother cargo handling at the regional airport feeding the local airport. Especially upstream, the resilience metrics are hardly impacted by the reduction in productivity at the local airport. A reduction of one third of the offloading capacity, and 30 percent of the warehouse processes, results in almost unhindered cargo flow. The limited impact of the no show of workers likely means the bottleneck at the airbridge results in a small enough input flow into the local airport, not to exceed the capacity. This conclusion is strengthened by the total delivery for the model with 30 percent no show, resulting in on average 1254 and 1397 delivered items.

No show workers	System component	Processed cargo		Idle cargo		Throughput time	
		dP2	4Dock	dP2	4Dock	dP2	4Dock
0	Aircraft arrival	39,7	35,0	147	503	41,1	59,6
	Regional airport operations	25,3	22,1	510	187	25,8	38,6
	Warehouse storage	25,1	21,9	46	33	79,9	132,9
	Local airport handling	2,0	2,2	834	621	190,3	203,7
30	Aircraft arrival	39,7	34,6	150	504	40,7	59,7
	Regional airport operations	25,3	21,8	523	185	25,7	38,5
	Warehouse storage	25,2	21,6	46	32	80,8	130,0
	Local airport handling	2,0	2,2	837	604	191,7	203,9

Table 21: Performance of the airport relief chain systems considering the dP2 and 4Docks policies combined with the double worker policy under randomized relief demand

8.6.2 Variation on demand and arrival schedule

The delivery of relief items and the resilience of the airport relief chain were assessed in the results section for the Sulawesi disaster scenario, and in the previous subsection for a more generic demand specification for the combinations of the most promising policies. This subsection is the last addition to this, in which the proposed change, from Veatch and Goentzel (2018), in the arrival schedule is made. The arrivals are doubled, to feed the arrival process of the regional airport, making it 100 percent utilized, leaving no room for improvement.

The increased number of arrivals was expected to result in reduced resilience, with especially the idle cargo and throughput time measures being negatively impacted. This was not the case for the scenario with lower and random cargo demand, leaving the conclusion that the full utilization of the aircraft arrival processes was already the case. This means the aircraft arrival was not only a bottleneck, but also fully saturated. The delay as such would be longer term and harder to resolve, as the influx far exceeds the capacity.

The most interesting result of this comparison with double the arrivals is the trade-off in the resilience metrics it presents. The aircraft arrival shows significant increase in the average idle cargo present, yet provides small improvements in the performance downstream. This notion held until the airbridge and the local airport. The average values for the resilience metrics showed improvement in table... in processed cargo, and a reduction in performance for idle cargo and throughput time.

No show workers	System component	Processed cargo		Idle cargo		Throughput time	
		dP2	4Dock	dP2	4Dock	dP2	4Dock
0	Aircraft arrival	39,9	34,7	546	950	57,6	76,9
	Regional airport operations	25,5	21,8	662	189	25,8	38,4
	Warehouse storage	25,4	21,6	47	32	90,0	134,7
	Local airport handling	1,9	2,2	839	608	189,6	203,3
30	Aircraft arrival	39,8	35,3	554	942	57,9	78,4
	Regional airport operations	25,4	22,2	645	198	25,9	38,9
	Warehouse storage	25,3	22,0	47	33	91,1	134,9
	Local airport handling	1,9	2,2	846	626	187,4	203,8

Table 22: Performance of the airport relief chain systems considering the dP2 and 4Docks policies combined with the double worker policy under randomized relief demand and arrival schedule

8.6.3 General conclusions

The different settings for the combined policies were used to formulate three conclusions on the airport relief chain model and the policies proposed. These hold for the model as a whole for the entire range of the lowest demand model and higher.

First conclusion
The airport relief chain model with the combined policies performs at the maximum of it's capacity, leaving little room for improvements given the available and assumed resources. In order to improve the system, the capacity of the processes have to be improved. The aircraft arrival process is saturated, meaning any improvement in the number of gates and unloading workers could provide an opportunity to process more cargo.

Second conclusion
The increase in cargo processing at the regional airport will almost fully be negated by the airbridge bottleneck, which is constrained in capacity. This constraint comes mostly from the number of available gates, which is aligned to the number of gates at the local airport. As such only strategic long term improvements at both the regional and local airport would provide opportunities to create significant increase in cargo allocation from the local airport.

Third conclusion
The incoming relief aid at the local airport is mediated by the bottleneck at the airbridge, resulting in overcapacity at the local airport for the assumed resources. The unloading workers could perform with two third of the allocated personnel and resources before any delays are seen in the airport relief chain system performance. With 30 percent no show of the personnel at the local airport the resilience metrics and delivery metrics remain on average very similar.

9 Verification and validation

Validation and verification are done to assess the strengths and weaknesses of the model as well as to review how well it describes the system it is meant to describe. The verification of simulation models is often described as does it do, what it is supposed to do? The validation is concerned with how well does the model represent the system it is supposed to represent. A formulation found in the work of Sargent (2010) is: Validation is the "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". This formulation will be regarded for the remainder of this research.

Firstly, the model is verified, which was done by performing verification runs with event tracing and run visualization. The building of the model was done in the visual representation section of the Visio simulation tool. This helped verifying model behaviour and process application by the model. The verification using the visual modelling prevented widespread mistakes and clarified the impact of model assumptions and decisions made for the translation of specific processes into the simulation model.

Secondly, the model was validated by means of animation, face validation, sensitivity analysis and comparison to other models. Aside from these techniques, several techniques were utilized, but not fully performed. The performed validation techniques, partly or fully, only cover part of the validation that would be preferably done. The selection of validation techniques is explained before the results of the validation techniques are analyzed. The selection of the performed validation techniques was based on available time and data to perform the validation techniques.

9.1 Verification of the activities

The verification was done for the most important activities in the airport relief chain system. The processes of interest were found in the simio models process environment. In order to test the logic on correct representation of the conceptual model logic, the verification is done by means of verification runs. The verification runs are done in separate submodels in the simulation environment, without interrelationships to other components in the airport relief chain. The submodels are assigned an individual seed to remain reproducible, the base seed for the Simio simulation environment.

The model verification runs are mostly meant to provide proof for the model performance of the airbridge and the working connection into the airport models. These airport models are based on a verified model build by Feil (2018), meaning the process of prioritization and loading into the aircraft at the airbridge had to be verified. The performance of these components was as conceptualized, with the exception of airbridge time distribution. The time schedule for a generic day of the disaster relief process could be found in the work of Arend (2018, December 19), but was neglected as the arrival into the regional airport was on a different level of detail. The connection between the airports was in the model implemented with the same accuracy as the arrival into the regional airport instead.

A full verification of the airport relief chain model is hard to perform within the given time frame for the master thesis, leaving a lot to be desired. What has been done aside from the verification runs with the intent to show conceptualization correctness is degeneracy testing, and continuity testing. The degeneracy testing provided several limitations to the model, two of those being in the number of workers. If no workers show up the model will stall, similarly to a reduction in the airbridge capacity to zero. The last value at which the system would collapse is a 100 percent no show value for the workers. The latter collapse would be seen only at the local airport, keeping the remainder of the airport relief chain system intact. As such it can be concluded that the system requires mandatory non-zero values for airbridge capacity and above 7 and above 2 values for the unloading workers and the warehouse workers respectively.

The other end of the spectrum also yielded system requirements, with values not being allowed to approach infinity. These parameters include the unloading time, the aircraft capacity, and the various processing times throughout the system. Contrary to the parameters not being allowed to be below a set value, these parameters do not completely disrupt the processes after the failing process. For all parameters not allowed to approach infinity the processing becomes really slow, except the aircraft capacity. For the aircraft capacity the resilience of the aircraft arrival plummets, yet does not directly affect the remainder of the system, which performs similar to the maximum of the tested policy.

The continuity of the system comparing the input to the output was successfully performed by all parameters that did not show an unequal relationship to the relief items, and were not the arriving aircraft. The change in the processes which required more than one resource to operate provided large change in system performance for a small change in quantity. This is in line with the sensitivity analysis of the unloading workers. The inverse can be seen in the time at which for example trucks would arrive. The trucks require multiple entities of relief aid to operate, with a small change in the truck arrival or truck capacity providing a smaller influence on the system.

9.2 Validation method selection

The validation of the simulation model is an extensive and time consuming process, which is limited by the time frame of this research and the availability of data. Sargent (2010) described the validation process as "too costly and time consuming to determine that a model is absolutely valid over the complete domain of its intended applicability". Instead test and evaluations can be conducted until sufficient confidence is obtained that the model is valid for its intended purposes (Sargent, 2010). In this section process of selecting and omitting validation test is explained. For each of the validity tests a brief explanation for inclusion or omission can be found in appendix D.

The validation tests considered come from the work of Sargent (2010), whom made an overview of validation techniques from the findings of a simulation conference. The overview included the validation techniques in table 23. The first column is the name of the technique, while the last column clarifies the technique, by providing an explanation. These explanations are based on the work of Sargent (2010) as well.

name	explanation
Animation	The model's operational behaviour is displayed graphically as the model moves through time
Comparison to other models	various results of the simulation model being validated are compared to results of other (valid) models
Degenerate tests	The degeneracy of the models behavior is tested by appropriate selection of values of the input and internal parameters
Event validity	The event occurrences of the simulation model are compared to those of the real system to determine if they are similar
Extreme condition tests	The model structure and outputs should be plausible for any extreme and unlikely combination of levels of factors in the system
Face validity	Individuals knowledgeable about the system are asked whether the model and/or its behavior are reasonable
Historical data validation	If historical data exist, part of the data is used to build the model and the remaining data is/are used to determine whether the model behaves as the system does
Historical methods	The three historical methods of validation are rationalism, empiricism and positive economics
Internal validity	several replications of a stochastic model are made to determine the amount of internal stochastic variability in the model
Multistage validation	historical methods, but with interrelations and back-checking throughout the modelling of the system
Operational graphics	Values of various performance measures are shown graphically through time
Sensitivity analysis	This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behavior or output
Predictive validation	The system behaviour is compared to the model's forecast to determine if they are the same
Traces	The behaviors of different types of specific entities in the model are traced through the model to determine if the model's logic is correct and if the neccessary accuracy is obtained
Turing tests	Individuals who are knowledgeable about the operations of the system being modeled are asked if they can discriminate between the system and the model outputs

Table 23: Validation techniques from the work of Sargent (2010)

The selection of a validation technique was done in several rounds, for which several techniques were dropped after each round. The first round filtered on the possibility to perform the test, with hard to perform and impossible to perform tests not making the cut. The tests dropping in this round are Degenerate tests, Extreme condition tests, historical data validation, multistage validation, predictive validation and Turing tests.

The second selection round was based on the usefulness in model building, versus the usefulness for the finished product. The techniques historical methods, operational graphics and traces were partly used through the model building phase, but mostly to ensure the correct translation from concept model to the simulation model. The focus on finished product validation was done, while various validation techniques were already partly used through the model building phase and done by Feil (2018) in the creation of the airport models which the airport relief chain model is based on.

The last selection criterion is the expected added value the validation technique would provide. The event validation technique would provide little additional value to the testing of policies on the bottlenecks. The events were both scarce and not all events could be found to their fullest extent. As such this method was omitted. The internal validity was regarded as of less added value, while the structure of the airport itself should be internally valid based on the work of Feil (2018), leaving only the airbridge to be internally validated.

For further validation of the model the selection process should be worked backwards, with the last eliminated methods being the first to add to the performed validation techniques. The internal validation test would likely be the test the airport relief chain would benefit from the most, considering the omitted validation techniques.

9.3 Animation

The animation validation test was initially regarded as useful for the model building, yet disregarded by means of the second round selection criterion. This was until the use of animation proved useful to review the behaviour of the airbridge, and most importantly, the difference in behaviour with the conceptualization of the airbridge. Under normal circumstance, aircraft had to be connected at the gate, meaning a gate would only be able to serve either aircraft arrival of departure at the time. An incoming flight would reserve the dock, blocking the use of the dock for airbridge operations. The same aircraft could then be used for the airbridge operations.

The simulation model is not directly in line with the real world system, while the gates were not modelled to be mutually exclusive. The defence for this approach is the scheduling of the airbridge flights. The schedule provided by Arend (2018, December 19) showed night flights for the airbridge operations. The handling of aircraft at the regional airport is done for a day schedule, meaning the first possible airbridge operation would be the night after the arrival of the relief items. The aircraft for the handling at the regional airport would be mostly handled before the night operations begin.

It is important to note here that even though the structure was simplified with respect to the mutually exclusive assumption, the model does operate even when gates serve double usage. As such the model is not entirely valid on the airbridge structure. The policy impact on the arrival process or the airbridge process might have a correlation because of this simplification.

9.4 face validation

For the expert validation two experts provided their expert knowledge, both from fields that were represented in this research. The experts were asked to review the process description of the conceptualization and to criticize assumptions made in the model building phase. The experts are knowledgeable in cargo logistics and freight, warehouse processes. These two perspectives provide a lens through which the conceptual model and the behaviour of the system were measured. The validation interviews can be found in appendices F and G.

The conceptualization was deemed correctly, though it is a strong assumption to dismiss the appearance of aftershocks in the system. In this research the only way this dismissal is compensated for is by stacking the relief aid at the local airport. This is done for the uncertainty of availability at the local airport of the resources. In case an aftershock appears, the system would have at least accumulated a buffer stock, when the relief aid is stacked in the local airport as well.

The bottlenecks found in the system aligned with what was expected, which was even staved by the view on the prioritization policies. Prioritization in early stages of relief aid delivery are strongly determinant for the airport relief chain performance. This is even more stressing when non-governmental organizations are involved. The prioritization is therefore one of the preferred policies for which insight into the delivery throughout the chain should be provided. The relief items are desired to be of more homogeneous mixtures for the handling of relief aid.

9.5 Sensitivity analysis

The experiments for the airport relief chain differ on three parameters, which can have significant impact on the outcomes of the policy testing. In order to see the impact of these parameters on the policies, a sensitivity analysis is performed. This sensitivity analysis is done for the Baseline scenario, with change to the BaselineAggressive scenario for the arrival rate. Firstly the parameters of interest are presented in table ... with the variation expressions. These are followed by the conclusions of the sensitivity analysis per parameter.

parameter of interest	variables of interest
Arrival rate	SulawesiDisaster arrival schedule, AggressiveApproach arrival schedule
Warehouse workers and unloading workers	limitations on performance of warehouse and unloading workers
No show of workers	0, 15 and 30 percent no show in the system

Table 24: Sensitivity analysis parameters and the variables of interest

Arrival rate
The arrival rate is based on data on the airbridge for the Sulawesi disaster. The aircraft were uniform in type, yet varied between 10 and 18 metric tons of cargo. This uniform distribution however is based on the airbridge. The work of Veatch and Goentzel (2018) gives an indication that it might be better to have a significantly larger influx of aircraft in the early stages of the relief chain.

As such, two arrival schedules were tested. The first schedule, the Sulawesi case study scenario, was doubled for the aggressive arrival schedule as proposed by Veatch and Goentzel (2018). In the testing of arrival schedules it was found that when the influx of relief aid exceeded the capacity of the airside docks at aircraft arrival, the system would be influenced only marginally. Given the influx of relief aid as one of the main reasons for the research, it was assumed that the influx would push the airport to near maximum performance.

Any decrease in the arrival schedule or the size of the incoming cargo in general creates better system performance as the bottlenecks would logically be less constrained, even when considered smaller numbers of cargo over time. Proof of this can not only be found in appendix C, but also in the last paragraph of the results section, in which the cargo delivery would decrease over time from a lower setting for the cargo demand.

Warehouse workers and unloading workers
The airport relief chain system showed the increase in deployed personnel to be one of the most effective measures to alleviate the bottlenecks. The increase in workers also showed a large increase in the airport relief chain system. The system as such is quite dependent on the deployed personnel. What is even more interesting however, is the relation between the workers and the processes.

The unloading workers only influence the system in pairs of eight, with any deviation leading to nonperformance from the residual workers. The inherited model of Feil (2018) provides a relation between an aircraft arrival and eight unloading workers, based on expert validation. This could be changed to six workers based on new expert insights from appendix F, yet would create the same performance and dependence on just a different number of workers. For the unloading processes, the workers in relationship to the aircraft unloading should be maintained, for the system to perform.

The warehouse workers have a similar relationship to the processes, with most processes demanding two specialist workers to perform the task. This significantly smaller number combined with the forklift loading process only demanding a single worker does warrant more variation in the number of warehouse workers. It goes to show that any uneven number of warehouse workers would result in a dedicated worker at the forklift loading process, as it would never participate in a process requiring two workers.

No show of workers
In the work of Feil (2018) two parameters were selected for variation in the scenario analysis. The first one is the no show workers, which is a dichotomous variable, set at either zero percent or thirty percent. These are included in this study as well, as changes in the relief chain on these variables could have far reaching implications previously unexplored in the work of Feil (2018).

The no show of workers affects only the local airport, which is aided by the mediated provision of supplies at the regional airport and the low capacity of the airbridge component in the system. The no show of workers was tested with the most promising policies found in this research active, considering a smaller demand for the item types.

The sensitivity analysis yielded that the airport relief chain system is only sensitive to the decrease in the unloading workers, with the impact being visible at any multiplicity of 8, with all workers left not forming a total of eight will remain idle. The cargo processing with warehouse workers is of no concern with a decrease by one team for the unloading workers.

9.6 Comparison to other models

The airport relief chain model was compared to both the practice-based model of Gralla and Goentzel (2018) and the resilience model of Feil (2018). These two models were found to have the closest resemblance to the airport relief chain model in terms of policies, structure and outcomes. The model of Feil (2018) was an obvious choice as the resilience model was the basis for the structure of the regional and local airport models from the airport relief chain model. The reason to incorporate the model of Gralla and Goentzel (2018) on the other hand was included to incorporate the larger system perspective. The network set-up for the practice-based heuristics for humanitarian transportation planning was from a hub node through in between nodes transporting the relief items to the demand nodes. This structure resembles the system with the regional airport representing a hub node, using in between nodes in the storage locations to supply the local airport and lastly the demand nodes in the HSA's.

9.6.1 Comparison to the model of Gralla and Goentzel

The network model was used to have experts from the field schedule the delivery of relief items. In this process a set of policies and scenarios were identified. The policies could be divided in the policies regarding item prioritization and destination prioritization and lastly short, which is closest to what the Baseline is in the airport relief chain model.

The policies iP-1, iP-2, dP-1 and dP-2 resemble to some extent the policies from the network model of Gralla and Goentzel (2018), but do so mostly under one of the scenarios. The combinations of the scenarios and the policies are explained in appendix C, in which a variety of conclusions were made. The most important conclusions are that the outcomes of the policies are in line with the expected shape, but are sensitive to the size of the demand and the in between distances between alternatives. The short distances of the alternatives in the airport relief chain make the policies more resembling to one another, while differentiating less in utility.

The positive conclusion that could be drawn from this is that the policies have basis in a scientific study in relation with experts from the field, and that the policies show similarity in shape of performance. The actual size and values do not align too well, which makes the model only valid to the extent that the analyzed performance measures follow the expected shape for the timely delivery measures.

9.6.2 Comparison to the model of Feil

The work of Feil (2018) was in large part the basis of the airports in the airport relief chain model, which should behave similarly. The differences however are mainly on the parametrization, and the bottleneck occurrence within the system as spill over from the airbridge. The comparison to the Feil model aimed at utilizing the same arrival schedules, analyzing the same system parameters, but in the airport relief chain system. Slight changes, such as the arrival gate availability following the day work schedule can be tested for.

It is further used to compare the systems, considering the internal validity of the model of Feil (2018). The changes made to the airport relief chain system are in the addition of storage and omission of the customs. For the additional workers, no show is disregarded, while additional workers would logically be at full strength. These changes did not change the behaviour of the system.

When utilizing the same arrival schedule the only difference between the replications performed in the airport model, versus the replications in the airport relief chain model is slight change in personnel allocation at the regional airport processes. This relates a decrease in performance in the airport relief chain system. The shape of the warehouse processes remains of similar direction, but shows more volatile behaviour after the arrival of additional workers at day 11. As such there is slight difference in performance and the airport relief chain system is a bit more sensitive for the regional airport processes.

The change made to the system was the increase in replications for the experiments. In the airport model 20 replications for the 8 experiments were sufficient. In the airport relief chain system a similar or larger number of experiments were performed with 30 replications. This is an attempt to compensate for the change in sensitivity in the regional airport processes.

10 Conclusions

This section presents the conclusions on the alleviation of bottlenecks in the airport relief chain system. The findings from the research are presented first, followed by the societal relevance and contributions to humanitarian aid. Lastly a few propositions for future research are provided, which would provide more relevance in the field.

10.1 Insights gained from the research questions

The research questions consist of the main research question and four subquestions. The questions will be discussed in order of the subquestions followed by the main research question as aggregation of the subquestions.

MQ: How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief chain system, considering both the airport operations and network design?

1. SQ1: How can the prioritization of relief aid and the airport system network design be conceptualized?
2. SQ2: How can the performance of an airport relief system be evaluated?
3. SQ3: How can the airport relief chain system be modelled in discrete event simulation?
4. SQ4: What policies could decrease the impact of bottlenecks on the airport relief chain system?

Subquestion 1, How can the prioritization of relief aid and the airport system network design be conceptualized?

The airport system network was conceptualized by means of a process description in IDEF0, a process chain divided in four main activities throughout the chain for the purposeful delivery of relief aid. These activities describe the model logic and the routing of the relief aid. In order to finalize the conceptualization of the network, the system components were modelled in a class diagram and UML model. These components embedded with the activities form together the airport system network design.

The process model en class diagrams together answer part of the subquestion, but do not fully answer how prioritization of relief aid can be formalized. This process was done according to the cluster model of the UN and the response plan of October to December for the Sulawesi disaster. The division of the relief aid in priority levels considers four types of relief aid, namely medicine (health), hygiene (wash), food and shelter. These four relief types are discerned into various priorities, with medicine in the Sulawesi disaster as the most stressing form of relief aid.

The models together with the prioritization rules are the basis for subquestion 3, in which the conceptual models with all decision rules are implemented in a simulation tool. The conceptualization of the system is not fully finished, however, as the performance measures have not been described yet. This is done first in the second subquestion.

Subquestion 2, How can the performance of an airport relief system be evaluated?

The airport relief chain system can be conceptualized with the answers of subquestion 1, to analyse the delivery and bottlenecks in the delivery of relief aid. The performance of the system considering these bottlenecks is evaluated on two types of key performance indicators (KPI's). The fist set of KPI's is called the timely delivery which is the measurement of the performance for the airport relief chain in it's entirety. This is measured by the total output of the relief aid of the system and the share of priority relief aid delivered.

The timely delivery measures do not provide insight in solving the bottlenecks, for which resilience as KPI is used. The resilience consists of processed cargo, idle cargo en throughput time, which provide three viewpoints on the performance of system components to analyze the occurrence of bottlenecks in the system.

The performance of the system after evaluation of the resilience metrics can improve the timely delivery, if no other bottlenecks hinder the system. The answer to the subquestion is the combination of timely delivery and resilience measures. These two together provide total system performance and system trade-offs, while resilience provides insight in the occurrence of bottlenecks, which would be overlooked in the total system performance through timely delivery.

Subquestion 3, How can the airport relief chain system be modelled in discrete event simulation?

The airport relief chain system modelled in a discrete event simulation tool represents the Sulawesi case study in which a connection is made between Sepinggan airport on Balikpapan and Mutiara airport on the island of Sulawesi. The parametrization is based on the literature from the organizations reporting to reliefweb and information provided by experts. The case study is described in section 3.3.

The modelling of the airport relief chain system combines adequate detail from the airbridge, and extents this detail through the airport systems. The model building starts from the activity representation in IDEF0 format, for which in the implementation phase modelling choices are made to represent the activities.

For the activities, the required objects are modelled through the Unified Modelling Language, in which the relationships are represented. The combination of the two modelling techniques shape the outline of the model, which should be combined with a simulation tool in which queues and capacity shortages can be modelled.

Subquestion 4, What policies could decrease the impact of bottlenecks on the airport relief chain system?

In order to assess the policy influence on the bottlenecks in the airport relief chain the bottlenecks have to first be identified. The bottlenecks found in the airport relief chain model are the aircraft arrival, regional airport processes and the airbridge aircraft loading. These three bottlenecks were found to influence each other by means of spillover effects.

The policies as described in chapter six are divided in strategic policy and operational policy. The strategic policies change the system and are difficult to change in a short period of time. The operational policies can be implemented by on-site personnel with short term changes to the system. In the airport relief chain two main strategic policies are tested, the adoption of off-airport warehouses and the addition of gates for the processing of international relief aid. The off-airport warehouses policy is divided into two with separate prioritization rules for the cargo routing, namely priority destinations nearby (dP-1) and limited capacity (dP-2). The additional gates alternate from the baseline scenario by assigning only 4 or 5 gates.

The operational policies can be separated into two main operational policies. These are the Item prioritization and the deployment of additional staff. The item priority policy has two options, 1) the prioritization on relief aid, considering the most stressing relief aid demand (iP-1), and 2) the smallest quantity of demand items first (iP-2). The additional workers policy has two options as well, 1) assigning 16 new warehouse workers and, 2) assigning 32 new warehouse workers. These policies could be shifted in short periods of time since they are operational policies, yet were like the strategic policies considered as decisions at the on-set of the disaster to create coherent and transparent policy, with the same decision period for both levels of policy.

The strategic policies providing the most reduction in the impact of bottlenecks were policies dP-2 and the 4 gates system. These both improve the arrival of aircraft, reducing the bottleneck. They also reduce the bottleneck at the airbridge and the regional airport operations, respectively.

The operational policy providing the most reduction for the bottlenecks in the airport relief chain system was the policy with 32 additional warehouse workers additionally, resolving the regional airport processes bottleneck in comparison to the less effective version with 16 additional workers. The iP-2 policy could be effective as well, in future work with a longer response period.

Main question: How can prioritization of relief aid decrease the impact of bottlenecks on an airport relief chain system, considering both the airport operations and network design?

The prioritization of relief aid in the airport relief chain system can improve the airport relief chain system, by reducing the bottlenecks in both the aircraft arrival and the airbridge aircraft loading. The most promising form of prioritization was the destination prioritization, in which intermediate storage was adopted. The use of prioritization is generally less effective in improving total delivery throughout the airport relief chain system, but provides far more specific delivery. Hence, it could be well worth considering changing the network design to incorporate intermediate storage of relief aid.

The prioritization of relief aid as a stand alone policy does not prove to be effective enough to provide significant increase in delivery, and only small increase in the resilience of the airport relief chain system. In order to improve both resilience and delivery of relief items, two other policies showed promising results. These policies are the addition of personnel and the utilization of smaller numbers of gates.

Especially the increase in the workforce could decrease the size and impact of bottlenecks, with capacity being the main factor of constraint at the arrival process and the regional airport processes. The addition of personnel can be sufficient in resolving the regional airport processes bottleneck entirely, and do the same for the arrival process if sufficient gates are available. The combination of destination prioritization, with a focus on routing lower demand goods through off-airport storage, and the deployment of more skilled workers should be sufficient to improve flow through the regional airport.

The combination of destination prioritization with additional personnel has similar effect to the scaling of the gates for the arrival of relief aid at the regional airport with similar numbers of personnel. An ideal smaller number of gates, readying more dedicated gates and personnel for the airbridge is better than sharing capacity at the regional airport for the arrival process and the airbridge. Assigning dedicated gates and personnel to the airbridge together with additional workers would require less investment and would provide similar or better delivery, which is more of a mixture.

The significant difference between the policies is the prioritization and the effect of such policy on the delivery of specific relief items. If the demand for specific items is larger, or the capacity at the airbridge is most constrained, the policy combination with destination prioritization should be preferred. It provides both an increase in priority relief items delivered and functions as a buffer for the airbridge, alleviating the gates.

In the Sulawesi disaster or similar disasters with a small capacity of gates at the local airport, this constraint of the airbridge was observed. The airport relief chain system performs at the maximum extent given the airbridge capacity, when the proposed policies are implemented. Other improvements would likely be absolved in the bottleneck at the airbridge, and would require network design changes at the local airport to reduce this bottleneck. Such a strategic policy is hard to accomplish given the often poor state of the local airport after disaster.

The airbridge and the ability of the local airport to accept more relief items is determinant of the required workforce at the local airport. A decrease in the number of personnel does not negatively influence the local airport system, if the number of unloading workers is sufficient. The warehouse workers were non-determinant for the performance of the local airport is their number is not significantly smaller than the number of unloading workers.

10.2 Limitations

The research considering the airport relief chain was inherently subject to various assumptions and simplifications which lead to limitations in the power of the model to explain the real world system. These limitations have to be considered with the conclusions before the advised policies can truly be valued on their applicability in similar systems. Part of the limitations further come from the ability of the system to focus on the tested scenario's more so than on general systems. For different scenarios the outcomes are likely to differ, which has to be considered as well.

The system is created to analyze some form of prioritization in both relief items and the routing of the relief items. For both instances only first and to some extent second level prioritization is tested. It does not function for full priority chains in the prioritization policies. The logic connecting larger chains grows significantly in complexity, which could be researched in a time window which was unavailable within the scope of this research.

Aside from the limitation in prioritization, the system is severely influenced by the influx into the system. The relief aid demand satisfaction is dictated by the airbridge, yet the size of the bottlenecks is mainly dictated by the influx in the regional airport. Different arrival schedules require different levels of policy to make the regional system performance more resilient, while the total chain performance remains similar in behaviour and numbers.

The policies have limitations in the extent to which the real world system can be represented by the policies. The behaviour of the policies on the other hand is a lot more stable throughout the sensitivity analysis. Those are on the other hand only tested as action before influx, which is than applied throughout the entire handling of the disaster. The lack of adaptive policy is one of the strongly recommended additions in future work, whereas the behaviour of the system shows strong theory of constraints behaviour. It would be more ideal to perform the first policy and later apply a variety of policy options whenever a constraint appears. This is to some extent cheated as the combined policy immediately repairs the new to be found bottleneck, before the actual appearance.

The policies all showed unfulfilled recovery, except for the additional workers policy. The policies did, however improve the system creating an uncertainty as to how effective the policies could be. The item priority policies would likely improve more when truly uniform flow occurs in the system requiring a longer time frame for the system performance evaluation.

The role of the National Disaster Management agency (NDMA) is neglected, with experts dedicating a large share of the prioritization policy implementation to this critical actor in the system. Any implementation of especially item prioritization would best be done in relation with the present NDMA.

The last limitation found is inherent to the use of a case study. The Sulawesi disaster case study provides a relevance, but also a narrow scope for the use of the models. The more generic case at the end of the results section is an attempt to provide some broader relevance, yet the model would require different parametrization to be of relevance to other disasters. In the current form the policies cannot without clear consideration of the narrower scope of the case study be applied to other airbridge systems.

10.3 Scientific contributions

The last airmile research aimed at assessing the impact of policies on bottlenecks in the airport relief chain system. The policies were considered on both the strategic and operational level, after the constraints in the airbridge were identified. This focus came from the literature review of section 2, in which three main research gaps were found. The research gaps were addressed in the research, filling the void in literature. These knowledge gaps are:

(1) *The academic literature is lacking with regard to the influence of the airport resilience on the airport relief chain*

(2) *The literature on inventory management in the humanitarian logistics does not take into account the intermediate storage of supplies for on-time delivery*

(3) *The academic literature has mismatching scopes between airports and relief chain models, without clear interdependence, leaving the system-wide impact of bottlenecks understudied*

Each void filled is considered a scientific contribution. Aside from these independent contributions the research fills a specific position at the intersection of the three domains for which it contributes. The domains are resilience, with specifically the focus on last airmile networks, humanitarian logistics and lastly the airport and transportation modelling fields. The domain dependent scientific contributions are:

Proof of theoretic relationship between the resilience of the airport as an important node in the network, and the performance of the airport relief chain system
The airport network systems are often studied with little regard for the specific position of airports within the network system, as a hub and for the bundling and allocation of relief items. On the other hand airport models considering resilience are often microscopic models considering the airport as a standalone system, without evaluating the impact on the humanitarian supply chain. This research adds to the literature the connection between the resilience of the airport and the delivery of relief items through the humanitarian supply chain. When the resilience metrics are improved, the relief chain performance is improved as well, unless the improvements are hindered by the occurrence of bottlenecks. The identification and application of this connection is a scientific contribution.

Insight into the usefulness of the intermediate storage of relief items on the delivery from the humanitarian supply chain
The intermediate storage can provide moderate increase in delivery, but especially help with the bundling and selective delivery of relief items. The use of prioritization has been studied, but generally for the delivery of specified quantities to demand nodes. This delivery does only take into account route constraints when enforced on the network, or cost as goal of the optimization. The optimization of the flow of relief items could benefit from prioritization through intermediate storage, making an additional use of prioritization a first contribution to the literature. The use of intermediate storage as a policy option to reduce bottlenecks is a second contribution to the literature.

A new scope for the identification bottlenecks throughout the relief chain and the downstream influence of bottleneck reduction
The modelling of bottleneck identification and reduction is limited, especially in variation of scope. The detailed queuing models assessing the bottleneck occurrence tend to focus on a specific process even within the airport model, while network models lack detail and process delay outside the processes in the model. The contribution of this study is the connection of the airport model and the network models, setting a level of detail required to assess the bottlenecks which is consistent throughout the relief chain. In section 8.1 the relationship between process and bottleneck is identified for each of the identified processes from the conceptual model of section 4.1.

In the results a clear relation between bottleneck reduction and increase in other bottlenecks can be seen, which indicates the downstream impact of which could not be seen with the limited scope often applied for airport models in researching bottlenecks. This effect is in line with the theory of Goldratt (1990), which was already published in 1990. The scientific contribution of providing bottleneck identification and the influence of the identified bottlenecks on the relief chain system within the scope of a single model is a logical one, which makes it even more interesting that this is one of few examples filling this void.

The contribution to the intersection of the domains
Lastly this research is meant to fill the void at the intersection of the three domains which regards the connection between different scopes of models, while doing justice to the function of the airport within the network structure. This means the model implements a connecting scope, through which the impact of resilience and bottlenecks at the airports is studied for the airport relief chain system, in which two airports and an airbridge are modelled.

This approach herein is a first to connect airport and relief chain, with different levels of detail, into a single model. The policies can to this end also be implemented on different levels, with system design changes as strategic policies and behavioural changes as operational policies. This connection can provide a new interrelated point of view on disaster management and disaster handling. It is an initial attempt at rescoping problems to include multiple disciplines within the field of humanitarian aid.

10.4 Societal contributions

Aside from providing insight into technical solutions to deal with the influx of relief aid in the airport relief chain system, and contributing to the scientific literature, this research has to deliver a social contribution as well. This societal contribution would ideally help as much as possible with the grand challenge as was defined in the introduction. The size and occurrence of natural disasters is increasing, while delivery of relief items becomes increasingly hard through affected airports. The affected communities have long waiting times, being at risk longer than possibly necessary.

Especially provision of the most stressing relief items is critical for these affected communities, with lives on the line, dependent on the timely delivery of relief aid. The delivery however, is not only hindered by the damaged infrastructure, but also through uncontrolled influx of relief items in the airport. The allocation of less useful items and overstocked equipment is a problem in these disaster situations, with every humanitarian worker having their own share of war stories. This is regardless of the humanitarian relief chain utilizing a single disaster struck airport or an airbridge system.

this research aims at providing scientific support to the process of relief handling and allocation within airbridge systems by identifying bottlenecks and providing policies and policy combinations to improve the timely delivery of relief items. Similar research is available dealing with the situation for single airports, but the relief chain system has the added dynamic that prioritization could early on benefit the specific delivery of relief items. The more constrained the system is, the more effective the prioritization policies are at providing priority relief to the affected communities. The available personnel is critical in reaching the maximum performance within the boundaries of the system.

10.5 Future Research

During the conceptualization phase and the expert validation conversations a variety of study directions were found for future research. These were not included in this research given the limited time window and the difficulty to appropriately integrate some of these ideas for future research. The directions found are the role of the governments in prioritization, the dynamic policy adoption in the airport relief chain and lastly the idea of creating a digital twin to test the airport relief chain system.

The first study directions concerns the role of governments in the delivery of relief items, while the government can reduce the bottlenecks in the system by providing prioritization rules to all collaborating parties, before the problems occur. The role of the government as such could provide strict implementation for the prioritization of relief aid and the routing of the items. In this research the impact of unnecessary cargo from mostly non-governmental organizations has been left out and would be interesting to combine with the policies. The policies providing uniform flow through the system would likely perform better and the iP and dP policies have at the very least unresolved potential in such research.

The second study direction, dynamic policy adoption, could be studied as in this research it was found that bottlenecks have spill over effects, which is described by the theory of constraints. Whenever a policy resolves a bottleneck, another will pop-up holding back the positive impact the policy could have. In order to have a well performing system automated triggers should be found at which a new bottleneck would occur, so a layered policy combination could be implemented. In this research the graphs for the resilience metrics provide the on-shift moments of the new bottlenecks, yet those are case-sensitive and are not yet automated.

Lastly the digital twin idea could be studied. The model created for the Sulawesi case study is in essence closely resembling a digital twin of the real airbridge system which would make policy adoption more easily comparable. The use of the airport relief chain study with respect to a real world system which could be tested for hypothetical situations with a digital twin could be useful to fully measure the influence of the policies on the system.

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A Assumptions and parametrization

This section outlines the various assumptions made for the modelling of the airport relief chain, with regard to the relief chain itself as well as the airports. To this end this section is separated into the assumption for the airbridge system, Sepinggan airport and Mutiara airport. The last two also have overlapping assumptions which are listed as general airport assumptions. The parametrization is done in similar fashion moving down from the airbridge system to the detail of the airports. The parametrization directly represents the base case for the Sulawesi disaster and was essential in the evaluation of the results.

A.1 Airbridge system assumptions and parametrization

The assumptions listed in this section span outside the direct influence of the airports itself. Examples of such out of span feature are the cargo transportation to the airport, the overall external factors and the warehouse processes.

1. The inflow of cargo is arranged by DHL, as the only responsible party.
2. The cargo is split by the types of needs published by the Indonesian government.
3. The prioritization of goods is based on a ranking system.
4. The creation of cargo is always reliant on the cargo schedule implemented for the regional airport. Earliness and tardiness are completely neglected as part of the schedule.
5. The aircraft used for all transportation of cargo are Lockheed C-130s of the Hercules model. This aligns with the strict rules on aircraft uniformity of the Indonesian government.
6. Any constraints on the air transportation are left out if it does not directly involve cargo processes. I.g. weather, crowded airspace or wind.
7. The warehouse processes are simplified to match the airport processes without significant delay. The time is on activation basis.
8. Infrastructure breakdowns are not considered after the initial time step in the main model.
9. An aircraft is either meant for airbridge operations or not, a seperate flow of aircraft is connected to the airbridge.
10. All relief aid is seen as international relief aid, domestic relief aid is assumed in the experiments to vary availability.
11. The arrival of aircraft can not happen after the workers stop unloading, until the start of the next day at 12 p.m..
12. All aircraft operations for the airbridge happen at night.

Table 25: Airbridge system assumptions

Aside from the assumptions in table ... the arrival process was quantified, with regard to arrival schedule, cargo allocation per plane and other variables with close relation to the airbridge syste.

Variable	Parametrization	Source
Airbridge aircraft population	10 aircraft	Andersen and Semaan (2018d)
Daily flight schedule for the airbridge	8-10 flights	Andersen and Semaan (2018a, 2018b, 2018e)
Daily arrival of aircraft	¿10, 18 assumed	-
Ratio of relief types	kit selection with $[1 \leq i \leq 5]$	Nirody and Lacy-Hall (2018)
Level of relief aid	50.5 million dollar	Nirody and Lacy-Hall (2018)

Table 26: Parametrization of the arrival process

A.2 Airport assumptions and parametrization

The airports have many commonalities, especially regarding the various processes that have to happen. The capacity is the determining factor of the regional airport, which has to satisfy the demand for relief aid. The difference as such is mainly the gates and equipment, yet all other functions are comparable between the two airports. As such a few assumptions were made that count for both airports, more than for one in particular. In table ... the assumptions are listed. The parametrization is done independently for each airport as the airport models require case specific parametrization.

1. Marshal equipment are not included in the airport submodel.
2. Unloading resources are simplified to high loaders and workers.
3. Workers, both unloading and warehouse, are able to do any process within their cluster.
4. Workers can never change their type, they are either unloading or warehouse workers.
5. All airport processes such as unloading of an aircraft are the same for the local and regional airport.
6. Any gate can process at most one plane, even if creative parking is used.
7. The gates could overlap for the airbridge and arrival. It is avoided through time scheduling.

Table 27: General airport assumptions

A.3 Sepinggan

The regional airport, which in the case study called Sepinggan airport, requires a set of assumptions as well. The assumptions have to be met by any regional airport or exact measurements should be installed. The list below takes into consideration the regional airport of the case study. This airport has a set number of resources and specific parameters as well. The order of this subsection is to list the assumptions, before setting the parametrization.

1. Inter arrival times are scheduled according to available data and assumed rate tables. The focus is more on the airport processes than the arrival times.
2. Marshal operations are part of the unloading time, aircraft parking is seen as turnaround at an available gate for which the travelling time could be neglected.
3. The number of trucks available for transportation to warehouses is set to infinite.
4. The number of forklifts remains the same throughout a model run and require a fixed capacity.
5. Transport time for forklifts to the warehouse are an assumed minimal time, based on a 200 meter distance from gate to warehouse.
6. Aircraft loading is estimated at 1.15 times the unloading time, based on expertise on webfora as estimations vary and real numbers are lacking.
7. The amount of gates available to international aid is limited to at most 6 gates.
8. The incoming relief aid is assumed based on the reported weight per few days.
9. The warehouses have a maximum capacity, but are provided high capacity levels not to become over saturated.
10. Airbridge gate selection occurs solely on item priority.
11. The airbridge gates are supplied equally with aircraft, as creative parking would allow a maximum number of aircraft which would be reached with 10 aircraft per night.

Table 28: Sepinggan airport assumptions

The parametrization of the model used various sources such as the reports DHL, the report of OCHA and other reports of the situation in Indonesia. This was supplemented by the work of Feil (2018), whom had made the mesoscopic model on which the airport models are based, including various parameters. The values are therefore not at all times verified, yet are how the actors in the field assessed the situation. This makes the numbers even if somewhat incorrect the most trustworthy to use for parametrization. For the regional airport the arrival process, terminal operations and a connection to the warehouse operations are included. Lastly the airbridge parametrization is connected to Sepinggan airport for the connection of departure from the airport.

Aircraft arrival process

The parametrization of the aircraft arrival processes can be seen in table ....

Variable	Parametrization	Source
Cargo delivery from the airbridge	90-104 metric tonnes	Andersen and Semaan (2018c)
Total cargo to Sepinggan	rate table * U(10-18)	Arend (2018, December 19), assumption
Distance to gate	700 meter	assumption based on Feil (2018)
Worker population	24 workers	Andersen and Semaan (2018d), assumption
Workers needed for unloading	8 workers	Interview transcript of Feil (2018)
High lifter population	3 high lifters	assumption
High lifter needed for unloading	1 high lifter	Interview transcript of Feil (2018)
Unloading time	X $\sim \mathcal{N}(119, 66)$	Feil (2018)
Cargo per aircraft	8 cargo units	narrow body Feil (2018)

Table 29: Parametrization aircraft arrival at Sepinggan airport

After the arrival of cargo at the airport with the unloading process performed, the cargo has to be processed in the terminal area. This process is mostly in the field of the warehouse workers already with the warehouse workers responsible for the terminal operations and the warehouse operations. The terminal operations are bound by a small set of assumptions regarding the operations time. The model component was further simplified as result of the critical path analysis in appendix H.

Terminal and warehouse operations

Variable	Parametrization	Source
Forklift network	1 2 network(s)	Assumption
Unloading dolly	3 minutes	Schuppener (2016)
Cargo component breakdown	$\mathcal{U}$(10,30)	Interview transcript of Feil (2018)
Warehouse processing	3 - 9, scaling with distance	Based on assumption of Feil (2018)

Table 30: Parametrization of terminal and warehouse operations Sepinggan airport

A.4 Mutiara

The local airport, in the case study named Mutiara airport, is the receiving airport for relief aid. As such no filled aircraft have to leave the airport completely disregarding any loading time for the aircraft. This, together with the lack of intermediate warehousing, makes the model somewhat simpler. The assumptions for the general airport are as such mostly sufficient for the local airport. The most inherent changes to the regional airport requiring assumptions at the local airport regard the downtime of the airport. The constrained airport processes due to the disaster have a form of cool down period before airport operations can proceed similar to the regional airport. The assumptions are presented below in table....

1. The inflow of forklifts only happens at one moment within a model run.
2. The number of trucks can not change throughout a model run.
3. The constraints on outflow are either on or off, set to last six days.
4. All constrained gates have to maintain the cargo, no additional parking/storage space.

Table 31: Mutiara airport assumptions

Item priority value	high priority	medium priority	low priority
5	66,7	65,8	67,5
4	100	50,9	49,1
3	100	100	0
1	100	100	0

Table 32: Airbridge delivery verification

B verification

The verification of the airport relief chain model is done for the decision processes that impact the routing and the performance of the system most. These are controlled for by means of verification runs. Aside from these verification runs, similar method is used for completely out of scope input values for the parameters. These latter provide insight in the strengths and weaknesses of the simulation model to cope with out of bounds input and misuse of the model.

verification of the airport relief chain model
In this section the first three verification systems are meant to provide proof of correctly behaving system components. The fourth system represents the airport relief chain in its entirety, with the degeneracy tests. The degeneracy testing is performed only on the airport relief chain system as a whole. The last system is the airport model similar to that of Feil (2018), with the customs evaluated for the need to be included.

The process of airbridge dock selection
The airbridge dock selection aims at prioritizing the relief aid airbridge flight to leave as fast as possible with uniformity of cargo. This is done by selecting three levels for cargo uniformity. The decision rules behind the three levels differ based on the item priority setting, which represents prioritization policy. When the policies are turned of the general uniformity is undone, with even division among the three levels.

In the table below, table ..., the verification process of the various levels for the item prioritization are shown. Item priority one means all high priority demand is handled by the highest level and the rest is sent to the low priority, or if there would be level 2 and 3 priority items these would end up at medium priority. This is the case for any priority value than as tested below four, which also favours the priority relief aid, yet sends the other items in equal share to the remaining levels.

The verification test was performed with 100 priority one items, and 100 priority four items. These are divided among the above described decision rules, with close to the expected number of expected output to the levels in which probability occurs and exact throughput were necessary makes the process performed as expected.
Arrival and Breakdown process of cargo
The verification model inserts a distribution based on interarrival time, versus the arrival of aircraft demanding cargo through process based cargo creation. The latter has to perform exactly the same as the interarrival time, while the logic is the exact same. The only difference turned out to be caused by the slightly longer roads and minimal processing time of sending

cargo after arrival of the aircraft, which could mostly be solved by setting all logical lengths in the systems to zero.

The dolly unloading and breakdown process further verify the correct overlay of multiple workers in the same process. The breakdown process is dependent on two processes happening simultaneously for the system not to flood within a matter of hours. The fact that the systems remain stable means the processes are performed correctly.

Truck loading

The loading of trucks at the airport is a crucial part of the system for the prioritization processes. The flow through the airport without the additional warehouses was found to be satisfactory for the regional airport processes, including the utilization of the forklifts. The truck loading is regarded to take four minutes for the quantity of items, multiplied by three for the time a single item takes to load. The truck loading is behaving correctly, with twelve minute loading for the system utilizing the same logic as the truck loading.

Regional airport operations

The degeneracy tests analyze the influence of system components on the airport relief chain model. These components were regarded for mostly input related variables and internal parameters. The evaluated parameters are the aircraft capacity, unloading time, number of warehouse and unloading workers, no show of workers and lastly the airbridge capacity. These were all set to the specific extremes which should derail the simulation model.

The verification of the full model with specific focus of correctness of the regional airport processes up to the airbridge. The airbridge was found to be the lasting bottleneck, which would eventually dictate the throughput of relief items to the local airport. The verification consists of six runs with each run representing one of the tested parameters. The runs for the airbridge capacity of zero and the infinite aircraft capacity crash the model by overflowing the calculating boundaries. The others all make the system either fail or tediously slow.

Unimportant customs verification

The customs process is part of the resilience airport system of Feil (2018), which was implemented to make the model representative of the real world system. In the critical path analysis, the customs were not affecting the system, with the breakdown processes requiring significantly more time and diminishing the total impact of the customs process. In the verification model, the total influence of the customs in the system is insignificant.

C Selection of validation techniques

The validation techniques were defined in the work of Sargent (2010), whom provided both an extensive list and explanations of the techniques. The use of each and every one of these is impossible, for two possible reasons. The first reason is the time constraints this master thesis is subjected to. The second reason is the lack of proper experts or data. In the first instance in future work these validation tests could still be added, with the second instance making the test wholly impossible.

A short explanation of the decision to either include or exclude a validation test is presented below, with a header presenting an individual technique. In the end a few techniques were fitting for the research considering bottlenecks in the airport relief chain model. These were animation, comparison to other models, event validity, face validity, historical methods, internal validity, sensitivity analysis and traces. From this list a selection was made including those expected to provide the most additional value in the least amount of time. The selected validation techniques are animation, comparison to other models, face validity and sensitivity analysis.

Animation

The animation validation technique was used throughout the modelling process, up to the experimentation phase. The simulation tool called Visio, used for this research, has a clear and easy to use facility window. This facility window is used for the implementation of the conceptual model, but could be used for the animation, historical methods and traces validation techniques.

Comparison to other models

The comparison to other models as described in table ... is arguably difficult, as no clear counterpart model could be found. The results of other models as such would be ill suited to do a full comparison. A comparison in part however, made sense, considering the policies and the model itself have a strong basis in other models. The models suited for comparison were the models of Feil (2018); Gralla and Goentzel (2018). These are mostly compared on behaviour and expected shape of the outcomes.

Degenerate tests

The degenerate test for the appropriateness could be tested for the model input and internal parameters. The availability of data is of concern for this technique, while contrary to the verification version of this test, the degeneracy of the model for validation has to be compared to reasonable values for the system. The represented system, from the Sulawesi case study, was hard to quantify with respect to specific parameters. Examples of the hard to quantify parameters are the arrival schedule for aircraft at the regional airport, and the tonnage of relief items of a specific cluster. The lack of such detailed data makes it difficult to establish what would be "appropriate selection of values".

Event validity

Event validation is an easy technique to compare the real system to the simulation model. For the airport relief chain however, it was considered of little added value. given the limited number of verifiable events. The only events found for the Sulawesi disaster, were the disaster on the 28th of September, the arrival of voluntary personnel of DHL at the 6th of October and lastly the re-opening of the roads from Mutiara airport on the ... of October. The first and third event were implemented with date accuracy. the addition of the DHL workers is combined with possible addition of staff from other organizations. The DHL staff was explained in appendix E to have a supportive role, not to perform all operations.

Extreme condition tests

The model would have to present plausible behaviour for extreme values, which was seen as a currently unobtainable goal. The behaviour of the airport relief chain is difficult already in terms of uncertainty. The identification of what is plausible behaviour in the airport relief chain system would require a knowledgeable individual to define the boundaries of system behaviour. The inclusion of such individual would be time consuming before the test could be performed, assuming a clear definition of plausible behaviour could be defined by a knowledgeable individual.

Face validity
The face validation technique is a strong basis for research, as not only the assumptions can be verified, but the target audience can also provide insight and weight the impact of the assumptions. The face validation technique was a preferred validation technique, especially with the involvement of experts at the start of the research from the HNPW conference. For this technique two experts were interviewed, and the findings of experts from the work of Feil (2018) were taken into account for the airport relief chain model.

Historical data
The specificity of the case study provided additional societal relevance, at the expense of of historic data. The recent disaster had limited data availability, which could hardly be used for the historical data validation. The closest analysis that could be made is on the basis of the disaster response calculations from appendix D.2. An estimation of the quantity delivered could be found, but would require a translation for the share to total tonnage and lacks distinction between the clusters.

historical methods
Historical methods is a logical approach, which was seen as an essential part of the modelling approach. The validation of the processes on the other hand can only be qualitatively be validated, with an assessment of the processes and a clarification of the transition from the concept model to the simulation model. This is mostly described in sections four and five of the master thesis.

Internal validity
The internal variability would cost time and an analysis of the outcomes from the experiments. The only internal validity test done in this research was a short analysis of the minimal and maximum values of the resilience metrics. The reason to do so is the lack of time to do all techniques for validation, while in the model of Feil (2018) the internal validity was tested. With the comparison between the airport relief chain model and the model of Feil (2018), the internal validity would be covered as much as possible without performing the validity test.

Multistage validation
this technique is an expansion of the historical methods, considering the input-output relations of the real system. The latter is a difficult to prove, while data on output quantification was scarce. The validation technique as such is not doable.

Operational graphics
The validation using operational graphics was done throughout the modelling, to review the model performance during the implementation. The inclusion was disregarded, as the key performance indicators were only taken into account for the total throughput. Including the resilience metrics for the individual components in the system would be time consuming and would be represented for individual runs. This would require to compensate for outliers.

Sensitivity analysis
The variation in output from change in input and internal parameters is part of the uncertainty of the model, while most parameters were based on either assumptions, or related standards. This uncertainty was already reviewed in the airport model of Feil (2018), but with the changes to the system structure and the connection of the airbridge provide additional parameters that could change the system behaviour. The assumptions such as the arrival, and the influence of workers in the system might change the system significantly. Especially given the larger impact of the resource related policies over prioritization, the sensitivity for these policies is subject to possible unrealistic sensitivity. The validity test as such is meant to make the policies and their influence on the system believable.

Predictive validation
The model was used to assess the occurrence of bottlenecks and policies to counteract these bottlenecks. The domain has to be valid is difficult to test in real world scenarios. In order to do predictive validation, data on policy implementation and more detailed data about the case study is required. A second option would be to change the model input and parameters to a known case study, for which policies were implemented and data is available. It is difficult however, as each case study is different.

The predictive validation technique was left out as it is simply too time consuming, lacks data and would require a form of real world application. The latter is very difficult to achieve, because it would require either collaboration shortly after the disaster from the NDMA (National Disaster Management Agency) and the airport authorities, or data gathering by the same actors.

Traces
The validation of the model through traces is done in part, to validate the implementation during the transition phase from concept model to simulation model. This was done for the various relief items and the aircraft in the system. The traces are remaining in the system, but the use of traces was done selectively to improve on the model building exercise. In order to validate the simulation model by means of the traces technique, statistical tests are required, which would simply be too time consuming to do properly. It would furthermore validate the routing of the entities, only validating for the prioritization policies, while with the animation validation technique a similar domain was analyzed.

Turing tests
The validation through Turing tests requires specialized experts to be aligned to the research, a luxury which was not enjoyed for this research. A few experts were interested and willing to help, such as with the face validation. This is less specific than the experts required for Turing tests. The experts from the face validation helped by providing insight, presenting on ground information and experiences. To do a Turing test they have to be able to discriminate the on-sight performance and output in the disaster region, which is often chaotic and reliable information is difficult to discern. It would be a long shot to ask from an expert to do so for the entire system.

It would be an improvement however, if experts could discern subsystem performance from the system. This would still need specialized on-side experts, but would be more approachable to start with. The inclusion of the Turing test was deemed too difficult and time consuming for this iteration of the research.

D Sensitivity analysis

D.1 Workers

The workers for the airport relief chain system are part of all the bottlenecks in the system, which can either be caused by physical limitations or lack of workers. In table ... below the number of workers is reviewed for the impact on the system considering the alternation for the warehouse workers to find the optimal point at the regional warehouse processes. The unloading workers are in this process maximized, whereas the unloading processes tend to always be a bottleneck and creative parking actually improves the system without generally be possible after a certain extent.

The starting value for the number of workers has little impact on the eventual performance with double that number providing similar results. The best setting for the workers is actually in most cases the equal 16-16 setting, with 16 warehouse workers at the disaster and an additional 16 after a period of nine days. It mostly comes from a more even flow with higher values for the warehouse storage, while the other system components improve in performance.

Number of workers and additional workers	Subsystem	Processed cargo	Idle cargo	Throughput time
24-48, 8-32	Aircraft arrival	48,7	228	46,2
	Regional airport operations	30,9	321	38,6
	Warehouse storage	30,6	46	199,6
	Local airport handling	2,1	1049	199,6
24-48, 16-16	Aircraft arrival	48,0	347	50,5
	Regional airport operations	28,6	182	37,0
	Warehouse storage	28,2	182	146,6
	Local airport handling	2,0	970	196,1
24-48, 16-32	Aircraft arrival	48,8	355	51,2
	Regional airport operations	30,8	38	36,0
	Warehouse storage	30,4	46	149,3
	Local airport handling	2,0	1102	196,7

Table 33: Resilience metric values for the variation in unloading and warehouse workers with significant variation in the settings for the warehouse workers

D.2 No Show workers

The workers initially expected to service the local airport in the airport relief chain system is lower than the number of workers usually servicing the airport. The reasons could vary from blocked access to injuries. In the work of Feil (2018) this is addressed by reducing the number of workers by a share of the no show. This is inherited in the airport relief chain model, but only implemented for the local airport. The regional airport should be able to provide the full extent of their workforce, or deploy assets from other airports in a short period of time.

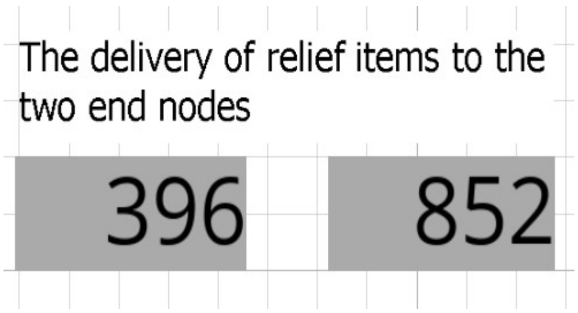

Figure 35: 15 percent no show

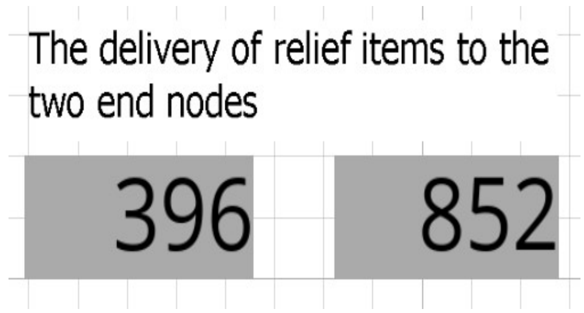

Figure 36: 30 percent no show

Generally the capacity at the regional airport is constrained by physical components and the workforce specialized enough to fully operate the equipment necessary to unload and load aircraft and transport relief aid. The sensitivity analysis for the no show of workers is meant to present the difference between first the impact of significant number of absent workers for both the promising policies, before showing the implications of the assumption a minimal number of workers is required.

The assumption stating a minimal and absolute number of workers is necessary at the start of the process makes the airport relief chain model highly dependent on specific numbers of workers. The difference for the unloading is any multiplication of 8, keeping it significantly simple. The warehouse operations are for the most part reliant on a factor 2 for the required personnel, with the only exception being the loading of the forklifts, which should be unconstrained for the most part. Any change in the number of warehouse workers could/should impact the system, unless little to no duress was observed in the warehouse operations at the local airport.

The proof of this small amount of duress is provided in two ways, and can be seen for small quantities of relief aid and independent of additional workers. The values remain the same for both the 15 percent and 30 percent worker no show. The first way this is shown in the model is a direct comparison of the number of relief items the airport relief chain outputs. The second is a comparison of the table values for both arrival schedules for the respective percentages no show.
The table shows in the upper section slight differences, but mainly on rounding values, with no more than a single digit difference between the different no show settings. A such no more than a very few minor queues could have occurred in the local airport, for either one of the two aircraft arrival schedules. This provides a proof based on the airport relief chain model,

Base case arrival schedule							
15	Aircraft arrival	39,7	34,6	150	505	40,7	59,7
	Regional airport operations	25,3	21,7	522	185	25,7	38,5
	Warehouse storage	25,2	21,6	46	32	80,8	130,1
	Local airport handling	2,0	2,2	837	603	191,7	204,5
30	Aircraft arrival	39,7	34,6	150	504	40,7	59,7
	Regional airport operations	25,3	21,8	523	185	25,7	38,5
	Warehouse storage	25,2	21,6	46	32	80,8	130,0
	Local airport handling	2,0	2,2	837	604	191,7	203,9
Aggressive arrival schedule							
15	Aircraft arrival	39,8	35,3	554	942	57,9	78,4
	Regional airport operations	25,4	22,2	645	198	25,9	38,9
	Warehouse storage	25,3	22,0	47	33	91,1	134,9
	Local airport handling	1,9	2,2	846	626	187,4	203,8
30	Aircraft arrival	39,8	35,3	554	942	57,9	78,4
	Regional airport operations	25,4	22,2	645	198	25,9	38,9
	Warehouse storage	25,3	22,0	47	33	91,1	134,9
	Local airport handling	1,9	2,2	846	626	187,4	203,8

Table 34: The comparison between 15 and 30 percent no show

that the model is effected solely by the unloading workers, with the no show of workers having to cross a represented value of 8 to diminish the performance further.

In the airport relief chain model, this is represented as three levels at which the system can perform. The values are 0, 33 and 66 percent. With any no show higher than two third of the total, the system would stop the local airport completely from processing relief items.

D.3 comparison to other models on behaviour

The actual quantification of a similar airport relief chain could not be found, making a full cross-validation difficult, but comparisons were still possible. The relief item distribution based on prioritization could be found in network systems, presenting a possibly similar case which could be used to validate the behaviour based on the output of the similar system.

The policies the airport relief chain system was subjected to are based partly on the work of Gralla and Goentzel (2018), and partly on the work of Feil (2018). The first of the two works followed a set of combinations between the priority rules and the scenarios. The policies attempted in the airport relief chain model are short, item-wtd and dest-wtd. The short policy is the base policy implemented whenever the values for iP and dP in the model are set to the base values at 5 and 3 respectively. The cargo will always prefer the shortest route and deliver and equal share of all relief items.

D.3.1 Item-wtd with the iP scenarios

The implementation of item-wtd is only reliant on the iP value in the model, with the options 1 and 4 as assigned for the simulation model. These are for the airport relief chain model connected to possible scenarios, as the policies themselves in the work of Gralla and Goentzel (2018) regard a full network, not a chain. The scenarios however, can be regarded mostly for a network and a chain. This difference proved to be possible connection point to find a scientific basis in the policies studied in this research.

More iP-1 items
The iP-1 policy behaves like item-wtd, providing a faster and more frequent route through the relief chain for priority items. The items of lower priority do flow through the system, but are regarded as in the more iP-1 items scenario. This scenario accounts a mixture of 70 percent iP-1 items, 10 percent for the iP-2, iP-3 and iP-4 items. Such scenario with the provided policy already shared a clear correlation, forcing a certain direction on the relief aid flow. The performance of the item-wtd policies tend to be the same as in item-lex policy implementation. This warrants an independence of the system on the exact share. It would depend on the preference of the policy maker which would be the preferred solution.

More iP-4 items
The iP-2 policy in this research is correlated to the more iP-4 items scenario combined with the item-wtd policy of the work of Gralla and Goentzel (2018). The item-wtd representation stems from the iP-2 policy assigning the majority of the flow on single routing, with actually the majority of the relief items taking the shortest route. It means the weighted mix is defined by the iP-4 scenario, in which 70 percent of the relief aid is iP-4 items and the rest is represented by 10 percent of the share each. This policy attempts to move the smallest quantity, which was assigned to iP-4 through the airport relief chain. This policy option would perform the same as the iP-1 policy in case the total delivery to the system does not exceed the demand of the iP-4 items. If it does a more uniform flow appears, improving the airbridge connection by providing reduced separation and faster filling of the airside dock with the required relief items.

Assessment on the comparable policy for item prioritization
The first connection made in the behavioural comparison is on item priority settings, requiring an implementation of item-wtd. This policy generally was regarded as performing slightly worse than the short policy as regarded in the baseline for the airport relief chain system, which is the opposite in the airport relief chain system. It does not prove a direct invalidity in the model, but warrants a better look at the system performance.

When considering the total delivery utility component from the work of Gralla and Goentzel (2018), the short policy provides around 42 utility compared to 40 utility for the item-wtd policy. This is equivalent to a five percent higher performance for the short policy in the network over the item-wtd policy. The iP- policies from the airport relief chain provide between 5-10 percent improvement in total delivery numbers. This means the difference in performance is either quite incomparable or the routing in the airport relief chain model is to favourable compared to the similar study.

A utility component that does provide desirable outcomes is the item prioritization, which similar to the item prioritization policies in the airport relief chain model shows significant increase in value. From 20 utility in the short policy to 25 utility for the item-wtd policy. About a quarter of the total utility provided by the item prioritization component is gained by additionally by the item-wtd policy. A similar increase in percentage for the delivered priority items can be seen in section 8.3, with the iP-1 policy.

The validity based on the item prioritization from the work of Gralla and Goentzel (2018) is hard to determine, given the different levels of expected delivery. The component for their work is an aggregation of all nodes and item priorities, while in the airport relief chain system the value is determined by a single or dual flow structure, with a different level of demand. When demand is decreased the performance improves drastically as can be seen in the iP-2 policy from section 8.3.

D.3.2 Dest-lex and dest-wtd with the destination distance scenarios

The implementation of destination priority in the airport relief chain system was implemented as the choice in dP values, with dP-1 and dP-2 representing a destination priority policy, and dP-3 representing the baseline case like in the short policy version. The airport relief chain system is in essence a network system, with the regional airport being a distribution node, and the regional airport warehouse and off-airport warehouses being demand nodes, before further distribution. This distribution together with the decision for the warehouses and the allocation to the separate HSA locations all fall under the destination priority policies. The HSA allocation decision making was of little concern, given the fact that the final distribution was outside the scope.

Dest-lex with dP-1 destinations closer
The dest-lex policy aims at sending as much cargo to the priority destinations, which in the simulation model means sending cargo only through the airport warehouse, ignoring the off-airport warehouses as long as possible. This results in the airport relief chain system to the utilization of these off-airport storages as additional capacity. The scenario dP-1 destinations closer is the determining factor on what is in the airport relief chain system a priority destination. The airport warehouse is assigned as dP-1, when the scenario sets preference on close locations. This results in overflow of the capacity, eventually sending relief items to the storage.

Dest-wtd with dP-1 destinations farther
The dest-wtd policy aims at preventing single flow with no mixture, but does prefer the higher destination priorities. In the airport relief chain model this was implemented based on the dP-1 destinations farther, in which the far away nodes had preference over the close demand nodes. The majority of the relief items as such would be send to the off-airport storage locations, preferring the longer storage in which the airbridge would be relieved as well as reducing the strain on the resources of the regional airport.

Assessment on the comparable policy for destination prioritization
The dest-lex and dest-wtd policies vary quite a lot in the practice-based research of Gralla and Goentzel (2018), while dP-1 and dP-2 closely resemble one another. This difference is

mostly visible on total deliveries and destination prioritization utility. The difference in total is around 20 percent utility, far larger than what difference could be found between the destination priority policies in the last airmile research.

When comparing the heuristics for the associated scenarios the results prove significantly scewed, with the dest-lex performance for the dP-1 destinations closer scoring very similar to the dest-wtd utility score for the dP-1 destinations farther policy. These are the closest representation for the policies in the airport relief chain, making the outcomes at least similar as was expected based on the corresponding policy scenario combinations for the network model.

D.3.3 Conclusions on similarities and differences between the airport relief chain policies and the correlated policy scenario combinations from Gralla and Goentzel

The heuristics are compared in the paper on all scenarios presented, with scenarios B, C, D and E being those of interest to the airport relief chain model as it was conceptualized and implemented. The policies item-wtd, dest-lex and dest-wtd are compared to the short policy to provide correlation between the two systems and the expectancy for the output of a heuristic.

The item-wtd policy is expected to outperform the short policy, for both the more iP-1 items and more iP-4 items scenarios. This is a similar result to the iP-1 and iP-2 policies in the airport relief chain model outperforming the Baseline case. The concern here is that it also outperforms dest-lex, which would warrant that the dP-1 policy actually performs more in line with the dest-wtd policy.

The destination policies utilizing either dest-lex or dest-wtd should decrease performance for the most part with the first, while it increases with the latter. As both dP-1 and dP-2 from the airport relief chain study outperform the baseline and the item priority policies the nearest resemblance on the item-wtd policy. A possibility when assuming the policies to be valid in the airport relief chain system would be the switch build into the model, which would when reaching the threshold for the regional airport storage route the relief items similarly to the item-wtd policy.

The strongly differentiating result however, occurs when focusing the airport relief chain model on the farther destinations, in which case it performs too well compared to the dP-1 destinations farther scenario. In this scenario the worst performance is supposed to be found, which was clearly not the case in the airport relief chain model. The comparison between the distances in the chain and the network does not hold well.

E Prioritization for the Sulawesi case study

The case study into the Sulawesi disaster is complex with regard to the streams of relief aid. The demand was split in two main flows, one of international relief aid and one of domestic relief aid. These two streams were both supplied to the airbridge system with Sepinggan airport on Balikpapan as entry point, and the airport Mutiara on Sulawesi as exit point to the system.

The domestic relief aid, however did not have an easily accessible quantification which could be used for research. Among the domestic relief aid the supplies of medicine and shelter were seemingly high, while the Indonesian government reinstated the hospitals and reported the shelter. The quantities were difficult which were assumed to be of little influence aside from restraining the arrival gates at the hub airport.

The quantification of the relief aid is based on the country team's response plan in which 50,5 million dollars is allocated for the specific United Nations cluster approach quantifying the number of effected, and the urgency of the cluster. This document was used for the initialization of the model representing the information available on the Sulawesi disaster.

E.1 Clusters of the UN cluster approach applicable to the airport relief chain model

The airport relief chain model aims at assessing the impact of various policies on the bottlenecks occurring in the system after the influx of humanitarian aid. This mostly relies on the urgent relief aid versus the relief aid that has to be delivered shortly after the disaster before the recovery phase.

The clusters found in the response plan are the following:

1. shelter
2. water sanitation and hygiene (WASH)
3. camp management
4. child protection
5. gender-based violence
6. health
7. food security and livelihoods
8. logistics
9. education
10. early recovery

The decision to include or exclude the specific cluster is explained below. The choice to include a specific cluster means the cluster at the least was of urgency, directly influence those in need and not constitute to a specific group alone. The needs for the groups is hard to measure and the specificity would not align with the high level perspective of the rest of the research.

shelter: included

The shelter cluster was included, while it upholds all three criteria. independent of family composition, 12.500 households were affected and in need of relief aid at the time of construction of the response plan. This number is composed of the immediate shelter disaster and total houdeholds.

water sanitation and hygiene: included

The delivery of clean is of great importance in regions struck by tsunamis or floodings, while the water resources in the region are likely contaminated. The urban areas of Palu and Donggala suffered most from a lack of clean water with their respective piped-water supply systems damaged. The lack of clean water is urgent with the serious water shortages leading to defecation.

Aside from the fact that the WASH cluster is urgent, it furthermore directly influences the affected population of the disaster struck areas, whether it concerns latrines of fresh bottled water. Lastly the cluster does not discern specific groups within those affected, instead aims at providing aid to all those affected by the disaster.

camp management: not included

The camp management simply does not fulfill the requirement that it has to directly influence those in need. The camp management is needed to provide safe movement to basic services and the tracking of people, which is indirectly servicing people, but does not fulfill their base needs. The difficulty with clusters not providing goods and services directly, is to quantify the incoming relief aid necessary to restore the disaster struck area.

child protection: not included

The child protection cluster focuses on the specific needs of a target group. This group was quantified, which would mean it could be studied, yet it has significant overlap with other clusters such as WASH. This would cause redundancy in the outcomes of the model which would have to be compensated for. The cluster was left out on not fulfilling the criteria, and otherwise being represented by other clusters.

gender-based violence: not included

The cluster gender-based violence is aimed at women, which is a well quantified group, yet again does not have a need for specific goods. The cluster provides mostly services and immaterial assistance. This disqualifies the cluster for this research.

health: included

The health cluster was seen as the most stressing need for the most affected regions in Sulawesi. This makes it for priority decision making the ideal cluster for this research on bottlenecks and prioritization. The cluster does also hold up the three criteria described at the start of this section. It is a cluster defined by urgency, provides medicine directly to those in need and is not in particular subscribed to a subgroup in the population.

food security and livelihoods: included

This cluster mostly focuses on the population in need of food, that where completely dependent on local agriculture and fisheries. This cluster is urgent, with 80.000 people requiring food security. The food is directly provided to those in need and no distinction in the population is made.

logistics: not included

The logistics cluster is providing explicitly support and coordination, which makes it ineligible with the cluster lacking in direct provision to those in need. It is further described as a cluster for which significant resources where made available as predecessor to the response plan. This makes it hard to directly quantify even if the cluster directly provided to the population.

education: not included The education cluster aims at providing school materials and rebuilding schools, and the creation of learning spaces. Aside from the issue that the cluster tailors towards a specific subgroup in the population, it also is restrained by the high quantity of immaterial needs. This makes it difficult to include in this research. *early recovery*

The early recovery naturally falls at the end of the scope and is not an urgent cluster directly after the disaster. The early recovery as such is not included. It is mostly a cluster that could be added in other research with a scope moved to later stages of disaster response.

E.2 Disaster response calculations for relief aid

The disaster response for the model is selected from the included clusters, and the response size represented in the response plan. The response for the different clusters is further ordered by necessity from the report as well. The health cluster was reported to be the most pressing concern in the most severely struck areas making it the priority relief cluster. This is explained as well in the table. The priorities of a cluster can differ for certain goods, while in the shelter cluster there are those in dire need and those that have need for reparation materials, but can still make due.

The calculations are taken as the number of people that require the specific amount of relief aid, divided by 100. The calculations as division by 1000 which made sense to make it tonnes provided numbers that fall out way low, compared to similar studies. The assumption

cluster	quantity	priority
health	1910	1
wash	1910	2-3
food	800	3
shelter	625	2-4

Table 35: Relief aid arrival quantities and priority setting

to represent the values as 10 units per person fitting 100 in a tonnes made more sense providing a better corresponding outlook on the situation in the disaster area. The calculations as such are simple. The total quantities were 191.000 affected in both the health and wash cluster, 80.000 in the food security and livelihoods cluster and lastly 62.500 in shelter. These numbers are divided by 100 in table ... in the quantity column, left of the priority values.

The priority values reported in the third column of table ... are ranked from 1 to 4. The group other implemented in the model which is not used also has priority value 5. This value is reserved for all additional relief types with lower priority. The ranking system considers the lowest value to be the most urgent relief type. In the previous subsection it was explained what these rankings are based on, such as the notification that health items were the most stressing need in the response plan.

F Interview director of humanitarian affairs at DHL

The conversation starts with specifics of the humanitarian operations from DHL, then revolves around the operation in Mozambique of March 2019 and closes off with constraints and bottlenecks around the airports within the relief system.

The current outlook on the humanitarian operations for DHL
The deployment of equipment and personnel to the airport following a natural disaster are dependent on the region in which the disaster occurred, the size of the airport and likely also from the political situation of the country.

The current number of staff deployed range from four to ten active personnel. This number has decreased over recent years. Relief aid used to be brought in mostly by Russian aircraft with loose-loaded cargo which often had to be unloaded manually. Much of the relief cargo originating from European and Middle-Eastern donors is now containerized, which means off-loading can be done with fewer, more skilled drivers assuming suitable equipment is available. Overall, the need for supervisors has decreased, while the need for specialized workers has increased.

Offloading a B-747 can be done in 40 to 60 minutes, with 5-6 drivers assuming the cargo has been loaded correctly and the correct equipment is available. With manual labour it could easily take 20-30 labourers half a day up to a day to off-load the same tonnage.

Mozambique March 2019

DHL's volunteer ground handling crew consisted of six specialist drivers who worked with a local logistics company and Beira airport's ground handling contractor. The amount of donated relief aid flown in was lower than initially expected. This was caused by a number of factors, namely the long distance for the charter companies, the diplomatic relations and governmental connections and lastly the experience with disasters in the area.

Availability of shelter items could also be a factor of possible reduced influx of relief aid, with the stockpiles possibly not being of the same magnitude as in the past. Storage of shelter items is costly because, good quality tents and tarpaulins are heavy, bulky, relatively costly and have a finite shelf life. Good quality family tents suitable for hot climates can cost around 2000-3000 dollars per unit. A tarpaulin is an example of the hard to handle shelter, as the plastic tarpaulins tend to deteriorate in hot conditions. A cooled distribution centre or storage space is mandatory.

Even though low volume came in to Mozambique, the airport was severely damaged with its asbestos-cement roof panels suffering from the high winds, thus posing severe constraints on the relief chain. The main objectives were first the search and rescue teams and the medical teams with low volume, low weight and high value equipment. The provision of shelter was vital but rather limited.

Constraints and bottlenecks

Lack of information on the pipeline from donors and carriers is one of the continued frustrations in the field of humanitarian aid. What and when relief goods are being shipped is often not advised to the receiving airport. Such information is important for an efficient operation as it is hard to estimate without clear insights in the planned relief flow.

In airbridge situations this problem can be moderated to some extent, as you can do a form of prioritization at the staging airport. It furthermore enables a physical count as a self-informing measure.

The airbridge system is suitable where there is a strong NDMA (National Disaster Management agency), that clearly discerns what is needed and what should be banned. One of the key roles that should be studied is how the NDMA controls the relief chain and how that influences system performance.

Homogenous flows often perform better, when the distribution is independent of other relief items. Government-to-government donations are often preferred as their donations tend to be homogenous in nature, and the further use is of little concern to them. For NGO's the supplies will often be sent to sister organizations, have to be kept together and are built from what is in stock, instead of uniform types.

NGO's freight is the source of constraint in 80 percent of the cases. The combinations of goods are meant for projects, making the handling more difficult.

Indonesia was an example of a strong NDMA setting up the relief chain with items for which there was demand, while banning other items. The Indonesian government did not allow health items from NGO's to enter the country, which made the stream more uniform, and health items have to be checked more thoroughly which takes time.

G Interview with a professor of the Technical University of Delft, specialized in logistics

The validation considers an airbridge system for the transportation of relief aid with input of relief into a hub airport and the connection to the local airport for distribution to the disaster struck regions.

The focus is on the control in the regional airport to mediate the flow to the local airport. The approach aims at maximizing the airbridge capacity and as such the output of the local airport. The distinction between the regional and the local airport here is from a system perspective as tier 2 and tier 3, only considering air transportation. The regional airport combines the domestic relief aid and the international relief aid.

The scope does not consider the tier 1 system before the regional airport, nor the true output of the system past the local airport. The scope of the study involves the arrival process to the regional airport to the warehouse to the local airport. It is not last-mile, but could be last hundred miles. The last section is reported only as the demand.

The target of the thesis is to provide solutions for the bottlenecks with both operational and strategic policy. To do so the bottlenecks had to be found first. The theory considering the spill-over effects when the bottleneck is resolved is called the theory of constraints of Goldratt.

The regional airport combines the national and international cargo. There are two reasons to combine these flows in one airport. The first reason is the length of the airbridge connection. Closer airports are preferred in order to save fuel and to simplify the planning. The second reason is to implement a form of cross-docking. The international and domestic relief aid could be combined on the priority of the items.

In civil aviation the transportation is done in the belly. The use of standardized packaging is important, whereas the cargo aircraft can have a turnaround time of days. In the cargo handling for humanitarian aid this is shorter, yet still constraining performance. When the regional airport has suitable performance, the airbridge will always turn out to be a constraint.

The arrivals at the local airport are in the morning. There is no specific feedback reason to do so, but more tailored towards a single turnaround flow per day. The ideal schedule for the end-point delivery is difficult, as calculating downstream delivery is severely restricted by the infrastructural failures for local airport to disaster site delivery. The feedback mechanism aims at preference for earliest delivery.

The study has a priority on early delivery over fluid delivery through the system, because of the uncertainty considering again the infrastructural failure at the destination. The urgent items are delivered first in the set-up phase and the stability phase is then considered when the fluent delivery can be attempted.

The fluent delivery cannot be done immediately, because the influx of relief aid after the time of the disaster is considerably more than the system is able to cope with. The stress researched in the scope of the study is the stress from this influx of relief aid, more so than infrastructural failure. The failure of infrastructure is mostly considered at the outflow from the local airport.

The points from the validation to consider for the research are:
The inter dependency within the chain is very large. The dynamics in the system are inherently related to other components, while the relief of one occurring bottleneck could easily cause a new bottleneck to surface downstream in the airport relief chain system.
Cross-dock centre design is one of the possible design policies to provide improved airbridge performance. This design considers still the same docking system using pure freight, but alternates the decision rules with the intermediate storage connected to the docking system.
The airbridge in the meantime has to perform at maximum capacity. A shortage in the airbridge will always lead to lower delivery. This closely relates to the policies improving the performance in the regional airport leading to improved pressure on the airbridge.
This pressure together with the found bottlenecks is difficult to resolve due to uncertainties in the system. The metrics herein are very important, as trade-offs occur regularly. The system has to be both robust and fluent, to resolve temporary shut downs of components in the system, while queues hinder total performance.
System dynamics is suitable as it helps to capture the dynamics in the system. The dynamics are the key point for the study. The analysis of the dynamics in the system represents the behaviour really well. This invites adaptive policy, as described by for example Walker, to arrange influence in the system when a new bottleneck occurs. The autonomous triggers are where a new policy would preferably be implemented.
It is accepting that the system won't be perfect, but the focus is on making simple decision rules to provide insights in the trade-offs.

The last conclusion for the study as a pointer from the expert:
Mainly focus on what the research provides to the literature. What is new in the humanitarian logistics? Especially the dynamics with different layers in the small system is really a new outlook within the literature. The model resembles a model based adaptive control system. This is approaching a digital twin for the system where decision rules can be pushed forward for the control loop.

H Critical path analysis

The critical path analysis makes use of the chain of processes which have to be done in the airport relief chain. The CPA is a tool which outlines the processes dictating the throughput time of the system. The critical path could be described as the path from entry to exit node through a task graph consisting of a set of nodes and edges, for which the sum of cost is the maximum (Kwok, 1996). In this case the time is seen as the cost, the lower bound time for the throughput of relief goods in the system.

For the critical path analysis, a division is made between the flow of cargo and the aircraft movements, whereas the main track includes both. The aim of this analysis is to enquire the required level of detail for the modelling of the system. The bottleneck process chain is the model part which has to be included in detail, whereas the other chains could be simplified without losing explanatory power.

The cargo path takes up the majority of time, whereas the processes for the aircraft is determined by the refueling, taking up approximately Forty minutes, compared to the minimal throughput time of the cargo preparation of ... minutes. The process description of the aircraft is therefore, given the fact that the focus of the research is the throughput time of the cargo, sufficient if done in minimal detail. The aircraft have to be readied before the incoming cargo, which is the only requirement to the model.

As with the aircraft the flow of the cargo is also a determining factor for the terminal and warehouse processes, meaning the critical path will define the detail within these subsystems. Within the terminal various processes can be done in parallel, making the influence of processes such as customs unsubstantial. This makes customs, prioritization and the checking of the manifest inside the terminal potential processes to be simplified for the modelling of the airport relief chain.

$Taskletter$	$Task$	$Length$	$Type$	$Dependenton$	$Determinant for queuetime$
$Maintrack$					
A	$Aircraftlanding$	0	$Sequential$	$-$	0
B	$Aircrafttaxitogate$	$dist/v$	$Parallel$	A	$(dist/vV15)$
C	$Groundhandlerselection$	$5*$	$Parallel$	A	
D	$Highlifterselection$	10	$Parallel$	A, C	
E	$Unloadingaircraft$	$N(119, 66)$	$Sequential$	B, C, D	$N(119, 66)$
$Track1$					
F	$Unbindingcargo$	$(3V7, 5)$	$Sequential$	E	$(3V7, 5)$
G	$Cargopreparation for redistribution$	$U(10-30)$	$Parallel$	F	$U(10-30)$
H	$Customs$	10	$Parallel$	F	
I	$Storeatairport$	$dist/vcargo$	$Parallel$	G	$dist/v$
J	$Storeatregionalwarehouse$	$dist/vcargo$	$Parallel$	G	
$Track2$					
K	$Aircraftparking$	y	$Sequential$	E	y
L	$Airbridgeschedulling$	z	$Parallel$	$-$	z
$Maintrack$					
M	$Bundlingofcargo$	$N(119, 66)$	$Sequential$	$IorJ$	$N(119, 66)$
N	$Transportingbundledcargo$	$dist/vcargo$	$Sequential$	M	$dist/v$
O	$Aircraftloading$	$(3V7, 5)$	$Parallel$	K, N	$(3V7, 5)$
P	$Aircraftdeparturefromsystem$	$dist/v$	$Parallel$	K	$-$
Q	$Aircraftdepartureforairbridge$	$dist/v$	$Sequential$	P	$dist/v$
R	$Airbridgeflight$	$dist/vplane$	$Sequential$	Q	$dist/vplane$
S	$Aircraftunloadingatsecondairport$	$(3V7, 5)$	$Sequential$	R	$(3V7, 5)$
T	$Aircraftreturnflightairbridge$	$dist/vplane$	$Sequential$	S	$dist/vplane$