Resilient airports

Using a new resilience measuring approach to evaluate policies that improve the resilience of airports in the immediate post-disaster response.

Wouter Feil
Master Thesis
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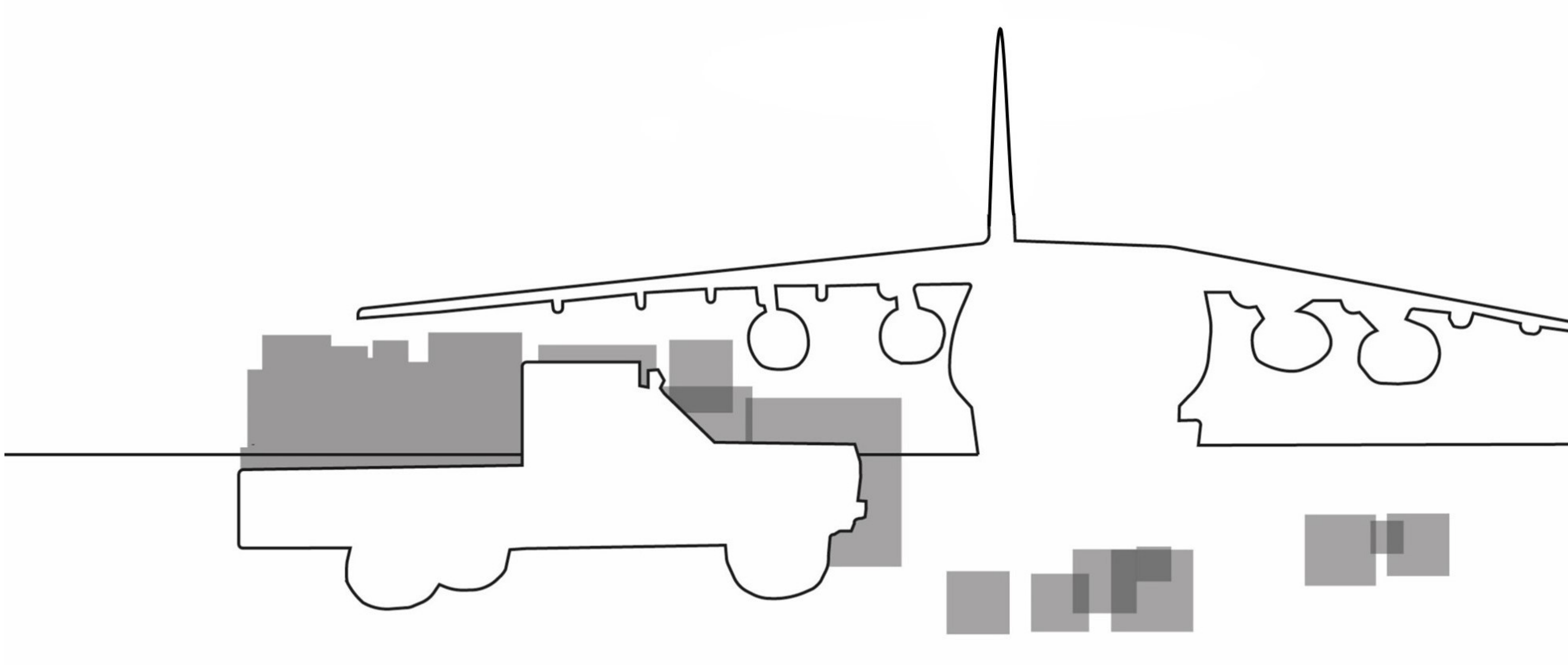

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The documentation of all codes used in this thesis can be found at:
https://github.com/feilos/thesis

Preface

The thesis in front of you concludes my Master of Science in Engineering and Policy Analysis. I would like to thank my graduation committee: Bartel Van de Walle, Martijn Warnier and Tina Comes for the time and effort they have put in guiding me through this final project.

Additionally, I would like to thank the people of the “EPA hok”. It was a pleasure to walk in every morning and see I was not alone in this journey. I also would like to thank my friends who provided me with encouragement and needed distraction from the thesis.

Furthermore, I would like to thank my family for their unconditional support, not only during my graduation, but throughout my eight yearlong student career.

Lastly, I would like to thank Basia for her listening, faith and encouragements.

Executive summary

Hurricanes Katrina, Harvey, Irma and the recent earthquakes in Haiti and Nepal is only a small enumeration of the natural disasters with a sudden onset in the past years. These disasters occur in different parts of the world, in countries developed and underdeveloped, small and large. They shape the political agenda and based on historical trends this will only increase.

Airports are a special critical infrastructure in a disaster response from a resilience point of view. They must overcome two types of shocks when they are affected by a disaster. They are not only hit by a disaster, which decreases their performances. Airports also need to function as a humanitarian and logistic hub for the disaster response which leads to an influx of aircraft. This influx requires the airport to increase their normal performance. In this research a mesoscopic model is built to compare different policies that can improve the resilience of the operations of airports during the immediate post disaster response. This problem is stated in the following main research question:

How should airport services be improved to be more resilient during the immediate post-disaster response?

This study uses a mesoscopic discrete event model to capture the airport system. The mesoscopic characteristics of this model makes it adaptable to different airports and different natural sudden onset disasters. The mesoscopic model is divided into three model components: (1) gate selection, (2) aircraft unloading and (3) warehouse operations. By using the mesoscopic view, the lowest level of detail that is sufficient to perform analysis on is used. The following six policies are compared in this study: extra resources, prioritize on aircraft size, prioritize on cargo type, extra warehouses, extra holding area and a combined policy. These policies affect different components of the system and are tested for four scenarios with different percentages of loose cargo and different percentages of workers that will not show up after a disaster occurs.

To compare the effect of the policies on the level of resilience of the system, this study proposes a new resilient measurement approach that incorporates the bounce back and bounce up capacity of a system. This approach divides resilience into three aspects (1) absorption capacity, (2) adaptive capacity and (3) recovery time. This resilience measurement approach can be used when a system has the following two characteristics: (1) dynamic required service levels over time and (2) internal system changes.

To measure the resilience of the airport system, the three aspects of resilience are measured over all three model components for the three KPI's of the airport system: (1) processed cargo, (2) idle cargo and (3) throughput time.

The new resilient measurement approach that incorporates the bounce back and bounce up capacity of a system, creates insight in processes and problems within airports in human-

itarian logistics in the immediate response phase. This approach reveals the intertwinement of the system components. Policies that improve the level of resilience of the system affect multiple components and KPIs at once. Further studies about airports in humanitarian logistics in the immediate response phase should take this intertwinement of the system into account and should study the airport system as a holistic whole.

The answer to the main research questions is that a policy maker should implement the combined policy as soon after the disaster occurs, independent of the scenario the system is facing. This includes (ordered on level of importance): (1) ask aid organization and/or the military for extra resources and emphasize the need for a quick arrival of these resources, (2) ask aid organizations for mobile storage units, (3) create extra holding capacity and (4) implement a prioritization policy on cargo type and aircraft size. By following these steps, the airport has the best chance to stay operational.

The external effects have a large influence on the effect of the policies. The operations of the airport are influenced by two major external effects: (1) the percentage of loose cargo and (2) the percentage of workers that does not show up. The first effect can be minimized by emphasizing the negative effect of loose cargo to the humanitarian air cargo operators. If the humanitarian air cargo operators minimize the percentage of loose cargo, the airport can handle faster and more cargo. The second effect can be overcome by organizing upfront specialized extra workers that can act as a backup pool when the planned workers do not show up. These extra workers can come from the military as well from aid organizations like DHL. Theses extra workers minimize the performance loss of the airport and result in the effect that the airport can handle faster and more cargo.

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1 Introduction: Humanitarian airport logistics

Hurricanes Katrina, Harvey, Irma and the recent earthquakes in Haiti and Nepal are only a small enumeration of the natural disasters with a sudden onset in the past years. These disasters occur in different parts of the world, in countries developed and underdeveloped, small and large. They shape the political agenda and based on historical trends this will only increase (Alexander, 2017).

Our society becomes highly dependent on critical infrastructures. Critical infrastructures are infrastructures that greatly influence public welfare and economic prosperity. For example, airports and the financial systems (O'Rourke, 2007). Failures of these systems make the impact of a natural disaster even greater (Johnston, Becker, & Cousins, 2006; K. J. Tierney, 1992; Susan L Cutter, Boruff, & Shirley, 2003; O'Rourke, 2007; Comes & de Walle, 2014). Resilience is a key concept to limit the impact of these failures. These studies use the traditional definition of resilience, which is the ability to bounce back after being stretched.

The critical infrastructure of transportation plays a crucial role in disaster response. Transportation accounts for 80% of the disaster response costs (Trunick, 2005). The pace of humanitarian aid is highly dependent on the logistic relief operations (Thomas, 2003). However, almost half of logistic spending on relief operations is wasted. Due to the uncertainty in demand, supply and facilities humanitarian supply chains are created with limited information (Day, Melnyk, Larson, Davis, & Whybark, 2012; Balcik, Beamon, & Smilowitz, 2008; Van Wassenhove, 2006). This uncertainty aspect in combination with the time constrains and the duplication of work leads to half of logistic spending of relief operations being wasted. (Day et al., 2012). Within the supply chains of disaster response, airports are used as a humanitarian logistic hub and are often the bottleneck of disaster relief operation. (Kovács & Spens, 2007).

Airports are a special critical infrastructure in a disaster response from a resilience point of view. They are not only hit by a disaster, which decreases their performances. Airports also need to function as a hub for the disaster response which leads to an influx of aircrafts (Kovács & Spens, 2007). This influx requires the airport to increase their normal performance. The traditional definition of resilience to bounce back after being stretched is not sufficient, airports need to bounce up after being stretched.

This study will explore how resilience applies to airports in the immediate disaster response and which policies can improve the resilience of airports in this phase.

2 Background & Literature Review

In this section the problem of airports in the immediate disaster response is elaborated. This consists of three components: (1) airports in the humanitarian supply chain, (2) airport modeling and simulations and (3) resilience of airports in disasters. Below each component the knowledge gap of this component is presented in italics. These three components together show the scientific and societal relevance of this study.

2.1 Airports in the humanitarian supply chain

In the aftermath of a disaster, airports act as an entry point for humanitarian organization. This role as entry point also force airports to be used as a hub in disaster response logistic operations (Balcik, Beamon, & Smilowitz, 2008). The hub function of airports makes them often the bottleneck in disasters response operations. (Kovács & Spens, 2007). The costs and speed of disaster response is highly dependent on the logistic operations and airports are often the bottlenecks of these logistic operations (Van Wassenhove, 2006). This congestion strongly influences the humanitarian response and keeping airports open is critical to the emergency response (Economist Intelligence Unit, 2005).

The logistic operations of disaster response are often affected by the disaster. This negative shock consists of two elements: destabilized critical infrastructures and employees that will not show up. For example, destabilized critical infrastructures affected the Haiti airport during earthquake in 2010. The air traffic control tower broke down which resulted in the situation that the airport could barely cope with the arriving aircraft (Whitning, 2010). The airport is also affected by employees that will not show up. The reason for this varies widely from disaster. For example, employees are not able to reach the airport due to road damage or for example are hit by the disaster themselves (Director humanitarian affairs DHL, 2018).

The airport in the immediate response phase also faces a shock of a sudden influx of aircrafts which cause congestion. The combination of large amounts of in-kind aid, lack of appropriate infrastructure and unpredictable demand leads to piling up of stocks at the airports (Hanaoka & Qadir, 2005). Relief supplies are flown in from global donors, stored and distrusted from airports. Due to fact that so many organizations push their cargo to these entry point congestion occurs and thereby blocking the essential supplies (Economist Intelligence Unit, 2005). On top of that most airports in disaster situations are not designed to handle a full logistics support of that size. They mostly are designed to move visitors in and out quickly (Economist Intelligence Unit, 2005).

For example, during the Haiti earthquake in 2010. The aid organizations supported the local people with a large amount of donations. To bring these donations to the people of Haiti the donations had to pass the airport. However, the airport was already highly congested due to the large amount of humanitarian organizations present. The organization present at the airport could not handle these large amounts of donations. Because of this the disaster response operations were delayed, and the airport became an even larger bottleneck (Besiou, Stapleton, & Van Wassenhove, 2011).

Academic literature acknowledge the humanitarian logistic problems within airports (Kovács & Spens, 2007; Hanaoka & Qadir, 2005; Besiou et al., 2011; Van Wassenhove, 2006). However, there is a lack of academic literature about the logistic problems and processes within airports. Literature about the operations of airports are published in practitioner journals or online guides published by humanitarian aid organizations (Kovács & Spens, 2009; Leiras, de Brito Jr, Queiroz Peres, Rejane Bertazzo, & Tsugunobu Yoshida Yoshizaki, 2014). Humanitarian supply chain literature about the immediate response phase is mostly focused on the last mile problem and vehicle routing/planning problems (Gonçalves, 2008; Balcik, Beamon, & Smilowitz, 2008). This creates the following research gap:

Lack of academic research on the processes and problems within airports in humanitarian logistics in the immediate response phase.

2.2 Airport modeling and simulations

Modeling airport processes is a good way to study the airport system and is often used in research (Joustra & Van Dijk, 2001; Kiyildi & Karasahin, 2008; Andreatta et al., 1999; Verbraeck & Valentin, 2002; Miller & Clarke, 2007; Nsakanda, Turcotte, & Diaby, 2004; Manataki & Zografos, 2010; De Neufville, 2016). Airport models are divided into three categories: macroscopic, mesoscopic, and microscopic models corresponding to a low, medium, and a high level of detail (Manataki & Zografos, 2009).

For microscopic models, discrete event models or agent-based models are often used. This method is used to model detailed systems where complex, logistic processes are combined with limited infrastructure capacity (Verbraeck & Valentin, 2002; Udluft, Sharpanskykh, Curran, & Clarke, 2016). In Verbraeck and Valentin (2002) and Joustra and Van Dijk (2001) discrete event modeling is used to study passenger streams in airports and in Nsakanda et al. (2004) discrete event simulation is used to analyze air cargo operations. These detailed models are built over and over for each individual airport, although the questions for each model and airport are quite similar. Verbraeck and Valentin (2002) proposes simulation building blocks to overcome this problem. The study of Manataki and Zografos (2009) proposes the use mesoscopic models which are more generic models and can be adapted to a specific airport.

Macroscopic airport models have a high level of aggregation and are used for long term policy analysis. The system dynamics modeling approach is often used in generic models, for example to model airports runway capacities by Miller and Clarke (2007). Suryani, Chou, and Chen (2012) extends this model and adds scenario planning with optimistic and pessimistic cases. These generic models like the one used in the studies of Andreatta et al. (1999), Miller and Clarke (2007), Suryani et al. (2012), Galvin (2002) are limited in their possibilities to incorporate stochastic effects, possible interactions and feedback loops among the various elements of the airport terminal.

Mesoscopic models are the bridge between a microscopic operational models and aggregated macroscopic models (Shepherd, 2014). The study of Manataki and Zografos (2009) uses a mesoscopic model. This study splits the different processes of airports but keeps the interactions between them. An extension of this study also incorporates random arrivals, delays, and variations in schedules (Manataki & Zografos, 2010).

Although the scientific field of airport modeling is well covered, so far humanitarian airport processes are not modeled for humanitarian relief operations. This creates the following research gap:

Lack of academic research on airports modeling of humanitarian logistics in the immediate response phase.

2.3 Resilience airports in disasters

The concept of resilience is used in different fields of research ranging from engineering, ecology, psychology, sociology, to disaster response studies. There is no single definition of resilience. Different definitions are used together and none of them covers them all. In this section the following three concepts of resilience are discussed: (1) engineering resilience, (2) supply chain resilience and (3) disaster resilience.

In engineering resilience is defined as the ability to bounce back from a shock (Bruneau et al., 2003; Woods, 2015). From an infrastructural system point of view a resilience airport system is a system that can circumvent accidents through anticipation, survive disruptions through recovery, and grow through adaptation (Madni & Jackson, 2009).

In supply chain systems Berdica (2002) and Immers, Stada, Yperman, and Bleukx (2004) define resilience as "the capacity of the transport system to recover from unusual conditions, considering the maximum disturbance to the system, and its recovery speed and time." The study of Ponomarov and Holcomb (2009) defines supply chain resilience as the ability of a system to adjust or maintain essential functions under stressful and harsh conditions. Most of the supply chain resilience studies are on supply network level (Susan L. Cutter, Burton, & Emrich, 2010). Few studies have defined and created methods to measure resilience of a transport node like an airport (Bao & Zhang, 2018).

Disaster resilience has a different definition. Disaster resilience does not only include the engineering definition of (Bruneau et al., 2003). Disaster resilience should also include internal system changes (Comes & de Walle, 2014). Woods (2015) defines this definition of resilience as "resilience as graceful extensibility". These changes make the traditional definition of the ability to bounce back to the original system state not applicable for airports in the immediate disaster response, because the system itself has changed. The system must bounce up to a higher state. It can be concluded that there is no sufficient definition and approaches to measure resilience of airports in disaster situation. This creates the following research gap:

Lack of academic research on approaches of resilience measurements for airports facing dynamic required service levels over time and internal system changes in the immediate response phase.

2.4 Scientific and societal relevance

The use of quantitative models to improve the resilience of airport services is highly relevant from societal and scientific perspectives. An overview of the relevant scientific and societal aspects is shown in table 1.

From a scientific point of view this topic is relevant for the field of humanitarian logistics, airport modeling and resilience. Firstly, the traditional resilience measurement approach of bounce back capacity doesn't apply for airports in the immediate disaster response. Airports need to bounce back and bounce up. This study will strengthen the resilience studies with a new measurement approach that is able to measure the traditional resilience together with the bounce up resilience aspect. Secondly, the academic studies on operations within an airport in humanitarian logistics are new. This research strengthens the humanitarian academic field with insights about the airport services and how they are intertwined with each other in the immediate response phase. Thirdly, the use of mesoscopic models to create a better understanding of the operations within an airport in humanitarian logistics in the immediate response phase is an unexplored scientific area. Several airport models have been made, but the use of generic mesoscopic models which can be adapted to specific airports in the immediate response phase of humanitarian logistics is not yet covered in academic literature.

From a societal point of view this topic is relevant for the humanitarian aid sector. This study will create insight in the level of resilience of airport services, policies and external effects and how they affect each other. This understanding will help policy makers that have a relation to the airport in the immediate response phase to implement policies during the response which will reduce the economic and social damage caused by disasters. These actors include ground handlers, air traffic control, the military, aid organization and humanitarian aid cargo carriers.

Scientific relevance

- A new approach to measure resilience in situations of dynamic required service levels over time and internal system changes.
- Insight in the intertwinement of in the processes and problems within airports in humanitarian logistics in the immediate response phase.
- Insight in the level of detail that is needed to capture the airport system in humanitarian logistics in post-disasters response phase.

Societal relevance

- A time line of policy implementations and how they improve the level of resilience of the airport in the immediate post-disaster response phase.
- Insight in how the external effects on the operations at the airport in the immediate post-disaster response phase can be minimized.

Table 1: Scientific and societal relevance

3 Research goal and method

In this section the goal and scope of this research are discussed together with the main research question and method that is used to answer this question.

3.1 Research goal

The hub function of airports in the affected region makes airports often the bottleneck in disasters response operations (Kovács & Spens, 2007). Airport services need extra policies to be more resilient and therewith make them able to cope with the influx of aircrafts, change in aircraft & cargo type and risks of no turning up of employees. The main research goal is to create a model-based decision support system that helps to make the internal airport services more resilient in the immediate post-disaster situation. This model will enable the identification of bottlenecks and enable systematic improvement of the airport services. The improvement measures are short term measures and are implemented during the immediate response phase.

3.2 Scope

Disasters can be natural or man-made. They can also have a sudden-onset or a slow-onset (Van Wassenhove, 2006). In table 2 the different disasters are categorized. These four types disasters require different logistic efforts. Natural disasters with a sudden onset require the most logistic effort (Cozzolino, 2012). Therefore, this research is focused on natural disasters with a sudden-onset. In this research the word "disaster" refers to disasters that are natural and have a sudden-onset.

	Natural	Man-made
Sudden-onset	Hurricane Earthquake	Terrorist attack Chemical leak
Slow-onset	Drought Poverty	Refugee crises

Table 2: Disaster categories

This study will provide policies that make the airport more resilient and therewith make them able to cope with the influx of aircrafts, change in aircraft & cargo type and risks of no turning up of employees. This study does not include physical damage to the airport. The model used in this study is not applicable to all airports and all disasters. This research is aimed at large scale disasters, the so-called level 3 disasters (IASC, 2012). This type of disaster occurs when the urgency, scale, or complexity of the emergency overwhelms the immediate capability of the affected country. International aid is needed and will partly be delivered via the airport, which often leads to congestion at the airport. The framework of Rijken (2013) is used to define the characteristics of the disasters that are studied in this research. These characteristics are divided into six dimensions. The characteristics and the applicable dimension for this research are described in table 3.

Characteristic	**Dimension**
Affected population	International, Nationwide, Provincewide
Impact on beneficiaries	Immediate loss of lives
Economic impact	Above 1 billion euro
Time horizon of recovery plan	Ongoing months
Complexity of response	Cluster coordination
Level of preparedness	Basic response, None
Data availability	Limited data available
Frequency of the disaster	Once every 50-10 years
Environment	Developing urban regions
Event formation	Sudden on-set

Table 3: Disaster type that falls within the scope of this research

This research is focused on small airports that handle 10-150 flights a day. These airports have most of the time one runway and are badly prepared for a L3 disaster response. These airports characteristics are chosen, because most international airports in developing urban regions have these characteristics. Based on earlier disasters with similar characteristics as described in table 3 the time horizon of this type of disruption takes one to two weeks.

The main research goal is to create a model-based decision support system that helps to make the internal airport services more resilient in the immediate post-disaster situation. Resilience in the context of airports in the immediate post-disaster response is defined as the bounce back and bounce up capacity of airports. The bounce back capacity consists of the ability to cope with the disruption of employees not turning up. The bounce up capacity consists of the ability to overcome the change in aircraft and cargo type and influx of aircrafts.

Chapter 2 presents three research gaps. These gaps are translated into the following main research question:

How should airport services be improved to be more resilient during the immediate post-disaster response?

The main research question is divided into four sub-questions. The goal and method to answer these questions are elaborated on in section 3.3. The sub research questions are presented below:

1. How should the airport services be conceptualized?
2. How can an airport be captured in a quantitative model to model the effects of the immediate disaster response on airport operations?
3. What policies make airport operations more resilient?
4. In what way can this approach be generalized for similar airports?

3.3 Research method

The method that is used to answer the main research question is based on the method introduced by Van Dam, Nikolic, and Lukszo (2012). This methodology is based on executing certain steps to create the model. The different steps are: problem formulation and actor identification, system identification and decomposition, concept formalization, model formalization, software implementation, model verification, experimentation, data analysis, model validation and model use. Ultimately, this model helps to understand the system and create insights in which and how policies can improve the resilience of airports in the immediate post-disaster response.

3.3.1 Sub-question 1: How should the airport services be conceptualized?

The first sub-question is part of the model conceptualization and formalization phase. The goal of this question is to create a concept model of the airport system. This concept model includes insights of the actor identification and system decomposition. The concept model creates insight in the system environment and aspects of airport services during the immediate post-disaster response.

This research focuses on the internal services of the airport. The defined key internal services, also called components, in this research are: (1) gate selecting, (2) aircraft unloading and (3) warehouse operations. These components are displayed in figure 1. It is assumed that the aircrafts are already landed, and the airport system must process the aircrafts. These components are chosen, because the processes of these components include physical movement and they have an infrastructural aspect. On top of that, data about these components is available.

The system starts with the inflow of aircrafts and ends when the cargo is loaded for transport to the humanitarian staging areas. One type of cargo is used in this study, but multiple types of packing. For every component an overview of the actors, processes, external factors, internal structure and performance indicators is created.

First a concept model is made based on a literature study. This model will be improved based on information from experts. The conceptual model will be formalized with the help of a class diagram. The concept model is presented in chapter 4 and sections 5.1 and 5.2.

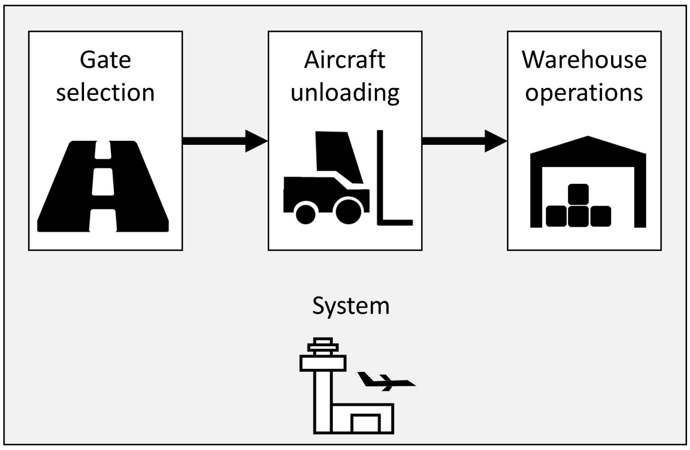


Figure 1: System overview

3.3.2 Sub-question 2: How can an airport be captured in a quantitative model to model the effects of the immediate disaster response on airport operations?

The second sub-question is part of the model implementation phase. The goal is to capture the system in a model. This is part of the approach of the use of model-based decision making the immediate post-disaster response. This is done with the help of a discrete event model. Discrete event airport simulations are used as a lens to capture the airport system in disaster situations. As mentioned in 2.2 there are different levels of detail in airport modeling. In this research a mesoscopic model is built which is based on the work of Manataki and Zografos (2010). This mesoscopic model will split the different processes of airports but keeps the interactions between them.

There are multiple reasons why discrete event simulation is chosen as the modeling approach for this research. Firstly, it allows for a generic model because it is a top-down modeling approach. In contrast to agent-based modeling which requires a bottom up approach. Secondly discrete event simulation is especially useful to model the flow of entities and allocation of resources, which is a key aspect in this research.

To create the mesoscopic discrete event model, the modeling cycle of figure 2 is used as a guidance. Due to the limited amount of data to quantify the model, this model is not a representation of a real disaster. The model represents a hypothetical case which is based on data of the Nepal earthquake of 2015 and the Haiti earthquake of 2010. The initial parametrization of the variables will be based on data of Haiti Port au Prince International Airport and Nepal Tribhuvan International Airport Kathmandu. The data can be combined into a hypothetical case, because the structure of both airports is similar, and the mesoscopic discrete event model does not require a high level of detail. The model implementation and the reasoning behind the data merge is presented in section 5.3 and section 5.4.

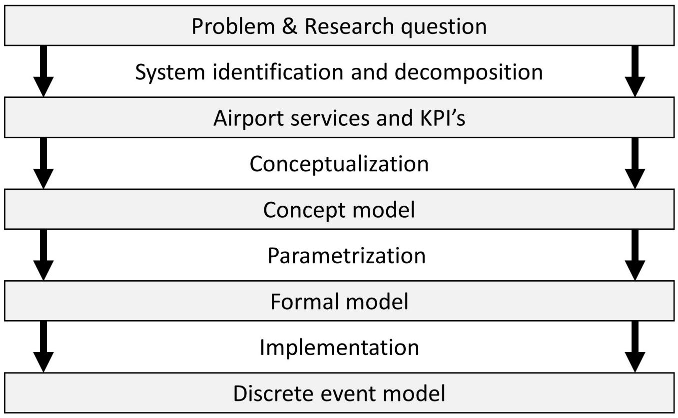


Figure 2: Model building steps

3.3.3 Sub-question 3: What policies make airport operations more resilient?

The third sub-question is part of the model use and synthesis phase. The goal of this question is to create policies and evaluate them on the improvement on the level of resilience of the system. This goal will be reached by completing the following two steps: (1) define how resilience of airports in the immediate post-disaster response can be measured and (2) define policies that make the system more resilient.

The exact policy space and the possible policies are defined based on a literature study and expert interviews. This is presented in section 6. The different policies are measured with a new resilience measurement approach. The key performance indicators to measure resilience are discussed in section 4.3 and the model results are presented in section 8. To validate the results, different pre-set scenarios will be used based on real world disasters which are discussed in section 7.

3.3.4 Sub-question 4: In what way can this approach be generalized for similar airports?

The fourth sub-question is part of the model use and synthesis phase. The goal is to show how and under which criteria the two approaches can be generalized to other airports and other systems. The two approaches are: (1) the use of model-based decision making the immediate post-disaster response and (2) the approach to measure resilience. In section 9.2 the evaluation of model-based decision making in the immediate post-disaster response is presented. In section 9.3 evaluation of the new approach to measure resilience is presented.

These sub-questions provide insight into which policies make the airport more resilient in post-disaster situations. The research flow of this study is graphically presented in figure 3. The left side displays the phase the sub-question is part of. The left white box shows which sub-question is discussed, the middle white box shows the method to answer the sub-question and the right white box shows in which section the sub-question is discussed. The main research question is answered in the conclusion chapter in chapter 10.

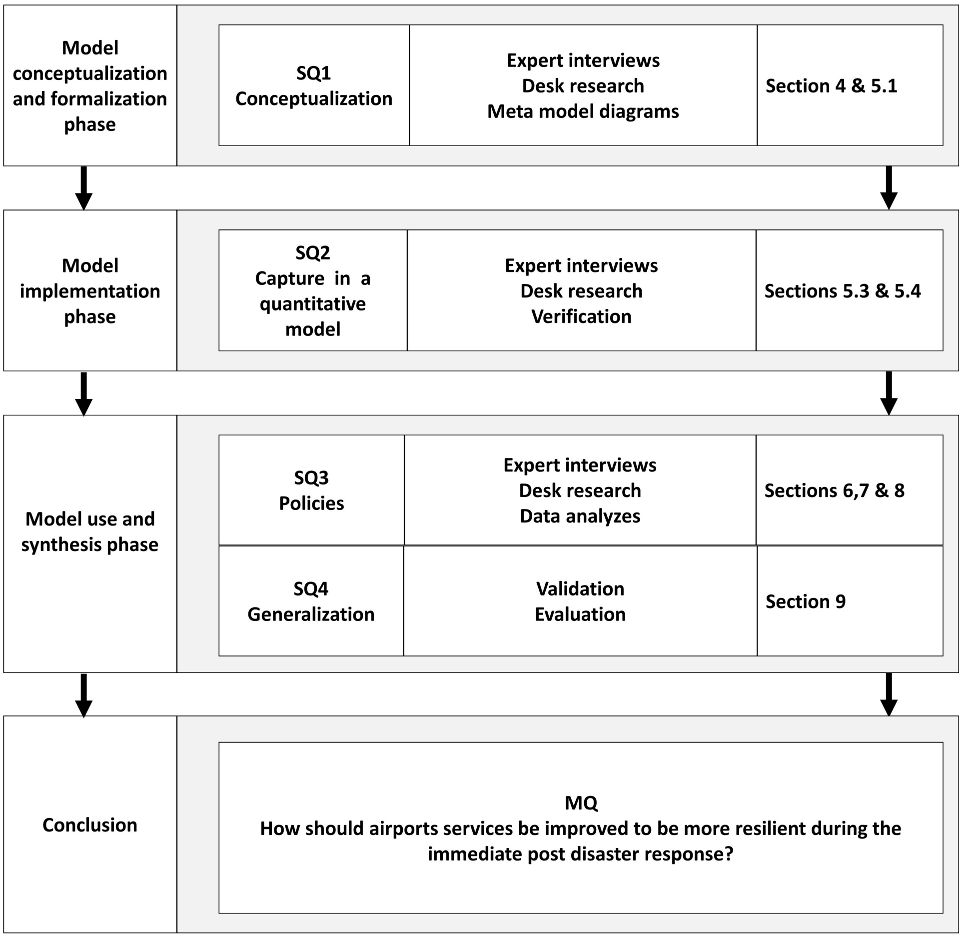


Figure 3: Research flow

4 The airport system in the immediate disaster situation

To study the congestion problems at airports in immediate disaster situations, the airport system is analyzed in this chapter. This includes an actor analysis, system decomposition and the identification of performance indicators.

4.1 Actor identification

In this section, the different actors involved in the formulated problem will be identified and described. The actor identification creates the foundation to define the system boundaries. Based on the actor identification a selection is made of actors that are part of the studied system.

An extensive method for structurally analyzing actors is explained by Enserink et al. (2010). Based on the method of Enserink et al. (2010) the field of actors and their influence on the operations of an airport is mapped based on the reports and studies of CAAN (2012), White (2015), UNOCHA (2014), Styles (2017), Pandey, Ventura, and Moser (2013). All the different parties that are active in or around the air cargo logistics chain at an airport are displayed in table 4.

Actor	**Objective**	**Core actor**
Local actors		
Local Emergency Management Agency (LEMA)	Help people in need	No
National military	High safety and security	No
Civil aviation authority	High safety and security	No
Customs & immigration	High safety and security	No
Air Traffic Control	High safety and security	Yes
Gate controller	High safety and security	Yes
Ground handlers	Profit & continuity	Yes
Fuel operator	Profit & continuity	No
Freight forwarder	Profit & continuity	No
Commercial aircraft companies	Profit & continuity	No
Humanitarian actors		
OSOCC	Help people in need	No
UN logistic cluster (WFP)	Help people in need	No
Reception & Departure Centre RDC	Help people in need	No
Aid organizations	Help people in need	No
Humanitarian air cargo organization	Help people in need	Yes
Air Coordination Cell	Help people in need	No

Table 4: Actor overview. Local actors are active before the disaster. Humanitarian actors arrive after the disaster. Core actors carry out physical movements of system elements.

The actors can be distinguished in multiple ways. Firstly, on their time of presence. Local actors, who are present before a disaster occurs and humanitarian actors who arrive after a disaster occurs. Secondly, on the objective of actors. Help people in need, profit & continuity and high safety and security are the three different goals of the actors . Thirdly, the actors can be distinguished on their importance for the airport operations. The actors distinguished in core actors and serving parties. The core actors will be incorporated in the model.

- Core actors are actors that carry out a physical movement of the system elements or make decisions that have an influence on the physical movement of the system elements.

- The serving parties are actors that do not carry out physical activities. The serving parties serve the core actors of the system and are not directly involved in operations.

The categorized actors with their interaction with each other are displayed in figure 4. The core actors are presented with a gray background. The modeled system involves the core actors and their interactions. The serving parties will be mentioned when needed. Some of them are involved in the implemented policies. An overview of all actor descriptions can be found in appendix A.

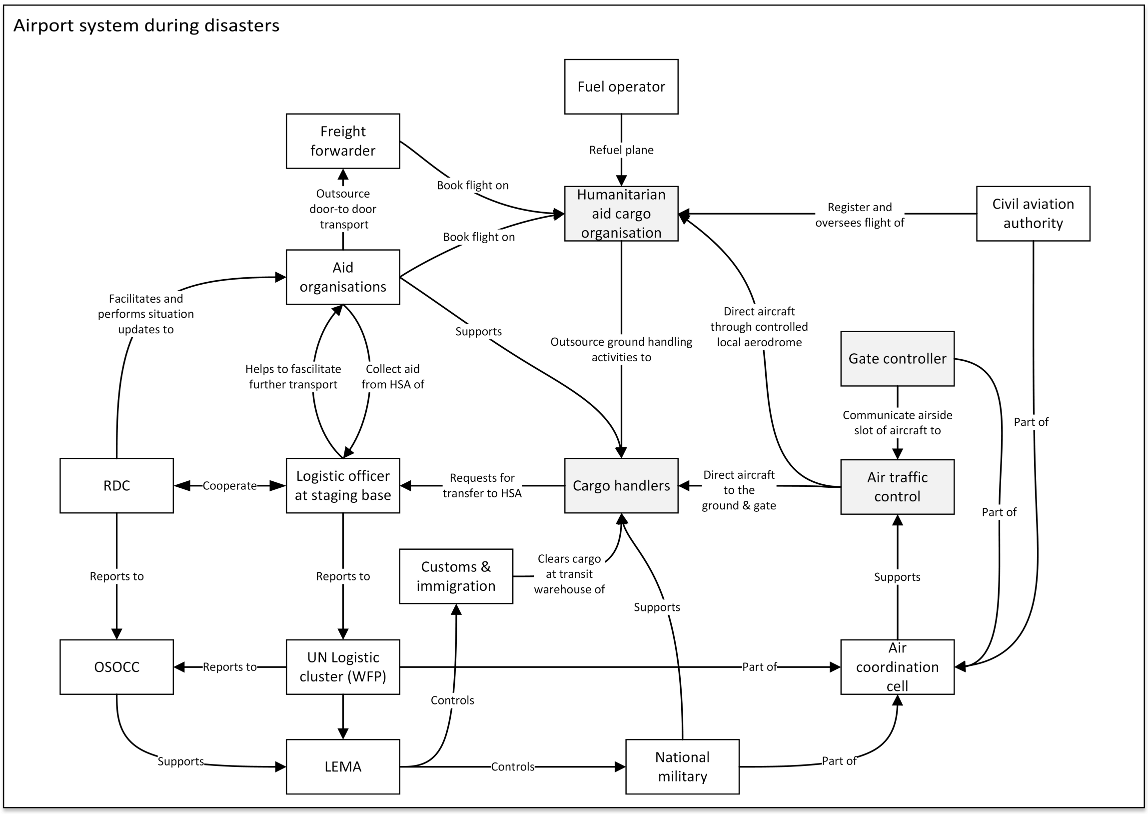


Figure 4: Actor interactions. Core actors have a gray background. Serving actors have white back ground

4.2 System identification and decomposition

In this section the airport system and the interaction of the core actors are identified and decomposed. The boundaries of the system are chosen, and the internal structure is identified to create an overview of all actors with all their interactions over time. In this section, 14 structural model assumption are defined and presented.

Humanitarian air cargo organizations

Humanitarian air cargo organizations are the actors controlling the aircraft. These organizations organize flights and own aircraft of different size and type. Due to the sudden onset of disasters these flights are not scheduled upfront. This results in the situation that every organization charters its own flights, with its own amount of goods, with its own way of packing and with its own arrival time.

Aircraft can be categorized into three categories: small aircraft, narrow body aircraft and wide body aircraft. Each type has its own characteristics. Small aircraft can park on grass and can land on softer runways but cannot carry large amount of cargo and take longer relative to their cargo weight (Franklin, 2015). There are two types of packing: unit load devices (ULD) and loose boxes, also called bulk cargo (Ballestero, 2017). These organizations fly their aircraft to the airport where multiple operations by other actors take place. This makes this actor responsible for two major factors that influence the system: the "type of packing" and the "number of arriving aircraft". After the handling operations are performed, the aircraft depart empty (More & Sharma, 2014; Wu, 2008; Abd Allah Makhloof, Elsayed Waheed, & El-Raouf Badawi, 2014).

Assumption 1: *Humanitarian air cargo organizations are responsible for inflow of aircraft.*

Assumption 2: *Two types of packing ULD and bulk.*

Assumption 3: *Three types of aircraft small, narrow body & wide body.*

Air Traffic Control

Air Traffic Control (ATC) will guide the aircraft of the humanitarian air cargo organizations to the ground and guide them during taxiing. Although there are multiple departments within the ATC tower and there are also actors active on the air side like apron control they are all combined into this single actor, which is responsible for the aircraft approach, landing and taxiing (Schulze, 2012). The landing and separation assurance of different aircraft types is out of the scope of this research. Based on the information of the gate scheduler the ATC will direct the aircraft to the right gate/parking spot (Hansman & Odoni, 2009).

Assumption 4: *Landing and separation assurance of different aircraft types is not included.*

Gate scheduler

The gate schedulers will assign gates to aircraft based on several input factors. The main inputs for gate scheduling are the flight schedule with flight arrival times and the ground handlers' capabilities and capacities. Other factors that influence the gate allocation are: flight or airport breakdowns, flight earliness or tardiness, emergency flights, severe weather conditions and other reasons (Dorndorf, Jaehn, & Pesch, 2008, 2012). These factors are outside the scope of this research, due to time constrains and they have limited impact on the system, compared to the flight arrival times and the ground handlers' capabilities and capacities.

Assumption 5: *Weather conditions are not included.*

Assumption 6: *Infrastructural breakdowns are not included.*

Assumption 7: *Earliness or tardiness are not included.*

Ground handlers
Ground handlers will take over the aircraft control from the ATC when it approaches the gate assigned by the gate scheduler. They marshal the aircraft into the right parking spot and unload the aircraft. The marshal operation and parking of the plane will be aggregated in the unload time of the aircraft. This is done to prevent the model to be too microscopic.

Hereafter the aircraft is unloaded. The unloading process requires workers, heft trucks, high loaders, tractors and dollies to unload the aircraft (Franklin, 2015). These resources are simplified into workers and high loaders, because the high loader is often the critical equipment (Director humanitarian affairs DHL, 2018). When the cargo is unloaded from the aircraft the cargo is delivered to the warehouse. At the warehouse the cargo is unloaded from the dolly, checked by customs, broken down and loaded to the vehicle for further transport to the HSA. The transport of cargo from the transit warehouse at the airport to the HSA is performed by the Log Off and outside of the scope of this research.

The time the ground handler needs to unload the aircraft, store and reload the cargo is dependent on internal and external factors. The internal factors are the total available number of workers, gates, unloading equipment and the surface of the warehouse. The workers are divided into two groups based on the model components: warehouse workers and aircraft unloading workers. Every worker can perform each task within its component. For every vehicle/equipment a fixed number of workers is needed, otherwise the equipment cannot be used. The external factors are the type of aircraft and the type of packing (More & Sharma, 2014; Wu, 2008; Abd Allah Makhloof et al., 2014).

Assumption 8: *Marshal equipment and personal is not included.*

Assumption 9: *The marshal & parking operations are aggregated in the unload time of the aircraft.*

Assumption 10: *The unloading resources are simplified to high loaders and workers.*

Assumption 11: *Infinite amount of trucks for further transportation to HSA.*

Assumption 12: *Equipment needs fixed number of workers to be operational.*

Assumption 13: *Workers are divided in two groups: warehouse workers and aircraft unloading workers.*

Assumption 14: *Workers can perform every task within its component.*

The environment of this system consists of the number of incoming flights with its amount of cargo, the way the cargo is packed and the attendance rate of ground handling workers. These factors are external and uncertain and have influence on the system. The other serving parties are part of the system environment.

4.3 Resilience performance indicators

The problem this system is facing is the inability to cope with the influx of aircraft, change in aircraft & cargo type and risks of no turning up of employees, which lead to congestion at the airport and because of that the airport system becomes the bottleneck of the total humanitarian response. The ability of this system to cope with this problem is measured via the key performance indicators (KPI). The KPIs of the system are the factors that indicate to what extent the problem is solved. The problem defined in section 2 is addressed by making the airport services more resilient in the immediate post-disaster situation. Traditional resilience studies for disaster event use the resilience triangle displayed in figure 5 (K. Tierney & Bruneau, 2007).

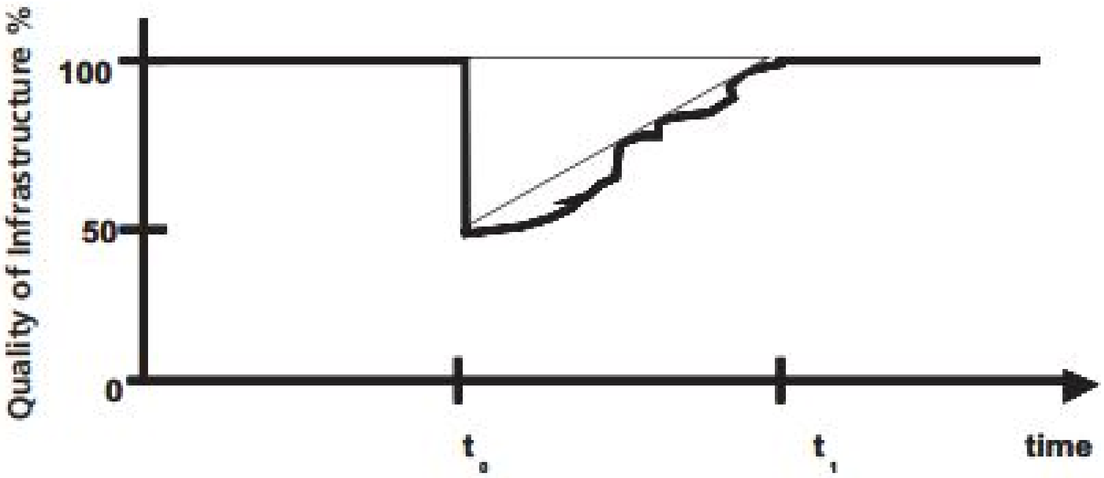


Figure 5: Traditional resilience triangle (K. Tierney & Bruneau, 2007)

This triangle can be defined by three characteristics which are displayed in figure 6. These characteristics are: absorptive capacity, adaptive capacity and recovery time. The absorptive capacity is the percentage drop of performance. The absorptive capacity is the degree to which a system can absorb the impacts of system perturbations and minimize consequences with little effort. The adaptive capacity is focused on the recovery process to the base level. The adaptive capacity is the ability of a system to adjust to desirable situations by undergoing some changes. This factor defines how the curve goes back to the base level. The recovery time defines how long it takes to reach the base level. The recovery time of the system is characterized by the rapidity of return to the base level by an implementation of an adaptive measure.

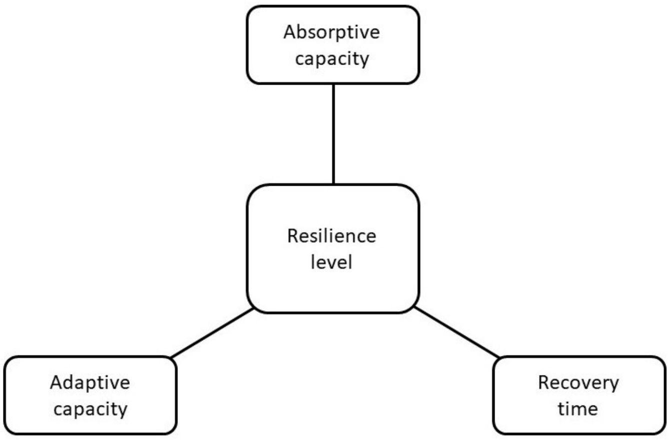


Figure 6: Resilience characteristics

This traditional concept of resilience is focused on minimizing the surface of the triangle. This definition of measuring resilience is applicable to systems that must recover to pre-disruption performance levels. This definition and method to measure resilience is not applicable to airports in the immediate post-disaster response, because the pre-disruption performance levels are not sufficient in the immediate post-disaster situations (Whitning, 2010). In the immediate post-disaster response, the system must perform better compared to pre-disruption event (Economist Intelligence Unit, 2005). This is in line with the study of Comes and de Walle (2014) that acknowledges that the system itself changes in the immediate post-disaster situation. Woods (2015) defines this better performance compared to the base level as resilience as graceful extensibility. Woods (2015) states that adaptation at the boundaries can be very positive and lead to success.

The performance levels for the airports in disasters situations are schematically displayed in figure 7. A new black triangle occurs which also influences the system's resilience level. This makes the traditional measurement of resilience by measuring the surface of the triangle not applicable anymore.

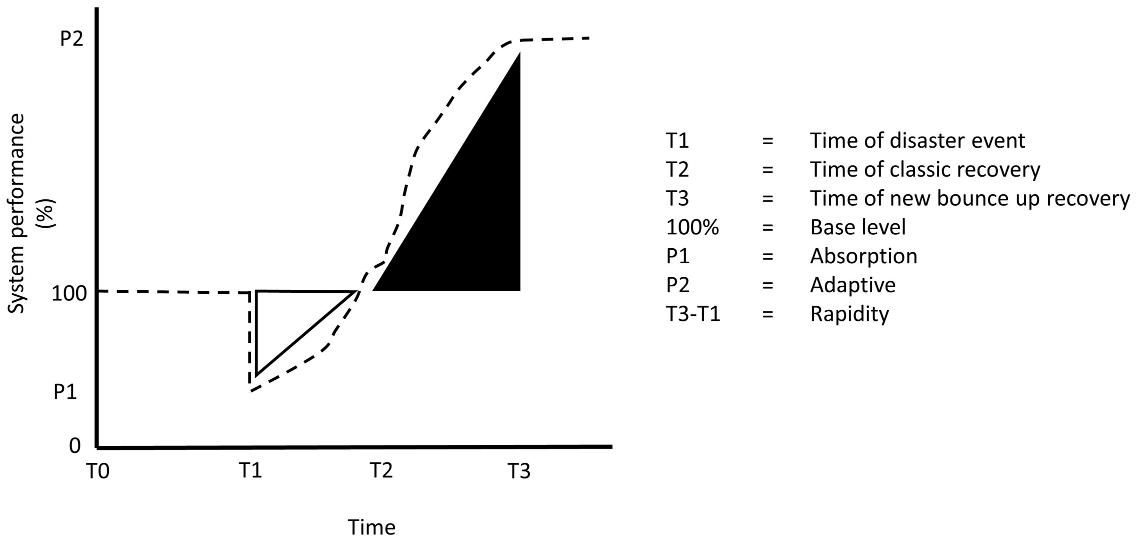


Figure 7: Redefined resilience triangle

This new concept of resilience is harder to quantify compared to the traditional white triangle. The surface of the black triangle cannot be used as an indicator of resilience. The adaptive (height of the black triangle) of the black triangle has a positive influence on the resilience, but the time between traditional recovery and new bounced up recovery level (width of the black triangle) has a negative influence on the resilience score. This new approach to measure resilience requires a prespecified service level of P2 per analyzed system. In the system of airports during the immediate response this level is set to 400% of the normal operations. (Neudert, 2010; Veatch & Goentzel, 2015; Franklin, 2015).

To quantify this black and white triangle, the performances of airport services are measured in three ways: (1) throughput time of one unit of cargo, (2) amount of cargo handled and (3) the amount of cargo that is idle and still in the system. The KPI's of throughput time of one unit of cargo (throughput time) and amount of cargo that is idle and still in the system (idle cargo) can be partly captured with the traditional resilience triangle. The amount of cargo handled cannot be captured with the traditional resilience triangle.

Throughput time (hours)

The cost and speed of the disaster response is highly dependent on the logistic operations and airports are often the bottlenecks of these logistic operations (Kovács & Spens, 2007; Hanaoka & Qadir, 2005; Besiou et al., 2011; Van Wassenhove, 2006). This makes the throughput time of cargo a key aspect performance indicator of the system.

The throughput time displayed in figure 8 is quantified by measuring the three resilience factors. Absorptive capacity is measured by comparing relative the difference between P0 and P1. Adaptive capacity is measured by comparing the relative difference between P2 and P1. The restorative capacity is measured by measuring the differences between T0 and T2. The performance of this indicator is measured in hours. As seen in figure 8 the P2 level does not equal P0. This is not in line with the traditional resilience triangle which assumes a full bounce back. Since the airport system has changed due to the high influx of aircraft, the base level throughput times may be impossible to achieve. This does not mean that they cannot be reached. This schematic figure only shows that they can be different. The fact that P2 & P0 can be different makes it harder to check if P2 is reached. The point of P2 is defined at the moment that: all adaptive measures are applied; the effect of the measures is completed, and the throughput time reaches a stable state.

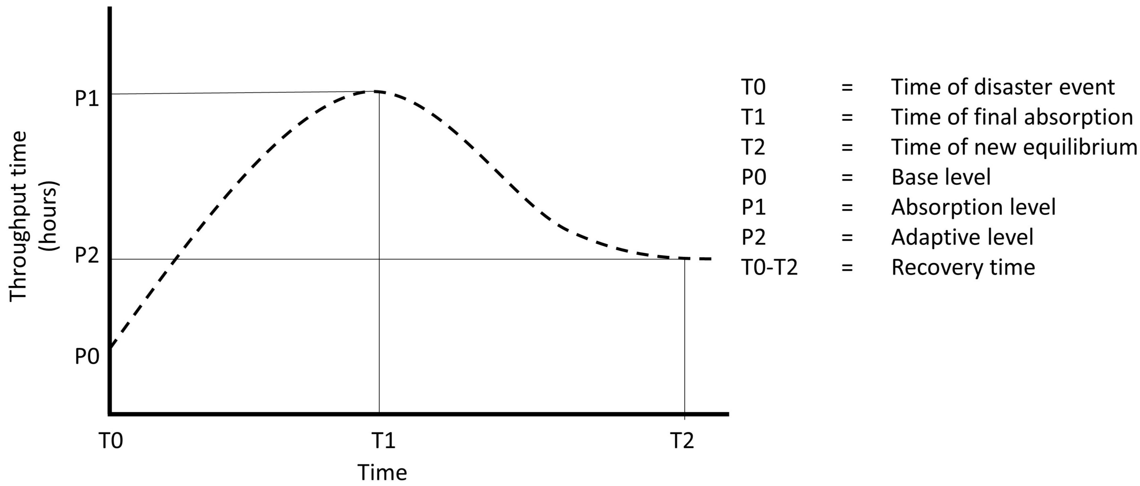


Figure 8: KPI: Throughput time

Idle cargo (tons)

Due to the sudden influx of cargo the airport system is unable to cope with inflow. The amount of unused aid at airports is a large problem and leads to congestion at the airport (Ng, 2015). The amount of congestion is measured by the amount of cargo that is not handled at the moment by the airport. The words "not handled" mean that the cargo is idle, and no operation takes place with the cargo. The flow of the amount of idle cargo is displayed in figure 9. This KPI is measured in tons. The P2 level does not equal P0. This is not in line with the traditional resilience triangle which assumes a full bounce back. Since the airport system has changed due to the high influx of aircraft, the base level amount of idle cargo may be impossible to achieve.

Idle cargo affects the system. Too much idle cargo will disrupt the system itself. For example, aircraft cannot land due to parked aircraft on the runway. The shape of the curve of idle cargo is influenced by two main factors: the inflow of cargo and the outflow of cargo. The inflow of cargo is outside of the scope of this study, the output of the system is studied in detail and is also the third KPI.

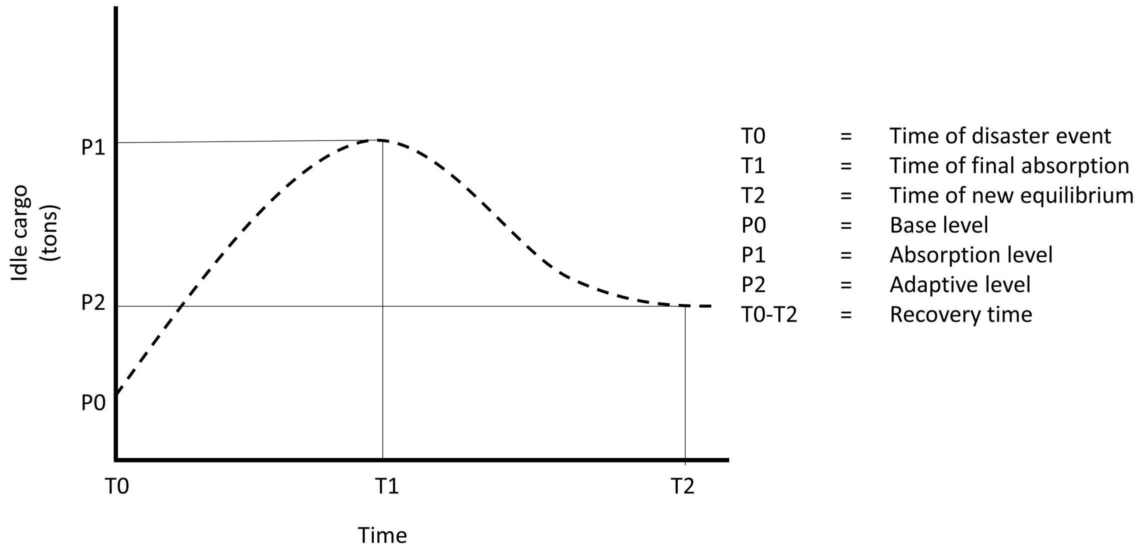


Figure 9: KPI: Idle cargo

Cargo processed (tons/hour)

The KPI cargo processed measures the number of tons of cargo that leaves the system per hour. This indicates the process capacity of the system. The amount of cargo handled has a different graph structure. This KPI cannot be measured with the traditional resilience triangle of figure 5 but will be measured by the new concept of resilience of figure 7. The amount cargo handled in the immediate post-disaster situation is schematically displayed in figure 10. This KPI is measured in tons per hour.

To visualize the resilience of this indicator a new framework is used. This framework is based on the definition of measuring resilience of Francis and Bekera (2014). Absorptive capacity is measured by comparing the relative difference between P0 and P1. Adaptive capacity is measured by comparing the relative difference between P2 and P1. The rapidity is measured by measuring the differences between T0 and T4. The performance decreases at time T3 because, the system moved all idle cargo out of the system. Hereafter the curve moves to P3 which is a stable state were output equals input.

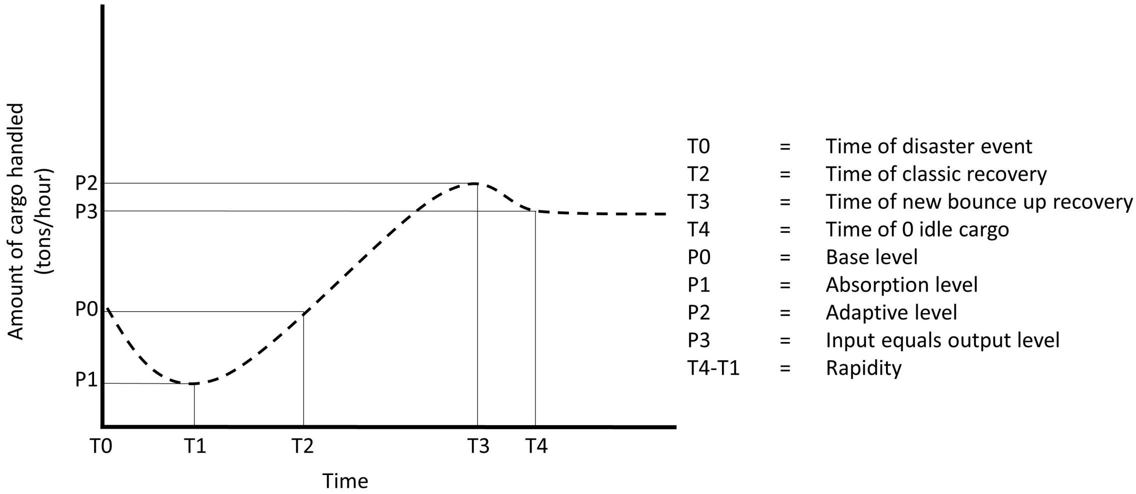


Figure 10: KPI: Cargo processed

These three KPIs: amount of cargo handled, idle cargo and throughput time are measured for all the subsystems/components of the system (1. gate selection, 2. aircraft unloading and 3 warehouse operations). By quantifying these indicators for every component an overall insight in the resilience of the whole system is gained. These KPI create insight when, where and how bottleneck appear in the system and how they relate to each other.

These KPIs are displayed separately and not combined into a single resilient score, because of three reasons: Firstly, the humanitarian aid system is a multi-actor system. As described in section 4.1 every actor has its own objective and the different actors value the KPIs differently. Secondly, the KPIs are linked to each other. Especially cargo processed and idle cargo. If the KPI cargo handled cannot keep up with the inflow the idle cargo will increase. This strong correlation between the KPIs make aggregating of the KPIs into one value inaccurate. Thirdly, the insights about how these graphs evolve over time are lost when the factors are combined in one resilient score.

5 Concept model of the airport system

At this stage, the system is defined, and the relevant involved actors and elements are identified. To create a precise description of the concepts that play a role in the system the model components are described, the assumption and parameterization are defined and finally the implementation and verification are discussed.

5.1 Meta model

The meta-model serves as a graphical representation of the discrete event model. The meta model is a simplification that shows the system components, their input and outputs and relations. The three model components are displayed in figure 11. Arrows from top to bottom represent the control factors of the operation. Arrows from bottom to top represent the resources needed. Horizontal arrows represent the inflow and outflow. Figure 12 shows the meta model with a higher level of detail.

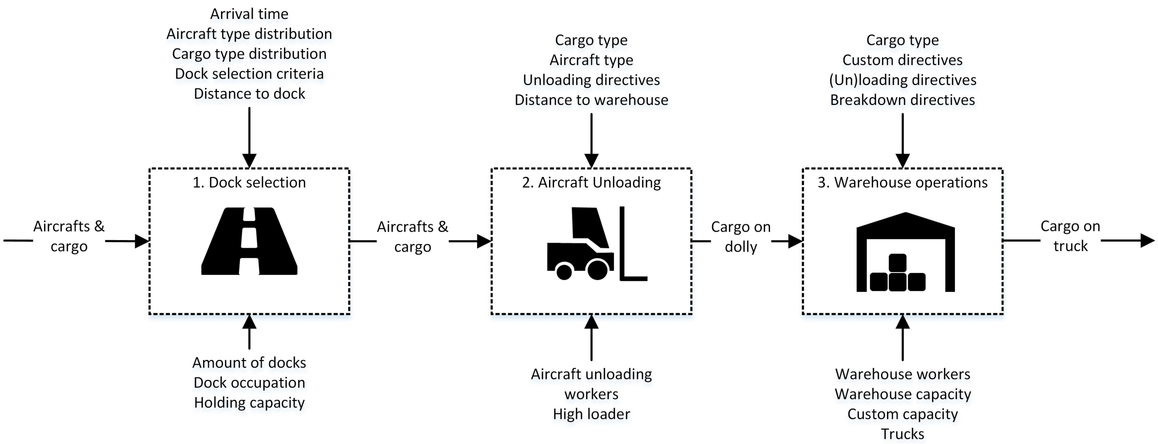


Figure 11: Meta model. Arrows from top to bottom represent the control factors of the operation. Arrows from bottom to top represent the resources needed. Horizontal arrows represent the inflow and outflow.

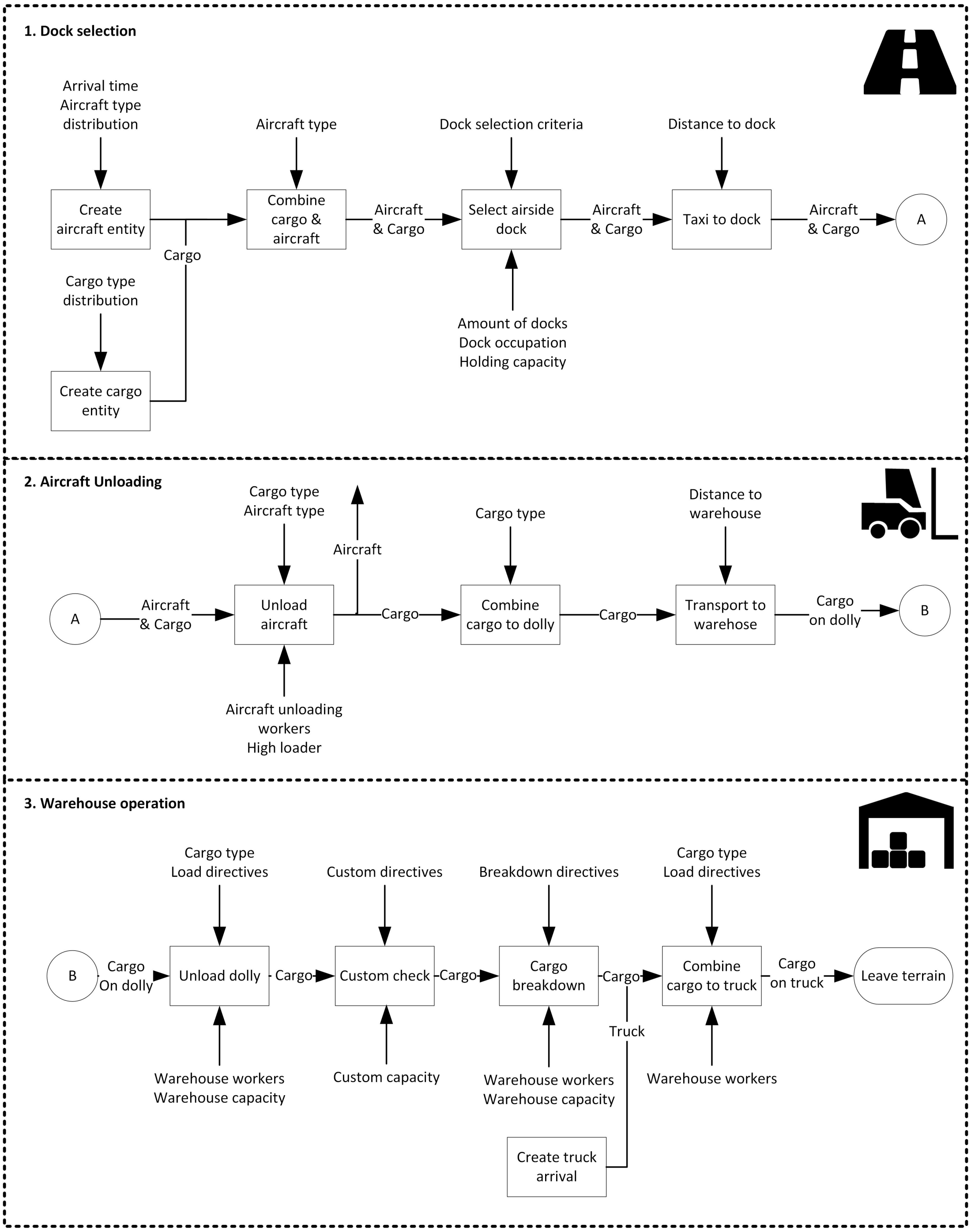


Figure 12: Meta model detailed. Arrows from top to bottom represent the control factors of the operation. Arrows from bottom to top represent the resources needed. Horizontal arrows represent the inflow and outflow.

1. Gate selection

In the first component aircraft and cargo entities are created. They are combined into one entity and arrive at the airport. Based on the selection criteria the airplane is assigned to the dock. The initial selection criterion is based on the first come first serve system (Franklin, 2015). Hereafter the aircraft taxis to the right dock. The travel time is dependent on the distance of the dock from the runway.

2. Aircraft unloading

The unloading component starts at the gate. Employees and high loaders are needed to unload the aircraft. The process time is depended on the aircraft type and cargo type. After this separation process is completed the aircraft leaves the system. The cargo is loaded and combined with the dollies. The cargo is moved to the transit warehouse where it is unloaded from the dolly. The travel time is dependent on the dock location and the dolly speed.

3. Warehouse operations

The warehouse operation starts when the dolly and the cargo arrive at the warehouse. The cargo is unloaded from the dolly. The time this process takes is dependent on the cargo type. The process also requires workers. After this process on a part of the cargo a custom check is performed. The moment the cargo is cleared the cargo is broken down and stored in the warehouse till the consignee arrives. When the consignee arrives, the cargo is loaded on trucks for transport to the HSA. The loading time is dependent on cargo type. The system ends when the trucks leave the warehouse.

5.2 Class diagram

In this subsection, the UML class diagram is presented to create an overview of all the relations that take place between the different entities in the system. Each box contains three compartments that all serve a role in the structure. The top compartment contains the name of the class, which is the main element. The middle compartment contains the attributes that are corresponding to the class. The bottom compartment contains the operations that the class can execute. The UML class diagram is illustrated in figure 13.

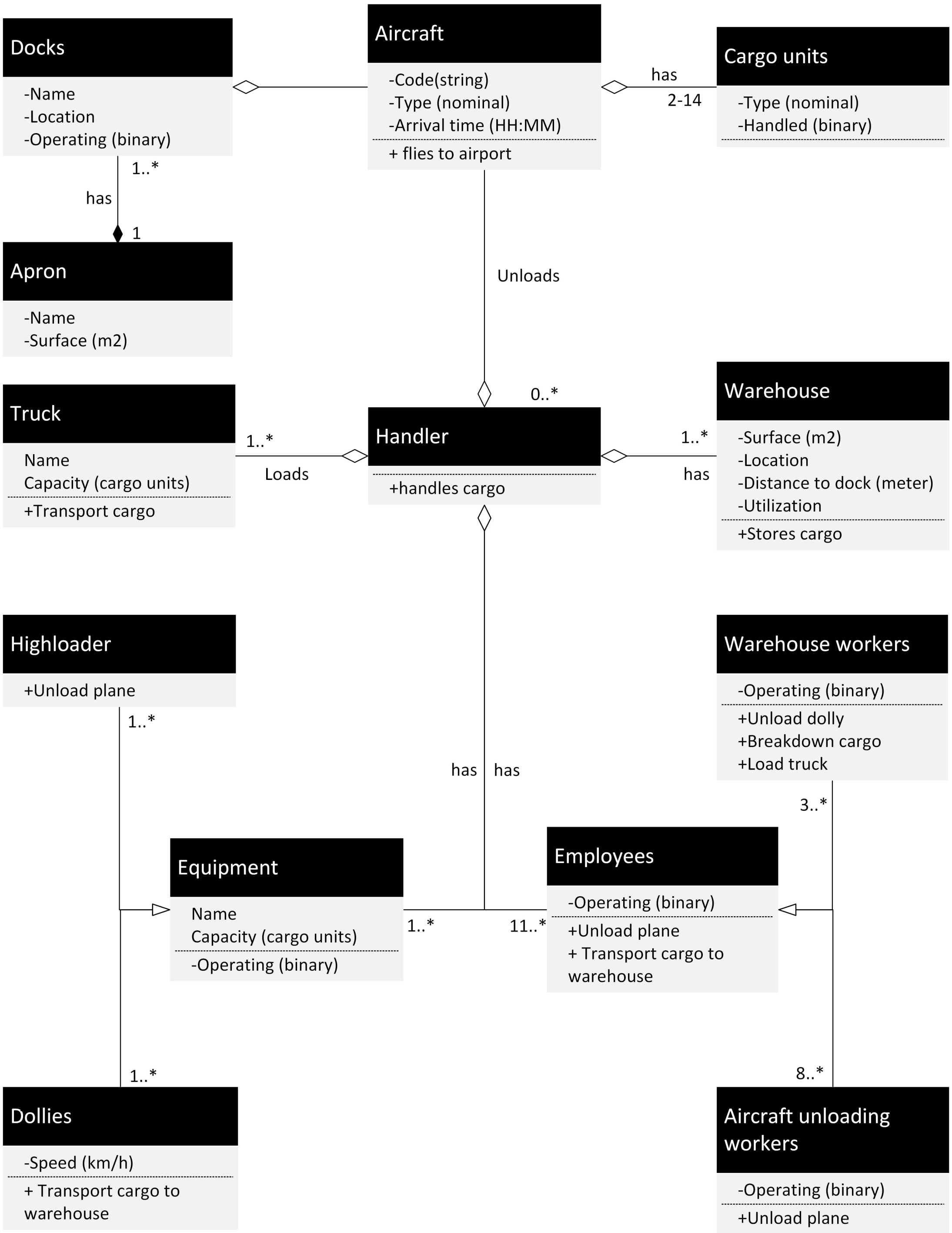


Figure 13: UML diagram of airport system

5.3 Assumptions and parametrization

This section explains the assumptions that are incorporated into the model the model and which parameter values chosen. A lot of assumptions are made to simplify the model. A too complex and too detailed model limit generalization of the model and makes analyzing results overly complex. The parametrization section explains based on literature and/or clear deductive argumentation which values are chosen for the parameters.

5.3.1 Structural assumptions

The structural assumptions are based on the system identification of section 4.2. The system starts with the inflow of aircraft and ends when the cargo is loaded for transport to the humanitarian staging areas. An overview of the assumptions is provided in table 5.

1	Humanitarian air cargo organizations are responsible for inflow of aircraft.
2	Two types of packing ULD and bulk.
3	Three types of aircraft small, narrow body & wide body.
4	Landing and separation assurance of different aircraft types is not included.
5	Weather conditions are not included.
6	Infrastructural breakdowns are not included.
7	Earliness or tardiness are not included.
8	Marshal equipment and personal is not included.
9	The marshal & parking operations are aggregated in the unload time of the aircraft.
10	The unloading resources are simplified to high loaders and workers.
11	Infinite amount of trucks for further transportation to HSA.
12	Equipment needs fixed number of workers to be operational.
13	Workers are divided in two groups: warehouse workers and aircraft unloading workers.
14	Workers can perform every task within its component.

Table 5: structural assumptions

5.3.2 Parameterization of model

Due the limited amount of data to quantify the model, assumptions about the variables must be made to define the initial model. The limited amount of available data makes this model not a representation of a real disaster. The model represents a hypothetical case which is based on data of the Nepal earthquake of 2015 and the Haiti earthquake of 2010. The data sets of these two disasters are gathered via expert interviews and literature research. On top of the combined data sets multiple assumptions are made to calibrate the model. For every assumption the approach how, the value is defined an explanation is given.

The values of the attributes of the entities defined in the class diagram are presented in the order of the model component of the concept model: gate selection, aircraft unloading and warehouse operations. The parameters are divided into three subsets: general, case specific and input parameters. By dividing these parameters, the mesoscopic model is generalizable to other airport and other natural sudden onset disasters like hurricanes. The gate selection parameters can be found in table 7, the unloading parameters can be found in table 9 and the warehouse operation parameters can be found in table 10.

<u>1. Gate selection</u>

The apron consists of pavements with one or more gates (parking spots). The initial number of gates is set to 10. Haiti Port au Prince International Airport - Toussaint Louverture (PAP) has a total aircraft parking area of 80,016 (m2)(Cochran, 2016). This apron holds 11 parking spaces. Only 10 were used in in the relief operations of 2010 due to reservation of one parking spot by the UN (Veatch & Goentzel, 2015). Tribhuvan International Airport in Kathmandu Nepal (TIA) also has 10 parking spaces (Styles, 2015). Since both airports have the same number of gates the model is in line with both airports.

As described in 4.2 the aircraft types are categorized into three groups: small, narrow body and wide body aircraft. The distribution of aircraft that arrive during a disaster is based on the Haiti earthquake of 2010. Veatch and Goentzel (2015) studied arrival distributions and average amount of cargo per aircraft. This data is displayed in table 6. The amount of cargo is modelled as an entity of 2.5 tons. This is in line with the average weight of an BUP (Kallen, 2015). This entity is defined as one cargo unit.

Aircraft type	Distribution of arrivals [%]	Amount of cargo per aircraft [tons]
Small	41.3	5 tons
Narrow body	52.4	20 tons
Wide body	6.3	35 tons

Table 6: Arrival of aircraft

The taxi lane of the airfield is 2 km long and the aircraft taxis at a speed of 30 km/h (Jordan, Ishutkina, & Reynolds, 2010). The 2 km taxi lane is an assumption based on a measurement in Google maps. The PAP taxi way length is set as representative generic taxi lane length. The capacity of the taxi lane as a holding area varies from airport to airport. TIA has a parallel taxi way next to the runway and an extra parking area away from the main gates. PAP does not have this and has a smaller second parking bay. To quantify the holding capacity of the taxi lane cargo units are used instead of aircraft, because the aircraft vary too much in size. Due to limited available data an assumption is made. The assumption of holding capacity of the taxi lane is set to 150 cargo units, which represents 10 wide body aircraft. This parameter is defined as a case specific parameter.

The influx of aircraft compared to the normal operations is not a fixed number. Articles and report mention different numbers, but they vary from a threefold to tenfold fold of arrivals during peak days (Fraser, Hertzelle, Fraser, & Hertzelle, 2010; Franklin, 2015; Veatch & Goentzel, 2015). This variety in the multiplication factor is dependent on the original number of flights and the post-disaster number of flights. This multiplication mostly dependent on the original number of flights. When an airport must handle an a L3 level response the number of post-disaster flights is mostly defined by the maximum capacity of the airport. Due to the US military presence during the Haiti response the PAP was pushed to its limits. Therefore, the inflow of aircraft of the Haiti response is used in the model. During the Haiti response 80 aircraft arrived per day between 6 o'clock and 24 o' clock (Veatch & Goentzel, 2015; Neudert, 2010). To model the previous stated variety in influx multiplication of air movements, this variable is defined as dynamic. The arrivals during peak time will be 60, 80 or 100 flights per day.

Since the aircraft arrivals of the PAP airport are used for the number of arrivals during the response, the original arrivals will also be based on the PAP airport. During normal operations PAP handles 238 tons of cargo per day. Based on the aircraft type distribution of Veatch and Goentzel (2015) this results in 18 cargo flight arrivals per day (Cochran, 2016). Which represents a four times increase of cargo. The increase of aircraft happens after the disaster. In the model the disaster strikes at 6 o'clock in the morning of the sixth day. The increase of arrivals from 18 to 80 flights per day goes gradually with 50 arrivals on the fourth day after the disaster. This is the 10th day of the model simulation. (Neudert, 2010).

The ratio of flights that arrive with loose cargo also known as bulk cargo is uncertain, due to limited data availability. The aircraft with bulk cargo have huge impact on the throughput times (Franklin, 2015). The main factor that influence the amount of bulk cargo is which organization organizes the flight. If this cargo organization owns old Russian cargo aircraft, the type of cargo is often bulk. Which organization is responsible for the flight is mostly determined by the location of a disaster. These cargo organizations with old Russian cargo aircraft are mostly found in Africa and Asia and almost nowhere in North and South America (Director humanitarian affairs DHL, 2018). In conclusion it can be stated that the amount of bulk cargo is determined by the location of the disaster. Due to limited data on the exact ratio of bulk cargo this parameter is an assumption. The ratio of bulk cargo is set as a dynamic variable. Before the disaster it will be 0%. After the disaster it will be either 0% or 30%. This depends on the kind of scenario.

Model constant	Value	Source
General parameters		
Ratio of small aircraft	41.3 [%]	Veatch and Goentzel (2015)
Ratio of narrow body aircraft	52.4 [%]	Veatch and Goentzel (2015)
Ratio of wide body aircraft	6.3 [%]	Veatch and Goentzel (2015)
Amount of cargo per small aircraft	2 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Amount of cargo per narrow body aircraft	8 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Amount of cargo per wide body aircraft	14 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Weight cargo unit	2.5 [metric tons]	Kallen (2015)
Taxi lane	2 [km]	Measurement
Aircraft taxi speed	30 [km/h]	Jordan, Ishutkina, and Reynolds (2010)
Case specific parameters		
Arrivals per day	18 [aircraft]	Cochran (2016)
Number of gates	10 [gates]	Veatch and Goentzel (2015)
Taxi lane capacity	150 [cargo units]	Cochran (2016) & assumption
Input parameters		
Arrivals during peak days	(60,80,100) [arrivals per day]	Veatch and Goentzel (2015), Neudert (2010)
Ratio of bulk cargo	(0, 0.30) [bulk ratio]	Franklin (2015) & assumption

Table 7: Gate selection parameters

2. Unloading

The unloading time of an aircraft depends on its size and the way of packing. Ballestero (2017) states that bulk cargo takes up to 2.5 times the unloading time compared to BUP. This is in line with the study of Franklin (2015), which states that a bulk packed narrow body aircraft takes over 5 hours to unload. The time on ground (TOG) of different aircraft types with BUP cargo are based on Veatch and Goentzel (2015). This data set is based on TOG of aircraft in the Haiti response of 2010. It is assumed that this data can be used to define TOG for other disasters as well. Therefor this data is defined as a general parameter. This data is displayed in table 8

Aircraft type	TOG (BUP) [minutes]	TOG (bulk) [minutes]
Small	$\mathcal{N}(63, 55)$	$\mathcal{N}(158, 138^2)$
Narrow body	$\mathcal{N}(119, 66)$	$\mathcal{N}(298, 165^2)$
Wide body	$\mathcal{N}(183, 80)$	$\mathcal{N}(458, 345^2)$

Table 8: Unloading times

The unloading of aircraft requires two resources in this model: a high loader and workers. The number of workers needed to unload an aircraft is set to 8 workers (Ballestero, 2017; Project Manager & Vice president Dnata, 2018). These workers have different tasks during the unloading, but this level of detail is not included into the model. The initial number of workers in the system is 24. This is 8 times the number of initial high loaders (3). The number of high loaders is based on the calibration on the normal inflow of 18 cargo aircraft per day. To handle 18 aircraft per day 3 high loaders are needed.

To model the impact of the disaster itself on the daily operations a percentage of workers that will not show up is implemented into the model. This will affect the system performances. There is no data on this parameter and on top of that this parameter differs per disaster (Director humanitarian affairs DHL, 2018). This parameter is therefore defined as dynamic. It will be either 0% or 30%. This depends on the kind of scenario.

The speed of the dolly is set to 15 [km/h] (Schoenmaker, 2016).

Model constant	Value	Source
General parameters		
Dolly/Transporter/worker speed	15 [km/h]	Schoenmaker (2016)
Cargo amount small aircraft	2 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Cargo amount narrow body aircraft	8 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Cargo amount wide body aircraft	14 [cargo units]	Veatch and Goentzel (2015), Kallen (2015)
Workers needed for unloading aircraft	8 [unloading workers]	Ballestero (2017), Project Manager and Vice president Dnata (2018)
Equipment needed for unloading aircraft	1 [high loader]	Ballestero (2017), Project Manager and Vice president Dnata (2018) & assumption
Unloading time BUP packed small aircraft body	$\mathcal{N}(63, 55)$ [min]	Veatch and Goentzel (2015)
Unloading time BUP packed narrow body aircraft	$\mathcal{N}(119, 66)$ [min]	Veatch and Goentzel (2015)
Unloading time BUP packed wide body aircraft	$\mathcal{N}(183, 80)$ [min]	Veatch and Goentzel (2015)
Unloading time bulk packed small aircraft body	$\mathcal{N}(158, 138)$ [min]	Ballestero (2017), Franklin (2015), Veatch and Goentzel (2015)
Unloading time bulk packed narrow body aircraft	$\mathcal{N}(298, 165)$ [min]	Ballestero (2017), Franklin (2015), Veatch and Goentzel (2015)
Unloading time bulk packed wide body aircraft	$\mathcal{N}(458, 345)$ [min]	Ballestero (2017), Franklin (2015), Veatch and Goentzel (2015)
Case specific parameters		
Number of workers	24 [workers]	Assumption
Number of high loaders	3 [high loaders]	Assumption
Input parameters		
Ratio of no show of workers	(0, 0.30) [no show ratio]	Assumption

Table 9: Unloading parameters

3. Warehouse operations

The warehouse processes are labor intensive processes. The number of warehouse workers is defined based on calibration on the normal inflow of 18 cargo aircraft per day. The initial amount of warehouse workers is set to 24.

The unloading of the dollies requires 3 minutes per cargo unit (Schuppener, 2016). Bulk cargo requires 7 minutes per cargo unit. Ballestero (2017) states that bulk cargo takes up to 2.5 times the unloading time compared to BUP. The unloading of the dollies requires 2 workers. This number is an assumption and is based on Ballestero (2017) that states that most cargo handling processes require 2 workers.

Due to limited data availability on the custom operations in disaster, custom operation processes are copied from Schiphol. When the cargo is stored in the warehouse, the cargo is checked for customs. This is done by controlling samples of the total cargo. 10% of the cargo is taken as a sample on which the custom check of 10 minutes is performed (Schuppener, 2016). Due to lack of available data the custom capacity is unknown. In this model the custom capacity is set to 1 cargo unit.

Hereafter the cargo units are broken down and prepared for transport on to trucks. This breakdown processes takes between 10 and 30 minutes and requires 3 workers (Director humanitarian affairs DHL, 2018).

When the cargo is broken down, it is stored in a warehouse to get picked up by aid consignees. Director humanitarian affairs DHL (2018) states that in some occasions it took months to get the cargo picked up by the consignees and a 5-day waiting time is not uncommon. These values are difficult to model, due to limited data on this aspect no valid distribution can be made.(Director humanitarian affairs DHL, 2018). Therefore, the waiting time is defined as a uniform distribution of 1 to 9 hours. This distribution is derived from Schiphol (Schuppener, 2016).

Hereafter the cargo is loaded on a truck. A truck can hold on average 4 cargo units. The loading time of a truck depends on the type of cargo. It takes 3 minutes to load a BUP and 2.5 times longer (7 minutes) to load loose cargo. The loading process requires 2 workers (Schuppener, 2016). The amount of land side docks to load the trucks is not a limiting factor. Also, the amount of available trucks is set to infinite since this not included into the model.

The capacity of the warehouse is measured in cargo units. TIA and PAP have different warehouse capacities and these parameters vary widely per airport (Cochran, 2016; Styles, 2015). Under normal model operations of 18 cargo aircraft arrivals per day 50 cargo units are stored in the warehouse. In this model the warehouse capacity is set to 150 cargo units.

To model the impact of the disaster itself on the daily operations, a percentage of workers that will not show up is implemented. The reasoning and percentage of the number of workers that will not show up is similar to the unloading component.

Model constant	Value	Source
General parameters		
Unloading time dolly BUP	3 [min]	Schuppener (2016)
Unloading time dolly bulk	7 [min]	Ballestero (2017), Kallen (2015)
Workers needed for dolly unloading	2 [workers]	Assumption
Breakdown cargo	Random.Uniform(10 ,30) [min]	Director humanitarian affairs DHL (2018)
Workers needed breakdown operation	3 [workers]	Director humanitarian affairs DHL (2018)
Customs scan required	10 [%]	Schuppener (2016)
Customs scan duration	10 [min]	Schuppener (2016)
Customs capacity	1 [cargo unit]	Assumption
Loading time truck BUP of 1 cargo unit	3 [min]	Schuppener (2016)
Loading time truck bulk of 1 cargo unit	7 [min]	Schuppener (2016)
Truck capacity	4 [cargo_units]	Schuppener (2016)
Workers needed for truck loading	2 [warehouse workers]	Schuppener (2016)
Case specific parameters		
Number of workers	24 [workers]	Assumption
Warehouse capacity	150 [cargo units]	Cochran (2016) & assumption
Input parameters		
Ratio of no show of workers	(0, 0.30) [no show ratio]	Assumption

Table 10: Warehouse operation parameters

5.4 Implementation

This section discusses the implementation of the model into the modeling environment. First, the modeling environment will be introduced, then the programming practices that are used during the programming stage will be discussed.

5.4.1 Modeling environment

There are multiple modeling methods to model the airport system like static models, continuous models, discrete event models and hybrid versions. In this study, the discrete event simulation is used as the modeling environment. Discrete event simulation is a successful method to study material handling systems (Schriber, Brunner, & Smith, 2014). The application tool Simio is used as discrete event modeling application. This application is focused on object modeling. Based on this information this application and method match the concepts that this research studies.

5.4.2 Verification

In this section the results of the verification of the implementation of the model are presented. It demonstrates if the model indeed behaves in the way that is intended. The model verification consists of two components: (1) verification checks and (2) verification runs. The verification checks consist of: model correctness, balance checks, event tracking and run time visualizations. The verification runs consist of: degeneracy testing and continuity testing. The full verification results can be found in appendix B. Based on the performed checks and test runs it can be concluded that the discrete event model functions as intended in the concept model with one policy limitation.

This policy limitation occurs during the continuity testing and is discussed in appendix B.2. This limitation includes that a small change in the number of workers results in an out of proportional change of system performances. This is a limitation of the model. Policies that involve small changes in the number of workers can therefore not be implemented in this model.

6 Policies

To improve the problems at airports 6 pre-specified policies are introduced. The description of every policy consists of the following 6 elements: (1) introduction, (2) historic refence, (3) actor perspectives, (4) implementation time, (5) limitations and (6) model implementation. In table 11, an overview of the policies and their corresponding category is displayed. The policies are categorized into two groups operational and structural policies. Structural policies need physical changes and operational policies change processes.

Policies	**Category**
Extra resources	Structural
Prioritize on size	Operational
Prioritize on cargo type	Operational
Extra warehouses	Structural
Extra holding area	Operational
Combined policy	Structural & operational

Table 11: Experiment categories

6.1 Extra resources

One way to handle the influx of aircraft is by adding more resources to the system. These resources consist of unloading equipment and specialized workers. As displayed in figure 14, this policy affects the aircraft unloading component and the warehouse operations component. This policy is categorized as a structural policy because physical changes to the system are made. By adding these extra resources, the handling capacity of the airport increases (CFE-DMHA, 2015; Logistic Cluster, 2015).

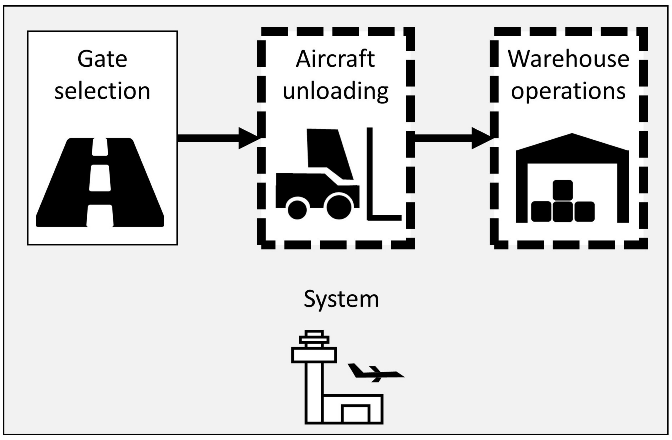


Figure 14: Affected components by extra resource policy

Adding extra resources into the system is a common way to handle a disaster response. During the Nepal and Haiti response local military, foreign military and aid organization like DHL supplied the airport with extra resources to increase the capacity (CFE-DMHA, 2015; Logistic Cluster, 2015; Styles, 2010; Director humanitarian affairs DHL, 2018).

From an actor perspective this means that aid organization and the military help cargo handlers to increase their resources.

The implementation time of the policy depends on agility of the aid organization and the military. In Nepal, DHL arrived on the third day of the disaster, but in Haiti DHL arrived on the fifth day (CFE-DMHA, 2015; Styles, 2010). The unloading equipment of UK government arrived even later (Logistic Cluster, 2015). It can be concluded that the implementation time of this policy is dynamic.

The limitation of this policy is that the selected workers should be specialized workers. A firefighter is not able to help during the unloading process of an aircraft and will do more harm than good, because aircraft unloading requires a special set of skills that cannot be trained in such a small-time frame. (Project Manager & Vice president Dnata, 2018; Director humanitarian affairs DHL, 2018).

The above described policy is simplified and implemented into the model. In the model the amount of extra resources is defined as the amount of resources that is needed the maximize the improvement of the system. In practice this means that the number of high loaders is similar to the number of gates. The number of added workers is calibrated based on the number of workers that are needed to serve all high loaders. The ratio of no show workers is considered in this calibration. In the model the graduate arrival of extra resources is simplified to one arrival moment for all resources. This arrival time of the all resources is dynamic. This occurs on the third, fourth or fifth day after the disaster. An overview of the changed model parameters can be found in table 12.

Model constant	Value	Source
Unloading process parameters		
Days till arrival of extra resources	(3,4,5) days	CFE-DMHA (2015)
Extra unloading workers	(56, 64) [workers]	Assumption (max extra)
Extra equipment	7 [high lifters]	Assumption (max extra)
Warehouse operation parameters		
Extra warehouse workers	24 [workers]	Assumption

Table 12: Extra resources policy parameters

6.2 Prioritization on aircraft size

A second way to handle the influx of aircraft is by creating a prioritization mechanism on aircraft size. Larger aircraft are prioritized over smaller ones. In practice this means that when two aircraft are waiting in the holding area on the taxi lane, the largest aircraft with the largest amount of cargo gets assigned to a gate first. If both aircraft have the same size, the traditional first come first serve mechanism is applied. As displayed in figure 15 this policy affects the gate selection component. This policy is categorized as an operational policy because no physical changes to the system are made and only the process of the gate allocation are changed from first come first serve to prioritization on aircraft size.

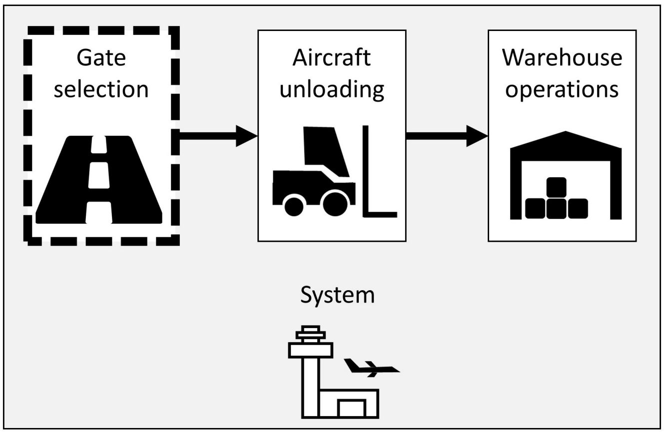


Figure 15: Affected component by prioritization on aircraft size policy

Wide body aircraft need less time on the ground per cargo unit compared to smaller aircraft (Franklin, 2015; Veatch & Goentzel, 2015). From this point of view larger aircraft should have a higher priority compared to smaller aircraft. Prioritization of aircraft in gate selection is rarely implemented in humanitarian aid situations. The only time prioritization was implemented at full scale was during the Haiti response (Styles, 2010).

From an actor perspective this means that the gate controller, air traffic control and the air coordination cell should reorganize their processes. This extra process of prioritization should be added to the responsibilities of these actors.

The implementation time of the policy depends on agility of the gate controller, air traffic control and the air coordination. Although no physical changes must be made, the organizational structure and responsibilities of the system change. To realize this the different actors should have the necessary system in place to realize this policy (Director humanitarian affairs DHL, 2018).

There are multiple limitations of this policy, the major limitation of this policy is that the air traffic control gets extra responsibilities which are out of the scope of their normal operations (Director humanitarian affairs DHL, 2018). The fact that the US military took over the airport during the Haiti response made this organizational change possible (Styles, 2010). The second limitation is that this new criterion, can in some situations result in long waiting times of multiple days for small aircraft. This is in practice impossible.

The above described policy is simplified and implemented into the model. After the disaster occurs the dock allocation decision tree in the dock selection node is immediately updated. Larger aircraft get priority over smaller aircraft and are assigned earlier to a parking spot. Smaller aircraft wait on the taxi lane till no larger aircraft is present.

6.3 Prioritization on cargo type

A third way to handle the influx of aircraft is by creating a prioritization mechanism on cargo type. This policy has multiple similarities with prioritization on aircraft size but differs on some aspects. In this section, only the differences are presented. Aircraft packed with buildup pallets (BUP) are prioritized over aircraft packed with loose boxes. In practice this means that when two aircraft are waiting in the holding area on the taxi lane the aircraft that holds BUP gets assigned a gate first. If both aircraft have the same type of packing the traditional first come first serve mechanism is applied. As displayed in figure 16 this policy affects the gate selection component. This policy is categorized as an operational policy because no physical changes to the system are made and only the process of the gate allocation are changed from first come first serve to prioritization on cargo type.

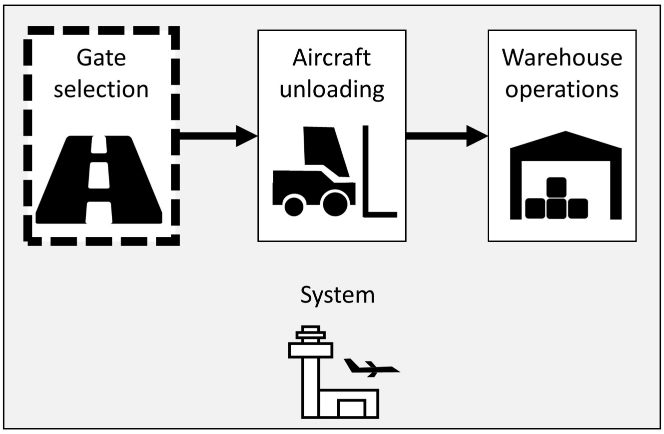


Figure 16: Affected component by prioritization on cargo type policy

Ballestero (2017) and Franklin (2015) state that loose cargo also named bulk cargo take longer to unload. Based on this information aircraft that packed in an efficient way are easier to process. Prioritization of aircraft in gate selection is rarely implemented in humanitarian aid situations. The only time prioritization was implemented at full scale was during the Haiti response (Styles, 2010).

From an actor perspective the same actors of the policy of prioritization on size are included plus the humanitarian cargo organization. Humanitarian cargo organization must communicate their way of packing to the air traffic control. This extra process of prioritization should be added to the responsibilities of these actors.

The implementation time and processes of the policy is similar to the policy of prioritization on size.

There are multiple limitations of this policy, the major limitation of this policy is that the air traffic control gets extra responsibilities which are out of the scope of their normal operations (Director humanitarian affairs DHL, 2018). The fact that the US military took over the airport during the Haiti response made this organizational change possible (Styles, 2010). The second limitation is that this new criterion can in some situations result in long waiting times of multiple days for aircraft that hold loose cargo. This is in practice impossible.

The above described policy is simplified and implemented into the model. After the disaster occurs the dock allocation decision tree in the dock selection node is updated. Aircraft with BUP get priority over aircraft with bulk cargo and are assigned earlier to a parking spot. Aircraft with bulk cargo aircraft wait on the taxi lane till no aircraft with BUP are present.

6.4 Extra holding area

A fourth way to handle the influx of aircraft is by increasing the holding area of the airport. By parking small aircraft on grass and use all available pavement on the airport to hold aircraft before they taxi to a gate the holding capacity of the airport is increased. As displayed in figure 17 this policy affects the gate selection component. This policy is categorized as an operational policy because no physical changes to the system are made, only the location where aircraft should wait before they can taxi to a gate are changed.

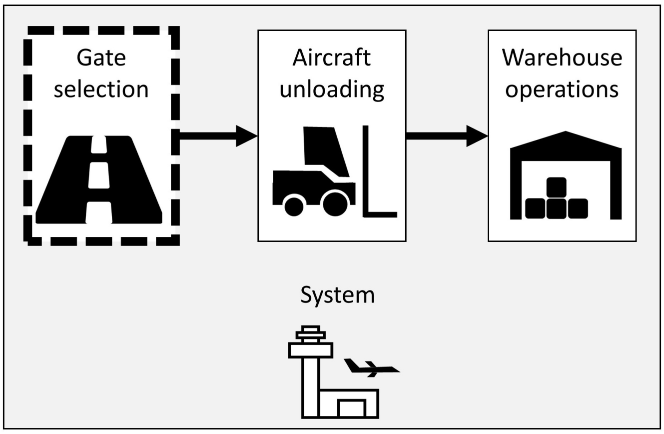


Figure 17: Affected component by extra holding area policy

This policy to increase the amount of parking spaces of an airport has happened before in the response of the great east Japan earthquake of 2011 (Hanaika et al., 2013). It also happened during the Haiti response (Styles, 2010).

From an actor perspective this means that the gate controller, air traffic control and the air coordination cell should reorganize their processes. This new process is still in line of the current responsibilities. Only the location where aircraft should wait is changed.

The implementation of this policy is relatively simple. The air traffic control assigns a new waiting spot for aircraft before they are assigned to a gate. Because of this there is no implementation time needed for this policy

The limitation of this policy is that there is little degree of freedom to implement this policy. If the current taxi way is small and there is no extra paved area on the apron, the effect of this policy is limited.

The above described policy is not implemented into the model. This policy will only result in extra buffer capacity of the system. The aircraft still need to be unloaded and the extra parking spaces don't result in extra throughput. It will only extend the time till the airport is overcrowded. Therefore, this policy is not modeled. However, this policy is implemented in the combined policy. To quantify the holding capacity of the taxi lane cargo units are used instead of aircraft, because the aircraft vary to much in size. Due to limited available data an assumption is made. The assumption of the extra holding capacity of the taxi lane is set to 150 cargo units, which represents 10 wide body aircraft. An overview of the changed model parameters can be found in table 13.

Model constant	Value	Source
Gate selection parameters		
Extra taxi lane capacity	150 [cargo units]	Assumptions

Table 13: Extra holding area policy parameters

6.5 Temporary warehouse

A fifth way to handle the influx of aircraft is by increasing warehouse capacity of the airport. By creating an extra warehouse, the capacity of the warehouse facility is increased. This creates extra buffer capacity in the system. As displayed in figure 18 this policy affects the warehouse operations component. This policy is categorized as a structural policy because physical changes to the system are made. The temporary warehouses don't have to be physical buildings. An emptied secure area away from the aircraft engines can also be used as a temporary warehouse (Director humanitarian affairs DHL, 2018)

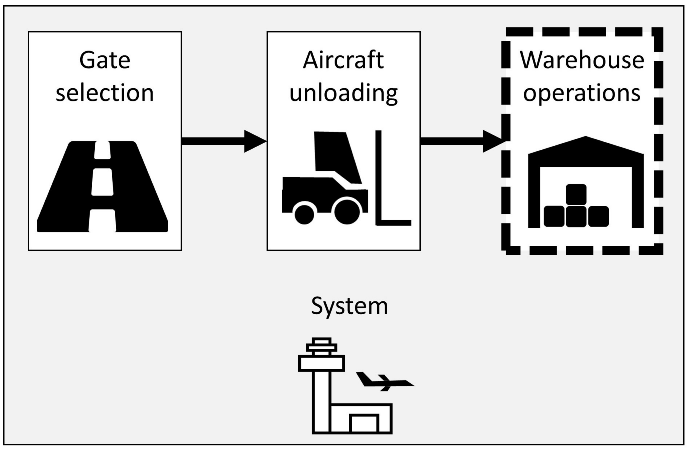


Figure 18: Affected component by temporary warehouse policy

Creating a temporary warehouse is a common way to handle a L3 response. During the Nepal response eight mobile storage units (MSU) were built (Massimo, 2015; Baptiste, 2015a). These were built by the aid organizations and acted as a buffer zone for the influx of cargo.

From an actor perspective this means that aid organization help cargo handlers to increase their warehouse capacity.

The implementation time of the policy depends on multiple aspect. The first aspect is the agility of the aid organization to supply the MSU. The second aspect is availability of people that can build the MSU and the third aspect is the time it takes to build a storage unit. The actual construction of an MSU takes 10 workers for 4 hours (WFP, 2018). This is relatively fast compared to the other processes in the system. The most critical aspect is the time of arrival of the MSU. In Nepal it took 3 days before the MSU's were operational (Massimo, 2015).

The limitation of this policy is the available space on the airport to place the MSU. If an airport is located on top of a mountain or on a small island the available space is limited. This constrains the increase of warehouse capacity.

The above described policy is not implemented into the model. This policy will only result in extra buffer capacity of the system. Cargo units still need to get processes in the warehouse. Extra warehouse capacity will only extend the time till the airport is overcrowded. Therefore, this policy is not modeled. However, this policy is implemented in the combined policy. A MSU can hold 840 m3 of cargo which represent 75 cargo units (Logistic Cluster, 2016; Kallen, 2015). Based on the Nepal response of eight MSU this results in 600 cargo units of extra warehouse space, which can be operational within 3 days after the disaster. An overview of the changed model parameters can be found in table 14

Model constant	Value	Source
Warehouse operation parameters		
Extra warehouse capacity	600 [cargo units]	Logistic Cluster (2016)
Days till extra warehouse capacity	3 [days]	WFP (2018), Massimo (2015)

Table 14: Temporary warehouse policy parameters

6.6 Combined policy

A sixth way to handle the influx of aircraft is by combining all the previous policies into one combined policy. As displayed in figure 18 this policy affects all components. This policy is categorized as a structural and operational policy because as well physical and process changes to the system are made.

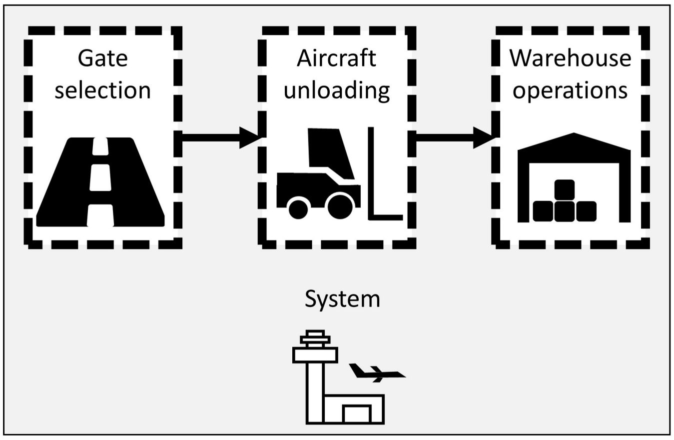


Figure 19: Affected components by combined policy

Based on historic cases it is normal that different policies are combined in these situations. During the Haiti response prioritization and extra resources were combined (Logistic Cluster, 2010). During the Nepal response temporary warehouses and extra resources were combined (Baptiste, 2015a; Massimo, 2015). With the previous five policies and their internal policy parametrization options 360 combination can be made. This is narrowed down to 3 policies. One for every possible arrival time of extra resources. This simplification step is made to simplify the output analyzes.

For this combination of policies, the same actor perspectives, implementation times, limitations and model implementations apply as described in the previous policies. This policy uses two types of prioritization. The first prioritization is made on cargo type and second on aircraft size. This is done, because as displayed in section 8 prioritization on cargo type is more efficient.

When policies are combined they can potentially affect each other. This is not the case in this combination. There are no performance dependencies, no time dependencies and no resilience dependencies between the policies.

The above described policy is simplified and implemented into the model. An overview of the changed model parameters can be found in table 15.

Model constant	Value	Source
Gate selection parameters		
Extra taxi lane capacity	150 [cargo units]	Assumptions
Unloading process parameters		
Days till arrival of extra resources	(3,4,5) days	CFE-DMHA (2015)
Extra unloading workers	(56, 64) [workers]	Assumption
Extra equipment	7 [high lifters]	Assumption
Warehouse operation parameters		
Extra warehouse capacity	600 [cargo units]	Logistic Cluster (2016)
Days till extra warehouse capacity	3 [days]	WFP (2018), Massimo (2015)
Extra warehouse workers	24 [workers]	Assumption

Table 15: Combined policy parameters

7 Experimentation

In this section the experimental design is presented. The experimental design defines the environment where the different policies are compared to each other. First, the experiment plan is formulated including the run length and replications. Hereafter the output values are presented and at last the scenarios are discussed.

7.1 Experimental plan

The run length of the model is 20 days. These 20 days are divided into two segments: a pre-disaster situation and a post-disaster situation. The split occurs at 6 o'clock in the morning of the sixth day. The scope of this research is focused on the immediate response. To model the immediate response phase at an airport a 14 days simulation is sufficient. Based on earthquake of Nepal 2015 and Haiti 2010 it can be concluded that the situations on the airport stabilizes within 14 days (Stanhope, 2010; Baptiste, 2015b). After these 14 days the recovery phase starts this will put less pressure on the airport (UNOCHA, 2011).

The number of replications of the experiment is set to 160. 160 runs are chosen, because of three reasons: First, the practical reason of stable output curves. With 160 replications the output curves are stable and don't have abnormal spikes. The second reason is that with 160 replications 95% of all model output fall within the confidence interval. This analysis is presented in appendix C. The third reason is the model run time. The model run time is minimized under the condition that the first two criteria are met. This results in 160 per experiment design.

7.2 Output values

The model produces 12 output values. The three different KPI's are processed cargo, idle cargo and throughput time which are further explained in section 4.3. These KPI's are measured for all three-model components (gate selection, aircraft unloading and warehouse operations) and the total system. The interval of measurement is one hour. In figure 20, the measurements are schematically displayed. For every graph plotted these diagrams will be used to schematically display the location and type of the measurement.

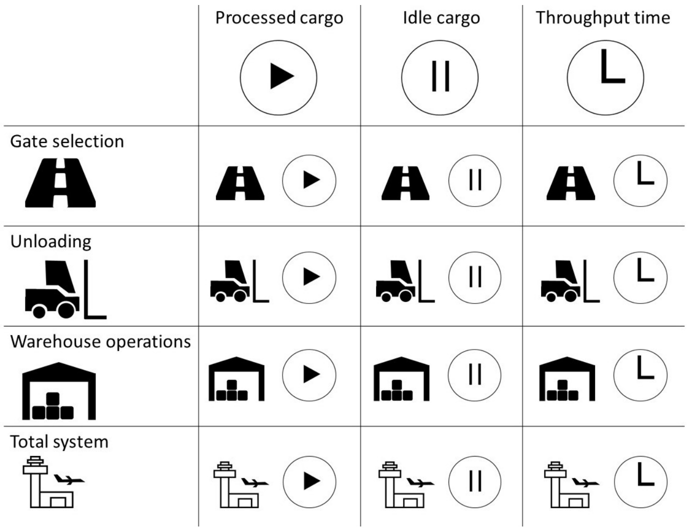


Figure 20: Output values

7.3 Scenario selection

In section 5.3.2 two input parameters are defined as dynamic. The percentage of workers that will not show up and the percentage of cargo that are loose boxes after the disaster occurred. Data on these two parameters is scares. The values of these parameters are simplified into two options 0% or 30%. By using only two values the outcome space is simplified. This benefits the communication of the results. The following four scenarios are created: (1) 30 % of worker will not show up and 30 % of cargo is loose boxes, (2) 30 % of worker will not show up and 0 % of cargo is loose boxes, (3) 0 % of worker will not show up and 30 % of cargo is loose boxes and (4) 0 % of worker will not show up 0 % of cargo is loose boxes.

8 Data analysis

In this section, the data obtained by running the experiments are displayed. For every policy an analysis is made.

The results of the different policies are displayed together with the applicable KPI. An overview of framework of section 4.3 is displayed in figure 21. This framework is used to analyze the effect of the policies on the level of resilience of the system.

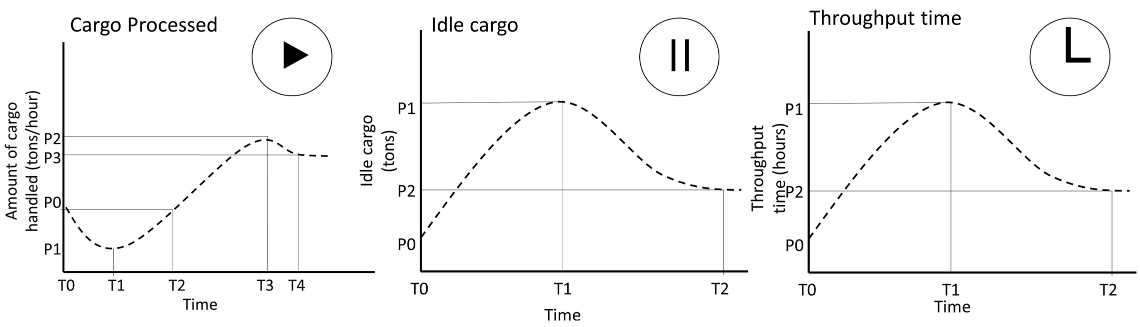


Figure 21: Framework of the KPI's. For every policy the different aspect of resilience of the 3 KPI's are analyzed.

Every plot consists of 5 lines. The legend of the plots can be found in table 16. The blue, green, yellow and red lines represent the scenarios. The analyzes is based on the blue scenario. This scenario highlights the two important aspects that can occur during a disaster namely: workers that will not show up and an increase of aircraft with loose cargo. This scenario has the largest negative influence on the system performance and is therefore chosen as the analyzed scenario. The other three scenarios are displayed to visualize the outcome space of the policies. The purple line is a smooth representation of the blue scenario. The purple line is used to measure the different resilience aspects (absorption capacity, adaptive capacity and recovery time) of the system.

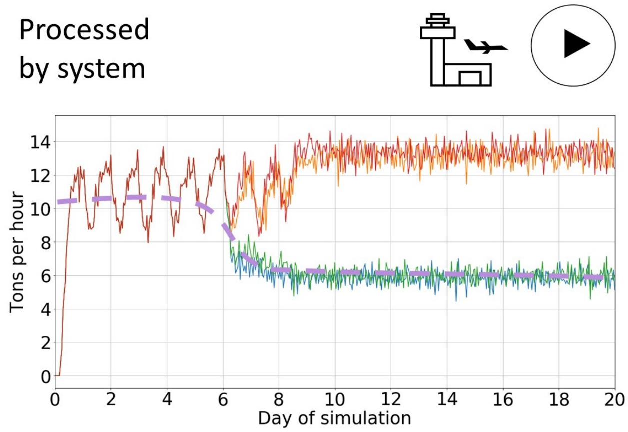
Scenario	Line color
30 % of worker will not show up 30 % of cargo is loose boxes	Blue
30 % of worker will not show up 0 % of cargo is loose boxes	Yellow
0 % of worker will not show up 30 % of cargo is loose boxes	Green
0 % of worker will not show up 0 % of cargo is loose boxes	Red
Smoothened blue scenario line which is used for the resilience measurement	Purple

Table 16: Plot legend of scenario's that are analyzed

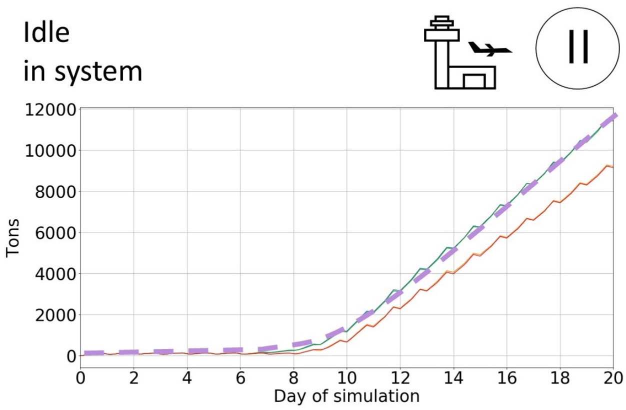
8.1 No policy

In figure 22 the results of the basic system with no policy implemented are displayed. This system is described in section 5.3. The middle and right plot show the collapse of the systems. The amount of cargo that is idle is almost 12000 tons at the end of the 20th day. Compared with the 88 tons during normal times it can be concluded that the airport cannot handle a disaster like this and will be overcrowded within the first few days.

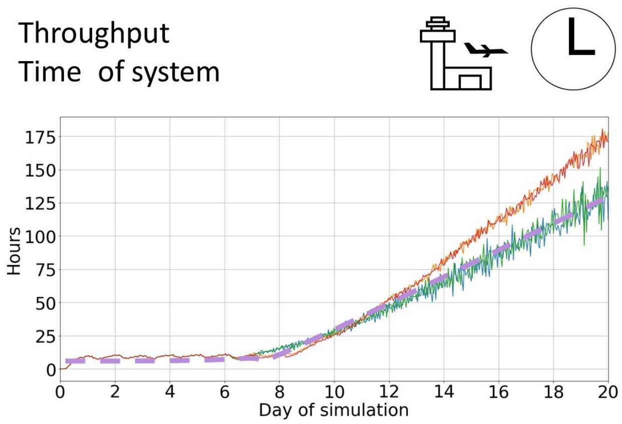
The resilience analyses are displayed on the bottom of the figure. With no policy in place the system cannot even recover to normal operation. Therefore, there is also no bounce up level. The left plot shows the difference between a no-show rate of workers of 0% or 30%. It can be concluded that this variable strongly influences the systems total processed cargo. With a 30% no show rate the absorption level is 5.8 tons per hour, but with a 0% no show rate the system does not need to absorb. It is even able to adapt to the new situation and the amount of processed cargo is improved. The reason for this is that the workers have continuous supply of work and are not affected by time gaps between aircrafts.



Time of disaster event	T0	6th [day]
Time of classic recovery	T2	None
Time of new bounce up recovery	T3	None
Time of stable idle cargo	T4	None
Base level	P0	10.6 [tons per hour]
Absorption level	P1	5.8 [tons per hour]
Adaptive level	P2	None
Input equals output level	P3	None
Rapidity	T4-T0	None



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None]
Time of new equilibrium	T2	None
Base level	P0	88 [tons]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None]
Time of new equilibrium	T2	None
Base level	P0	8.2 [hours]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None

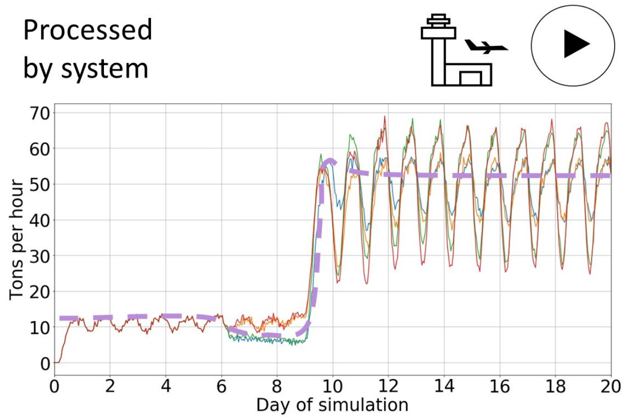
Figure 22: No policy results. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

8.2 Extra resources

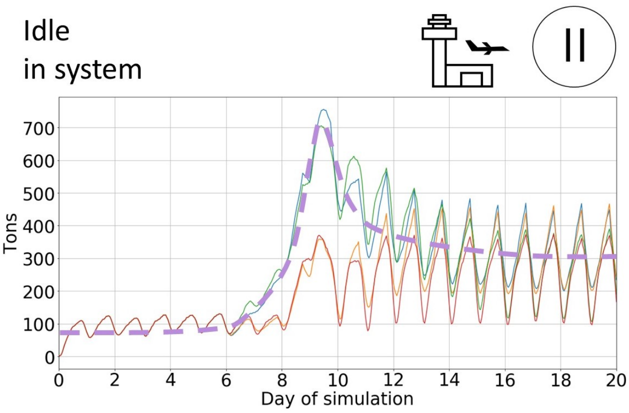
The extra resource policy is divided into three analyses. The analyses differentiate on the arrival time of the extra resources. This is on the 9th, 10th or 11th day. These systems are described detail in section 6.1.

Extra resources on the 9th day

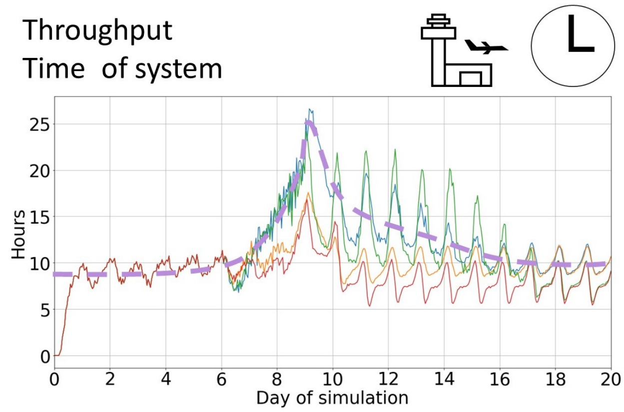
In figure 23 the analysis of the policy of extra resources on the 9th day is displayed. In this analysis, the holding and storage capacity of the system is not included. These two aspects will be covered in section 8.5. The purple line in the left plot shows the bounce back and bounce up capacity of the system. The middle and right plot show a new equilibrium after 14 and 18 days. This policy results in a 420% increase of processed cargo. It can be concluded that the airport can recover within the time frame from this type of disaster. The middle plot of idle cargo stabilizes at a new equilibrium which is different compared to pre-disaster level. The new resilience framework defines in contradiction to the traditional definition this new equilibrium as a full recovery, because pre-disaster levels don't apply anymore due to changes in the system



Time of disaster event	T0	6th [day]
Time of classic recovery	T2	9.1th [day]
Time of new bounce up recovery	T3	9.8th [day]
Time of stable idle cargo	T4	14th [day]
Base level	P0	10.6 [tons per hour]
Absorption level	P1	5.8 [tons per hour]
Adaptive level	P2	56.9 [tons per hour]
Input equals output level	P3	49.2 [tons per hour]
Rapidity	T4-T0	3.5 [days]



Time of disaster event	T0	6th [day]
Time of final absorption	T1	9.5th [day]
Time of new equilibrium	T2	14th [day]
Base level	P0	88 [tons]
Absorption level	P1	755.4 [tons]
Adaptive level	P2	315.7 [tons]
Recovery time	T0-T2	8 [days]

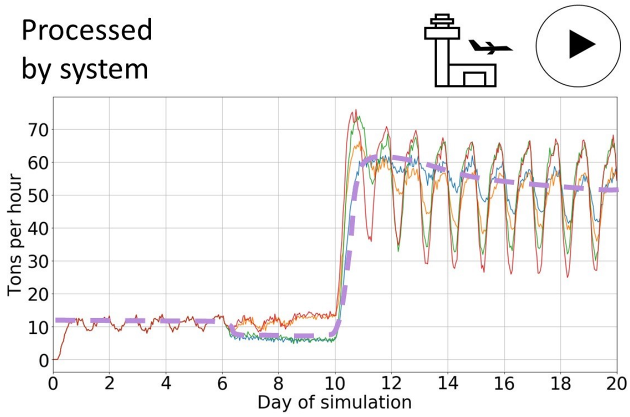


Time of disaster event	T0	6th [day]
Time of final absorption	T1	9.2th [day]
Time of new equilibrium	T2	18th day
Base level	P0	8.2 [hours]
Absorption level	P1	26.6 [hours]
Adaptive level	P2	10.0 [hours]
Recovery time	T0-T2	12 [days]

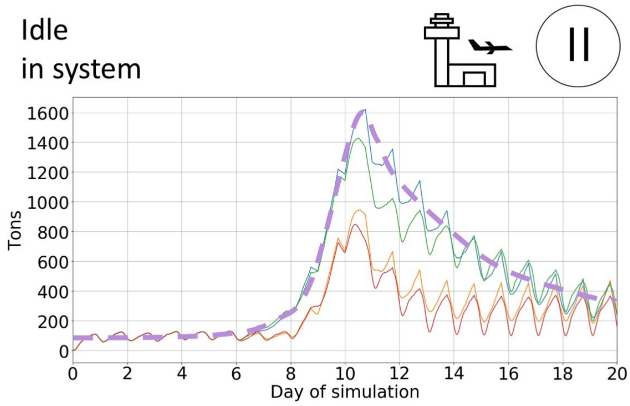
Figure 23: Extra resources at day 9. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

Extra resources on the 10th day

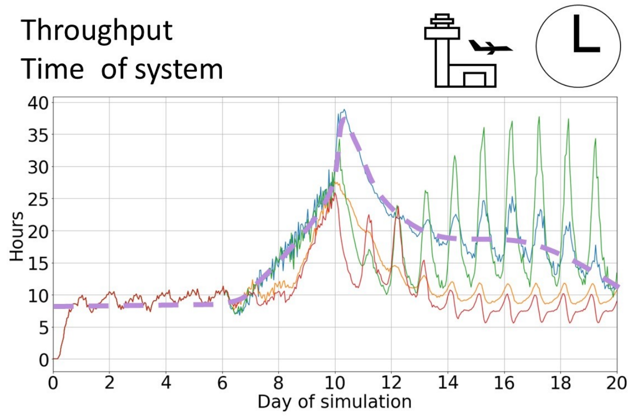
In figure 24 the analysis of the policy of extra resources on the 10th day is displayed. In this analysis the holding and storage capacity of the system is not included as well. The purple line in the left plot shows the bounce back and bounce up capacity of the system. The negative impact of arriving at the 10th instead of the 9th day is visible in the absorption levels of the idle plot (middle) and throughput time plot (right). The absorption levels are respectively double and triple times that high for the arriving at the 10th day policy. The middle and right plot show no full recovery of the system because no stable equilibrium is reached within 20 days. A one day later arrival of extra resources results in the inability of the system to fully recover within 14 days. Other scenarios where 0% of the workers will not show up (yellow & red) are able to recover within 20 days. This highlights the impact of this factor on rapidity aspect of the resilience of the airport.



Time of disaster event	T0	6^{th} [day]
Time of classic recovery	T2	10.1^{th} [day]
Time of new bounce up recovery	T3	11.0^{th} [day]
Time of stable idle cargo	T4	None
Base level	P0	10.6 [tons per hour]
Absorption level	P1	5.8 [tons per hour]
Adaptive level	P2	60.3 [tons per hour]
Input equals output level	P3	None
Rapidity	T4-T0	None



Time of disaster event	T0	6^{th} [day]
Time of final absorption	T1	10.8^{th} [day]
Time of new equilibrium	T2	None
Base level	P0	88 [tons]
Absorption level	P1	1621.7 [tons]
Adaptive level	P2	None
Recovery time	T0-T2	None

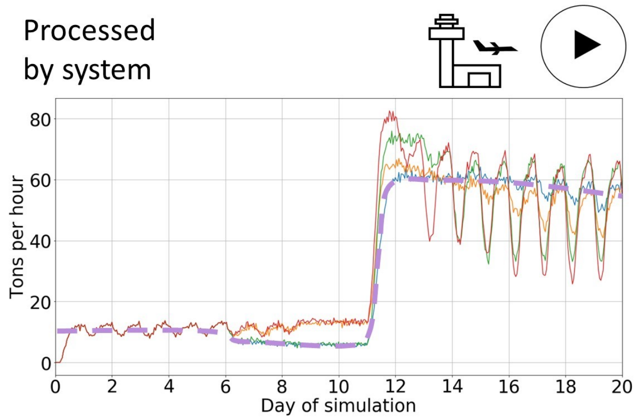


Time of disaster event	T0	6^{th} [day]
Time of final absorption	T1	10.3^{th} [day]
Time of new equilibrium	T2	None
Base level	P0	8.2 [hours]
Absorption level	P1	38.9 [hours]
Adaptive level	P2	None
Recovery time	T0-T2	None

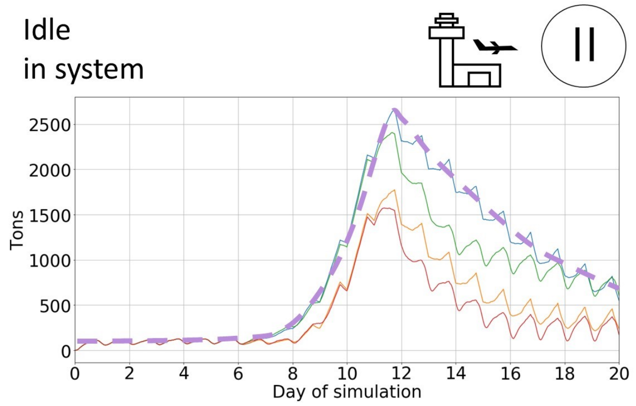
Figure 24: Extra resources at day 10. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

Extra resources on the 11th day

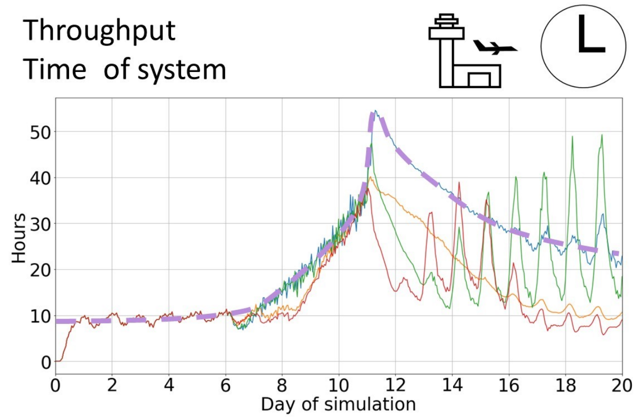
In figure 25 the policy of extra resources on the 11th day is displayed. In this analysis the holding and storage capacity of the system is not included as well. The development of the plots in this policy is structural similar to the extra resources on the 10th day policy. This policy is also not sufficient to let the system fully recover within 14 days in the blue scenario. The absorption levels of the idle KPI and throughput time KPI are even worse compared to the extra resources on the 10th day policy. This shows that the arrival time of the extra resources influences the absorption levels of the system and via the absorption level it also influences the other resilience KPI's.



Time of disaster event	T0	6th [day]
Time of classic recovery	T2	10.1th [day]
Time of new bounce up recovery	T3	12th [day]
Time of stable idle cargo	T4	None
Base level	P0	10.6 [tons per hour]
Absorption level	P1	5.8 [tons per hour]
Adaptive level	P2	60.5 [tons per hour]
Input equals output level	P3	None
Rapidity	T4-T0	None



Time of disaster event	T0	6th [day]
Time of final absorption	T1	10.8th [day]
Time of new equilibrium	T2	None
Base level	P0	88 [tons]
Absorption level	P1	1621.7 [tons]
Adaptive level	P2	None
Recovery time	T0-T2	None



Time of disaster event	T0	6th [day]
Time of final absorption	T1	11.3th [day]
Time of new equilibrium	T2	None
Base level	P0	8.2 [hours]
Absorption level	P1	54.6 [hours]
Adaptive level	P2	None
Recovery time	T0-T2	None

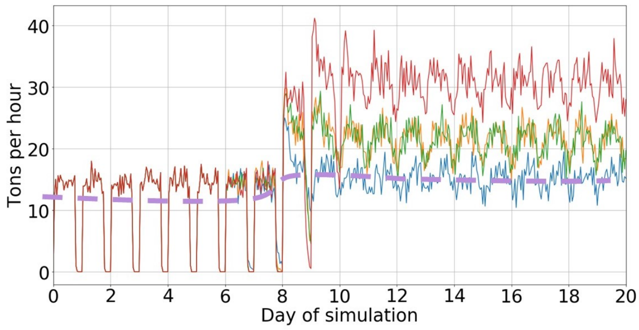
Figure 25: Extra resources at day 11. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

8.3 Prioritization on size

In figure 26 the analysis of the policy of prioritization on aircrafts size is displayed. This policy is described in detail in section 6.2. In this analysis the holding and storage capacity of the system is not included. The amount of cargo that is idle at the taxi lane is over 8000 tons at the end of the 20th day. Compared with the 0 tons during normal times it can be concluded that the airport cannot handle a disaster like this and will be overcrowded within the first few days.

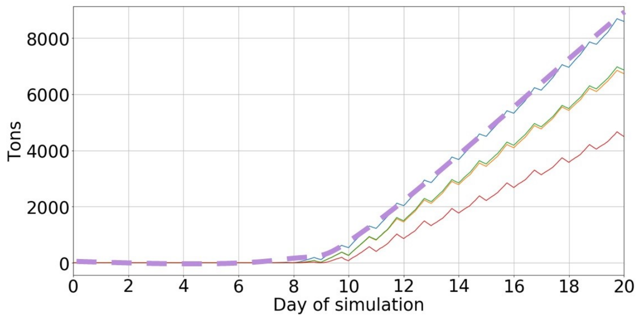
With this policy in place the system cannot equal the input with the output within 20 days. However, there is a small bounce up of capacity in the number of processed cargo at the gate selection (left plot). The process capacity/adaptive level of the gate selection moves to 15.1 tons per hour when needed. This policy does not require an implementation time and due to this the system can skip the absorption state and move directly to its adaptive level. This results in an equal base and absorption level. At the end of day 20 this results in 14% extra cargo processed at the gate selection compared to no policy.

Processed by gate selection



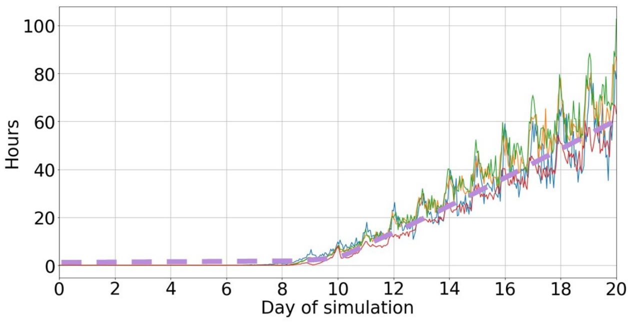
Time of disaster event	T0	6th [day]
Time of classic recovery	T2	6th [day]
Time of new bounce up recovery	T3	8th [day]
Time of stable idle cargo	T4	None
Base level	P0	11.0 [tons per hour]
Absorption level	P1	11.0 [tons per hour]
Adaptive level	P2	15.1 [tons per hour]
Input equals output level	P3	None
Rapidity	T4-T0	None

Idle at gate selection



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None
Time of new equilibrium	T2	None
Base level	P0	0 [tons]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None

Throughput time of gate selection



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None
Time of new equilibrium	T2	None
Base level	P0	0 [hours]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None

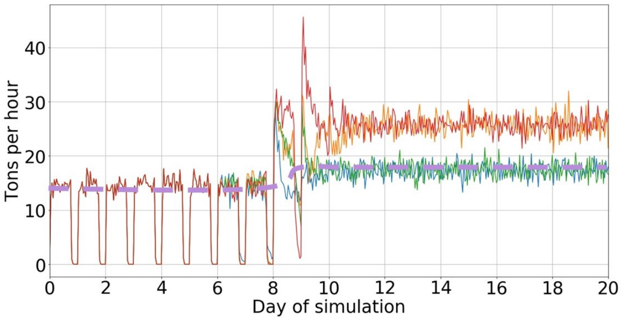
Figure 26: Prioritization on size. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

8.4 Prioritization on cargo type

In figure 27 the analyses of the policy of prioritization on aircrafts size is displayed. This policy is in described in detail in section 6.3. In this analysis the holding and storage capacity of the system is not included. The amount of cargo that is idle at the taxi lane is over 7000 tons at the end of the 20th day. Compared with the 0 tons during normal times it can be concluded that the airport cannot handle a disaster like this and will be overcrowded within the first few days.

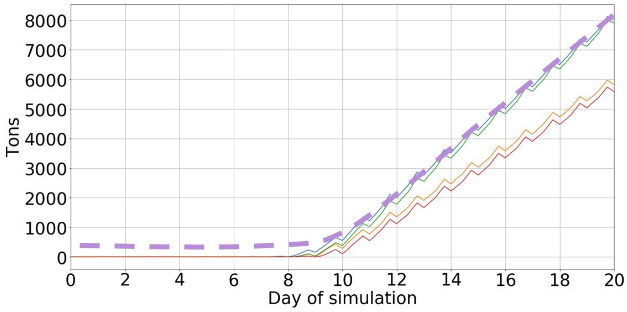
The behavior of the graphs of this policy are structural similar to the prioritization on aircraft size. However as can be seen on the scale they have different values. There is a small bounce up of capacity in the number of processed cargo at the gate selection (left plot). The process capacity/adaptive level of the gate selection moves to 17.3 tons per hour when needed. At the end of day 20 this results in 23% extra cargo processed at the gate selection compared to no policy. This makes this type of prioritization on the adaptive level of the processed cargo at the gate selection a better policy compared to prioritization on aircraft size.

Processed by
gate selection



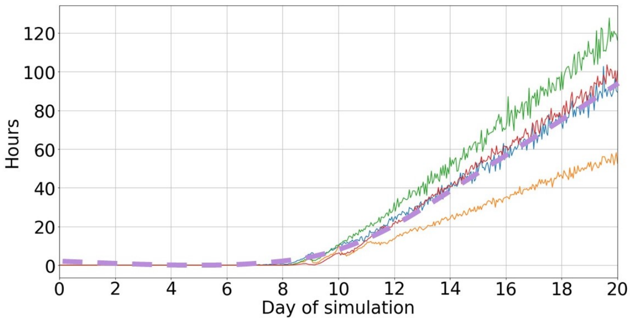
Time of disaster event	T0	6th [day]
Time of classic recovery	T2	6th [day]
Time of new bounce up recovery	T3	8th [day]
Time of stable idle cargo	T4	None
Base level	P0	11.0 [tons per hour]
Absorption level	P1	11.0 [tons per hour]
Adaptive level	P2	17.3 [tons per hour]
Input equals output level	P3	None
Rapidity	T4-T0	None

Idle at
gate selection



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None
Time of new equilibrium	T2	None
Base level	P0	0 [tons]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None

Throughput time
of gate selection



Time of disaster event	T0	6th [day]
Time of final absorption	T1	None
Time of new equilibrium	T2	None
Base level	P0	0 [hours]
Absorption level	P1	None
Adaptive level	P2	None
Recovery time	T0-T2	None

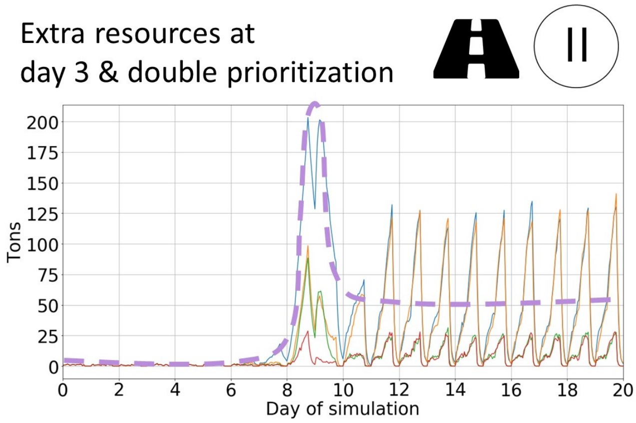
Figure 27: Prioritization on cargo type. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

8.5 Combined policy

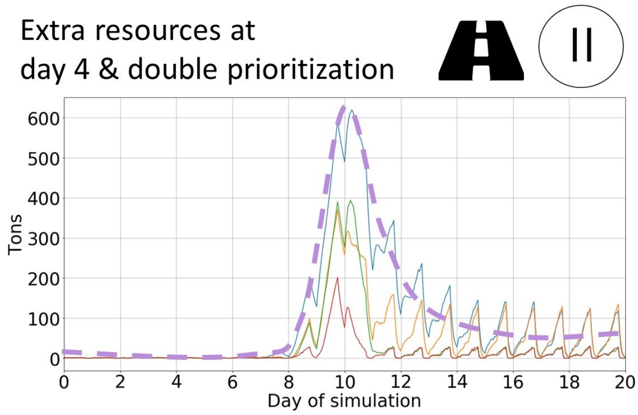
The extra resource policy is divided into six analyses. The analyses differentiate on the arrival time of the extra resources. This could be on the 9th, 10th or 11th day. The analyses are divided over two components, gate selection and warehouse operations.

Combined policy at gate selection

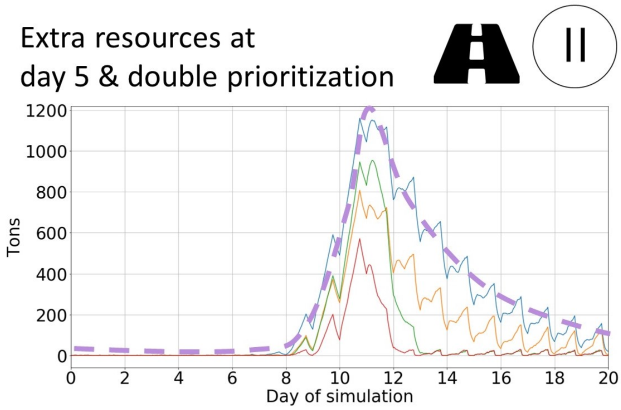
In figure 28 the analysis of the combination of all policies is displayed for the gate selection component. Combining the policies has a positive effect of 30% less idle cargo on the taxi lane compared to only the extra resources policy. In the combined policy the extra holding capacity factor is included. The initial holding capacity of the taxi lane was set to 375 tons. This amount is sufficient if the extra resources arrive at the 9th day, because the absorption level is just over 200 tons. If the extra resources arrive later extra holding capacity should be created. In section 6.4 the extra holding capacity was set to 375 extra tons with no implementation time. This creates in total 750 tons of holding capacity at the start of the 6th day. This will be sufficient if the extra resources arrive at the 10th day because the absorption level is just above 600 tons. If the resources arrive later than the 11th day the airport is unable to handle the incoming aircraft, because the absorption level is over 750 tons and should decline landing requests.



Time of disaster event	T0	6^{th} [day]
Time of final absorption	T1	8.8^{th} [day]
Time of new equilibrium	T2	10^{th} [day
Base level	P0	0 [tons]
Absorption level	P1	203.4 [tons]
Adaptive level	P2	50.6 [tons]
Recovery time	T0-T2	4 [days]



Time of disaster event	T0	6^{th} [day]
Time of final absorption	T1	10.3^{th} [day]
Time of new equilibrium	T2	16^{th} [day
Base level	P0	0 [tons]
Absorption level	P1	619.2 [tons]
Adaptive level	P2	50.9 [tons]
Recovery time	T0-T2	10 [days]



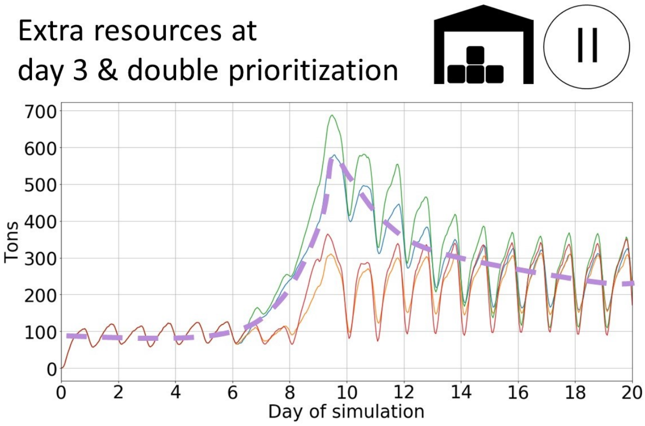
Time of disaster event	T0	6^{th} [day]
Time of final absorption	T1	11.7^{th} [day]
Time of new equilibrium	T2	None
Base level	P0	0 [tons]
Absorption level	P1	1372.3 [tons]
Adaptive level	P2	50.6 [tons]
Recovery time	T0-T2	4 [days]

Figure 28: Combined policy at gate selection. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

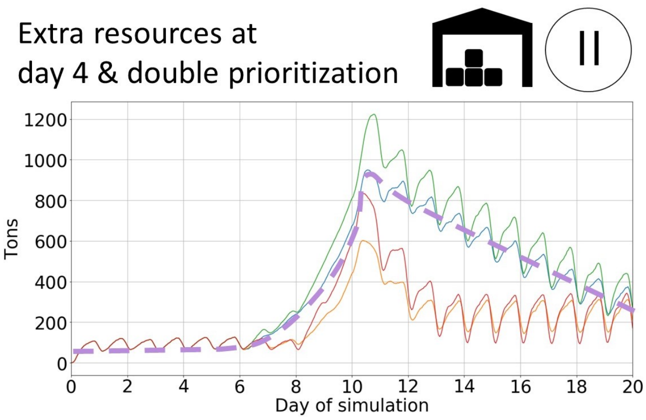
Combined policy at warehouse

In figure 29 the analysis of the combination of all policies is displayed for the warehouse operations component. Combining the policies does negatively affect the amount of idle cargo in the warehouses compared to only the extra resources policy. The reason for this is that there is no extra policy that changes the warehouse component processing capacity other than the extra resource policy. On top of this is the effect of the prioritization policy. results in the effect that, the amount of idle cargo moves from the taxi lane to the warehouse. From an airport perspective this is a preferred situation because the warehouse capacity/absorption level of idle cargo is easier to increase compared to taxi lane idle cargo capacity/absorption level.

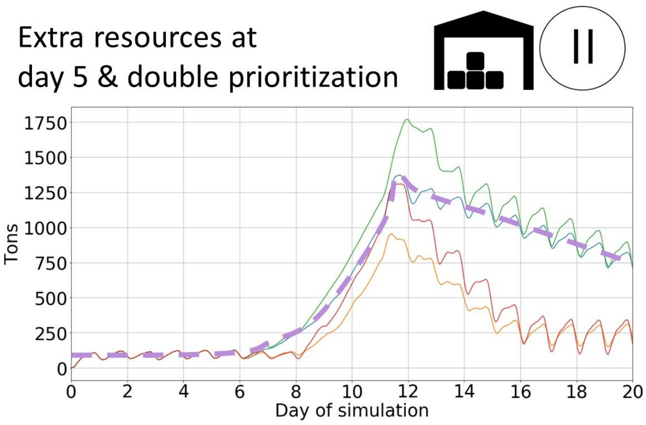
The time of arrival of the extra resources influences the absorption level of the amount of idle cargo the warehouse component can hold. The initial warehouse capacity was 375 tons. This amount is lower than the absorption levels of all three arrival times. In all cases extra warehouses should be build. In section 6.5 the extra warehouse capacity was defined as 1500 tons with a three-day implementation time. This creates in total 1875 tons of holding capacity at the start of the 9th day. This will be sufficient when the policy of creating extra warehouses is implemented directly.



Time of disaster event	T0	6th [day]
Time of final absorption	T1	9.6th [day]
Time of new equilibrium	T2	14th [day]
Base level	P0	125.9 [tons]
Absorption level	P1	579.6 [tons]
Adaptive level	P2	246.8 [tons]
Recovery time	T0-T2	12 [days]



Time of disaster event	T0	6th [day]
Time of final absorption	T1	10.5th [day]
Time of new equilibrium	T2	None
Base level	P0	125.9 [tons]
Absorption level	P1	949.0 [tons]
Adaptive level	P2	None
Recovery time	T0-T2	None



Time of disaster event	T0	6th [day]
Time of final absorption	T1	10.8th [day]
Time of new equilibrium	T2	None
Base level	P0	125.9 [tons]
Absorption level	P1	1159.5 [tons]
Adaptive level	P2	None
Recovery time	T0-T2	None

Figure 29: Combined policy at warehouse. The top row displays the KPI and the system component. The middle row displays the behavior of the component on the KPI. The bottom row displays the system resilience aspects based on the purple line.

8.6 Policy comparison

In this section the analyses of sections 8.1, 8.2, 8.3, 8.4 and 8.5 are compared with each other on component level. For every resilience aspect and component, the policies are evaluated if they reach the required service levels which are defined in section 5.3.2 and section 6.

8.6.1 Gate selection component

The policy effect on the gate selection component is displayed in table 17. In the gate selection component, the following three policies reach all required resilience aspect levels of this component: “Extra resources on the 9th day”, “Combined policy 9th day” and Combined policy 10th day. The absorption level of the idle cargo KPI is the critical factor. This factor is influenced by the holding capacity. The extra holding area increases the maximum capacity of idle cargo on the taxi lane from 375 to 750 tons. The extra holding area policy is included in the combined policy. This makes the “Combined policy 10th day” also a suitable policy.

As described in section 6.2 and section 6.3 the two prioritization policies influence this component. The positive effect of these policies is best visible in the processed cargo KPI. This KPI shows that prioritizing on cargo type is better compared to prioritizing on aircraft size.

Policy effect on gate selection component	**Processed cargo**			**Idle cargo**			**Throughput time**		
	AB	AD	RA	AB	AD	RA	AB	AD	RA
No policy	11.0	12.0	NA	NA	NA	NA	NA	NA	NA
Extra resources on the 9th day	11.0	61.3	4	276	80	4	9.4	1.3	4
Extra resources on the 10th day	11.0	61.3	10	930	77	10	22.1	1.4	10
Extra resources on the 11th day	11.0	61.3	NA	1831	NA	NA	38.4	4.7	13
Prioritization on aircraft size	11.0	15.1	NA	NA	NA	NA	NA	NA	NA
Prioritization on cargo type	11.0	17.3	NA	NA	NA	NA	NA	NA	NA
Extra holding area	11.0	12.0	NA	NA	NA	NA	NA	NA	NA
Temporary warehouse	11.0	12.0	NA	NA	NA	NA	NA	NA	NA
Combined policy 9th day	11.0	69.3	4	203	51	4	6.1	1.3	4
Combined policy 10th day	11.0	76.3	10	619	51	10	12.9	1.3	10
Combined policy 11th day	11.0	79.2	NA	1372	51	NA	21.4	4.27	12

Table 17: Policy effect on the resilience aspects of the KPI's of the gate selection component. The KPIs of the resilience score are divided into three sub columns which represents the three different aspects of resilience: absorption level (AB), adaptive level (AD) and rapidity of recovery (RA). The following units are used for the KPI processed cargo: AB and AD [tons per hour] and RA [days]. For the KPI idle cargo: AB and AD [tons] and RA [days]. For the KPI throughput time: AB and AD [hours] and RA [days]. Red means that the required service level is not reached and green means that the required service level is reached.

8.6.2 Aircraft unloading component

The policy effect on the aircraft unloading is displayed in table 18. In the aircraft unloading component all policies meet the required service level. The reason that all policies match the required service level is, that the limitations of the aircraft unloading component do not affect the component itself. If more aircraft arrive than this component can handle the gate selection component is affected and not the aircraft unloading component.

As described in section 6.1 and section 6.6 the three extra resources policies and the three combined policies influence this component. The positive effect of these policies is best visible in the processed cargo KPI. It shows that these six policies have a large impact on the system performance. It also shows that an early arrival of the extra resources in the combined policy has significant effect on the performance of the policy. This is due the effect of prioritization, which is stronger if more aircraft must wait in the holding area.

Policy effect on warehouse operations component	**Processed cargo**			**Idle cargo**			**Throughput time**		
	AB	AD	RA	AB	AD	RA	AB	AD	RA
No policy	11.0	11.8	6	3.7	3.7	6	7.2	7.2	6
Extra resources on the 9th day	11.0	61.3	4	4.5	2.1	4	7.2	2.7	4
Extra resources on the 10th day	11.0	61.3	10	5.6	2.2	10	8.3	2.9	5
Extra resources on the 11th day	11.0	61.3	11	5.6	2.9	11	8.4	3.6	6
Prioritization on aircraft size	11.0	15.0	6	7.5	7.5	6	8.1	8.1	6
Prioritization on cargo type	11.0	17.3	4	4.5	4.6	4	8.0	8.0	4
Extra holding area	11.0	11.8	2	3.7	3.7	6	7.2	7.2	6
Temporary warehouse	11.0	11.8	2	3.7	3.7	6	7.2	7.2	6
Combined policy 9th day	11.0	70.7	4	5.9	2.3	4	8.0	2.8	4
Combined policy 10th day	11.0	75.8	6	7.0	2.5	6	8.3	2.8	5
Combined policy 11th day	11.0	86.5	8	7.9	2.6	8	8.3	3.0	6

Table 18: Policy effect on the resilience aspects of the KPI's of the aircraft unloading component. The KPIs of the resilience score are divided into three sub columns which represents the three different aspects of resilience: absorption level (AB), adaptive level (AD) and rapidity of recovery (RA). The following units are used for the KPI processed cargo: AB and AD [tons per hour] and RA [days]. For the KPI idle cargo: AB and AD [tons] and RA [days]. For the KPI throughput time: AB and AD [hours] and RA [days]. Red means that the required service level is not reached and green means that the required service level is reached.

8.6.3 Warehouse operations component

The policy effect on the aircraft unloading is displayed in table 19. In the warehouse operations component only, the combined policy with extra resources arriving at the 9th day meets the required service levels. The warehouse capacity of 375 tons is the limiting factor. The temporary warehouse policy increases the warehouse capacity to 1875 tons. This is included in the combined policies and therefore the absorption levels of the idle cargo KPI stay below the maximum warehouse capacity. The combined policy with extra resources arriving at the 9th day is the only policy that recovers to a stable state within two weeks therefor this is the only policy that meets all required service levels.

As described in section 6.1 and section 6.6 the three extra resources policies and the three combined policies influence this component. The positive effect of these policies is best visible in the processed cargo KPI. It shows that these six policies have a large impact on the system performance.

Policy effect on warehouse operations component	Processed cargo			Idle cargo			Throughput time		
	AB	AD	RA	AB	AD	RA	AB	AD	RA
No policy	5.8	NA	NA	NA	NA	NA	NA	NA	NA
Extra resources on the 9th day	5.8	56.9	8	523	242	8	6.1	0.6	4
Extra resources on the 10th day	5.8	60.3	NA	693	NA	NA	10.7	1.0	8
Extra resources on the 11th day	5.8	60.5	NA	836	NA	NA	13.8	1.6	13
Prioritization on aircraft size	5.8	NA	NA	NA	NA	NA	NA	NA	NA
Prioritization on cargo type	5.8	NA	NA	NA	NA	NA	NA	NA	NA
Extra holding area	5.8	NA	NA	NA	NA	NA	NA	NA	NA
Temporary warehouse	5.8	NA	NA	NA	NA	NA	NA	NA	NA
Combined policy 9th day	5.8	62.2	12	580	247	12	5.6	0.6	4
Combined policy 10th day	5.8	68.1	NA	949	NA	NA	9.0	1.2	8
Combined policy 11th day	5.8	74.1	NA	1160	NA	NA	10.3	2.1	12

Table 19: Policy effect on the resilience aspects of the KPI's of the warehouse operations component. The KPIs of the resilience score are divided into three sub columns which represents the three different aspects of resilience: absorption level (AB), adaptive level (AD) and rapidity of recovery (RA). The following units are used for the KPI processed cargo: AB and AD [tons per hour] and RA [days]. For the KPI idle cargo: AB and AD [tons] and RA [days]. For the KPI throughput time: AB and AD [hours] and RA [days]. Red means that the required service level is not reached and green means that the required service level is reached.

8.6.4 Policy effect on total system

The effect of the policies on the resilience aspects of the system components and the effect of the policy implementation are combined into table 20.

The coloring of the resilience columns is based on tables tables 17 to 19 which represent the effect on component level. The coloring of the resilience score on the KPI's is as follows. Green means that in every component the resilience aspect level is reached. Red means that the required resilience aspect level is in one or multiple components is not reached.

The coloring of the implementation time is in contradiction to the resilience coloring not based on an exact numerical criterion, but on relative differences. The coloring is based on the following rules. Green means that the policy can be implemented directly. Red means that the policy implementation time is relatively long and takes multiple days. The exact implementation time of each policy is described in section 6

The coloring of the implementation effort is also based on the relative differences between the policies. The coloring is based on the following rules. Green means that the implementation requires no special extra workers and the implementation is not depended on serving party actors. Red means that implementation of the policy is dependent on serving parties actors and it requires extra specialized workers. The exact implementation effort of each policy is described in section 6

Table 20 shows that extra resources is the necessary policy and an early arrival of these resources is strongly preferred. The extra policies of temporary warehouse, extra holding capacity and prioritization are good add-ons on the extra resource policy, because they extend the absorption capacity of the system. Therefore, the combined policy is the preferred policy.

Extra resources are needed to prevent over congestion of the airport. The time of arriving of the extra resources have the strongest impact on the rapidity of the recovery. Adding prioritization to the extra resource policy will positively influence the absorption levels of the idle cargo at the gate selection component but will negatively influence the absorption levels of the warehouse component. This is a preferred situation over no policy, because the critical absorption level of the warehouse component can easily change with the help of extra warehouse capacity. The critical absorption level of the gate selection is due limited square meters of pavement less flexible.

In this hypothetical case with the scenario where 30% of the workers will not show up and 30 % of the cargo during the response consists of loose boxes, no policy is perfect. All policies have one or multiple limitations. The combined policy with the arrival time of extra resources at the 9th day (3rd day after the disaster) is the best policy in this scenario. The implementation limitations of this policy are acceptable. The core actors should be aware that this policy has two major limitations. First, the core actors are dependent in this policy on the serving party actors of the military and aid organizations. The second limitation is the implementation time of this policy. It takes multiple days of implementation before the extra resources and temporary warehouses are operational.

	Resilience									Implementation	
	Processed cargo			Idle cargo			Throughput time			Implementation time	Implementation effort
	AB	AD	RA	AB	AD	RA	AB	AD	RA		
No policy											
Extra resources 9th day											
Extra resources 10th day											
Extra resources 11th day											
Prioritization on aircraft size											
Prioritization on cargo type											
Extra holding area											
Temporary warehouse											
Combined policy 9th day											
Combined policy 10th day											
Combined policy 11th day											

Table 20: Policy evaluation on total system in the scenario where 30% of the workers will not show up and 30 % of the cargo during the response consists of loose boxes on three criteria: (1) resilience score on the KPI's, (2) the implementation time and (3) the implementation effort. The KPI of the resilience score are divided into three sub columns which represents the three different aspects of resilience: absorption level (AB), adaptive level (AD) and rapidity of recovery (RA).

8.7 Policy implementation

The analyses of section 8.6 show that the combined policy is the best policy in the scenario where 30% of the workers will not show up and 30 % of the cargo during the response consists of loose boxes. In the following paragraphs the time line with the effect of the three combined policies on airport system is presented under the four different scenarios.

1. Blue scenario

The time line of the combined policy in the blue scenario is displayed in figure 30. In the blue scenario of 30 % of worker will not show up and 30 % of cargo are loose boxes, the arrival time of extra resources is very important in this scenario. The airport systems cannot absorb and/or recover when the extra resources do not arrive within the first 3 days after the disaster. When the extra resources arrive at the 10th day, the system can absorb the influx of aircrafts, but cannot reach a stable level within two weeks. When the extra resources arrive at the 11th day the airport cannot absorb the amount of cargo and gets overcrowded.

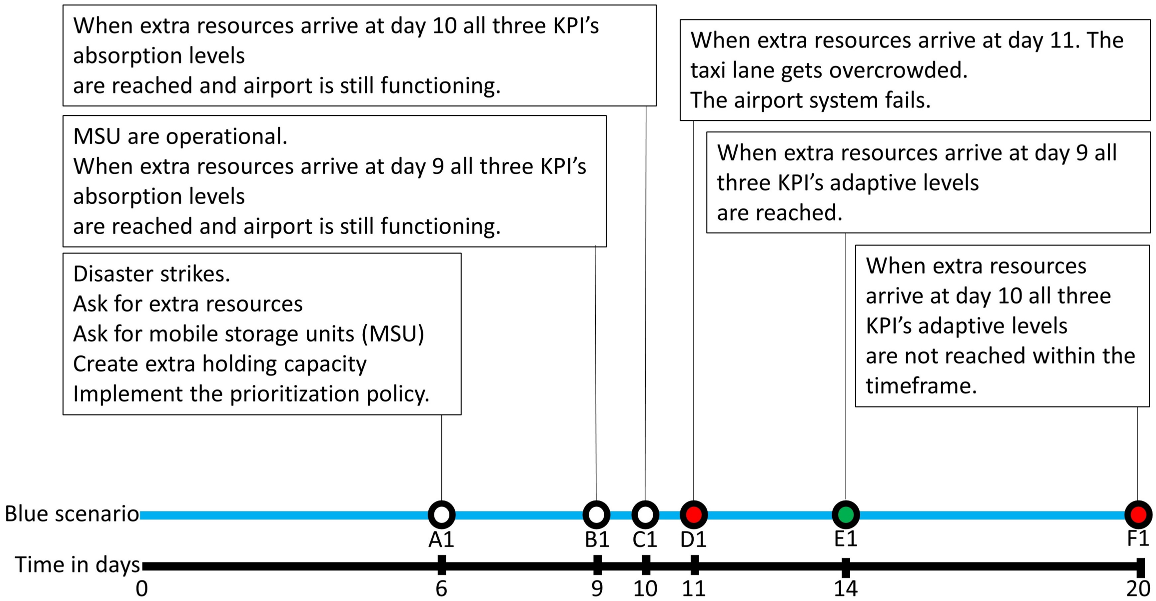


Figure 30: Time line of implementation of the combined policy in the blue scenario where 30% of the workers will not show up and 30 % of the cargo during the response consists of loose boxes.

2. Green scenario

The time line of the combined policy in the green scenario is displayed in figure 31. In the blue scenario of 30 % of worker will not show up and 0 % of cargo are loose boxes the arrival time of extra resources is also very important. The KPI's of airport perform on the resilience aspect quite similar as in the blue scenario. This shows that the amount of bulk cargo does not have a big influence on the system when 30% of the workers will not show up.

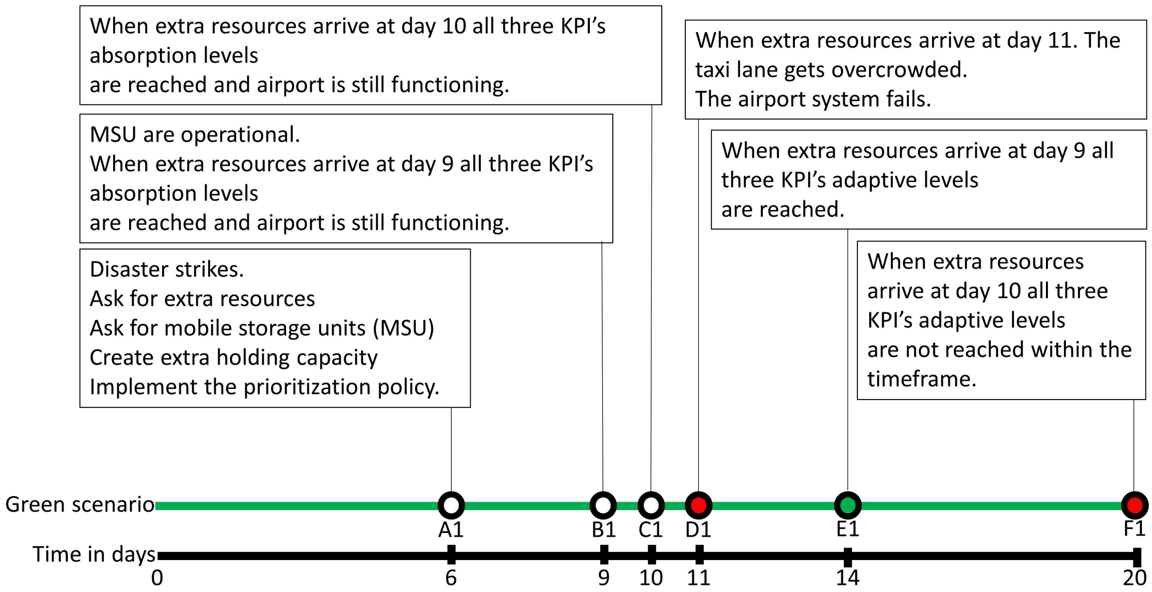


Figure 31: Time line of implementation of the combined policy in the green scenario where 30% of the workers will not show up and 0 % of the cargo during the response consists of loose boxes.

3. Yellow scenario

The time line of the combined policy in the yellow scenario is displayed in figure 32. In the yellow scenario of 0 % of worker will not show up and 30 % of cargo is loose boxes the arrival time of extra resources is also important in this scenario, but less important compared to the blue and green scenarios. As indicated by the two green circles the airport reaches all three KPI's adaptive levels when the extra resources arrive on the 9th or 10th day. When the extra resources arrive on the 11th day the taxi lane gets overcrowded. Based on the green and yellow scenario comparison it can be stated that the effect of percentage of workers that will not show up has a stronger influence on the system performances compared to the percentage of loose cargo.

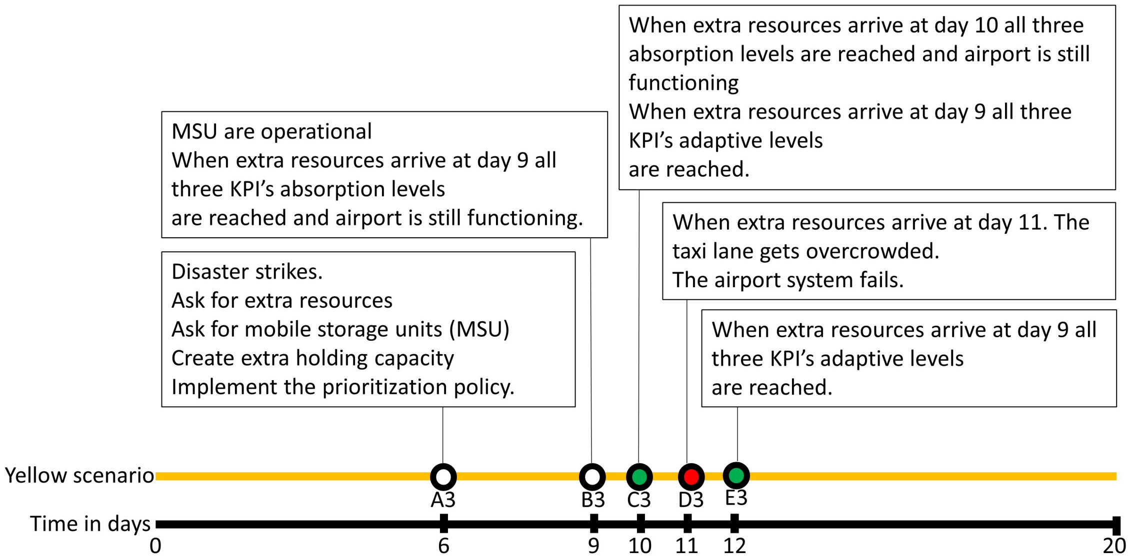


Figure 32: Time line of implementation of the combined policy in the yellow scenario where 0% of the workers will not show up and 30 % of the cargo during the response consists of loose boxes.

4. Red scenario:
The time line of the combined policy in the red scenario is displayed in figure 33. In the red scenario of 0 % of worker will not show up and 0 % of cargo is loose boxes the arrival time of extra resources is less important. When they arrive on the 9th, 10, or 11th in all cases the airport system is able to reach all three KPI's adaptive levels within 14 days. The three green circles indicate when these levels are reached. It can be stated when this scenario occurs the system is less vulnerable to the arrival time of extra resources.

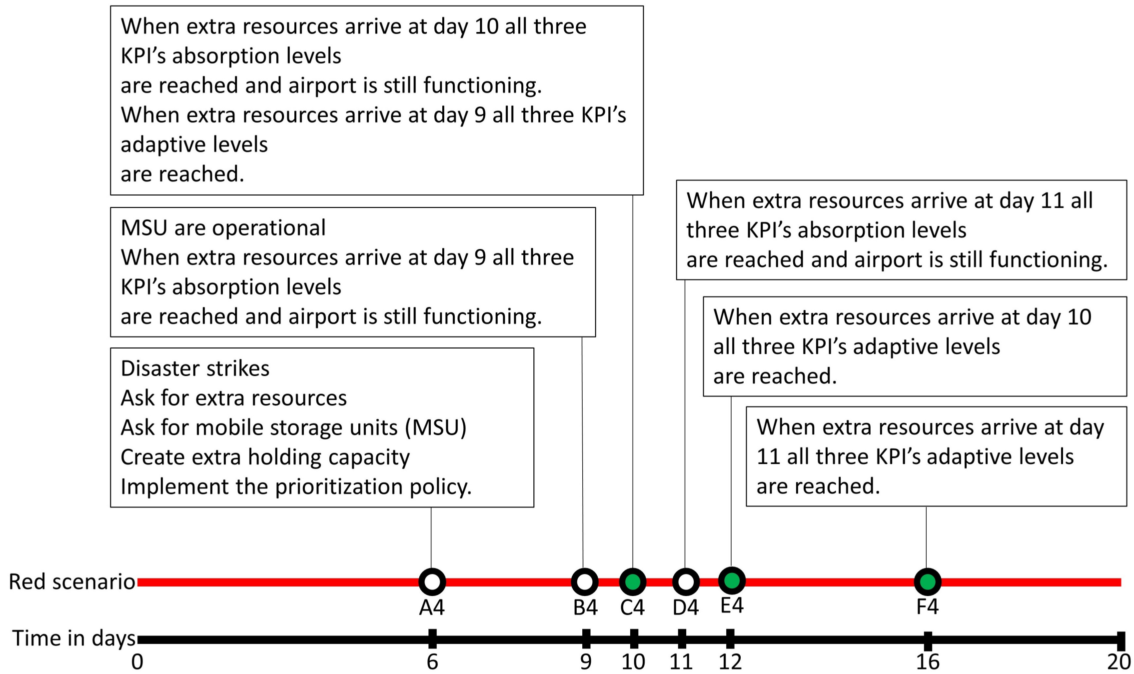


Figure 33: Time line of implementation of the combined policy in the red scenario where 0 % of worker will not show up and 0 % of cargo is loose boxes.

In conclusion these analyzes shows that the combined policy is the preferred policy and that the order of importance of the arrival of the extra resources is dependent on the scenario the airport system is facing. Scenario's where the percentage of workers that will not show up is high are the worst scenario's followed by scenarios where the percentage of loose cargo is high.

9 Validation & evaluation

In this section the model is validated, an overall policy evaluation is presented, the approach to measure resilience is evaluated and the limitations of this study are discussed.

9.1 Validation

This section provides insight in which parts of the model conform to reality and what parts are clearly a simplification that doesn't conform to reality. To define how good the model represents the reality the model is validated. Validation tests are used to test if the model is an accurate representation of the real-world system (Sargent, 2007). The validation test in this study is based on the study of Sargent (2007)

The validation of the model is divided into three aspects: (1) Assumptions validation, (2) input parameter values and distributions and (3) output values and conclusions validation (Hillston, 2003) These aspects will be validated separately with different approaches.

A complete validation of the hypothetical case study of this discrete event model is impossible since it does not represents a real-world disaster. Therefore, the validation consists of two components: the included validation and the preferred validation. In the included validation the model is validated with the help of different methods which are in the scope of this study. In the preferred validation the preferred methods to validate the model which are outside the scope of this study are discussed.

9.1.1 Included validation

The validation of the discrete event model in this study consists of the following four validations tests: (1) historic output validation to validate the output conclusions, (2) a face validation to validate the assumptions, (3) an internal validity test to validate the model output consistence and (4) a sensitivity analysis to validate the relation between the input values and the output values.

Historic output validation

Although the hypothetical case is not a real-world case the general conclusion on the output must be in line with reality. The conclusions of the model output are compared to events at the airport during the response of the Haiti and Nepal earthquakes.

The conclusion of the model result is that extra resources are necessary to overcome the influx of aircraft. The model results also suggest that on top of the extra resources policy a prioritization or temporary warehouse policy is preferred. This policy combination was also introduced in the response of Nepal and Haiti (CFE-DMHA, 2015; Logistic Cluster, 2015; Styles, 2010; Director humanitarian affairs DHL, 2018). The prioritization policy was an extra policy in the Haiti response (Styles, 2010). The extra warehouse policy also functioned as an extra policy on top of the extra resources during the response in Nepal (Massimo, 2015; Baptiste, 2015a). This makes the preferred policy based on the model output similar to the real-world policies. It can be concluded the conclusion of the model are in line with real-world events.

Face validation

A face validation is conducted to validate the assumptions of the model. The face validation is conducted during the modeling phase, so no final face validation is conducted. This makes this validation method not complete and is therefore also included in the preferred validation of section 9.1.2. With the help of interviews of aviation experts, the structural assumptions of table 5 in section 5.3 are validated (Director humanitarian affairs DHL, 2018; Koot, 2017; Assistant Professor, 2018). Most of the assumptions are acceptable, however the assumption of infrastructural breakdown is not included is a major simplification which weakens the validity of the model. The breakdown of the air traffic control tower in Haiti was the major reason for the downward shock of airport performances (Whitning, 2010). This assumption/simplification step makes the model less valid in the circumstance that the airport faces infrastructural breakdowns.

Internal validity test

Several replications of the model are made to determine the amount of internal variability in the model results (Sargent, 2007). With 160 replications 95% of all model output values fall within an acceptable range of the mean output. The largest internal variability consists of the throughput time KPI of the aircraft unloading component. This analysis is presented in appendix C. This makes the model internally valid.

Sensitivity analysis

The sensitivity analysis was also part of the verification of the model. In appendix B.2 the conclusion of the continuity test/sensitivity test shows that the workers are not modeled according to the concept model and are not in line with the real-world system. A small decrease in the number of workers has a disproportional influence on the number of cargo unit processed.

The reason for disproportional output performance is the assumption that one high lifter requires exact 8 unloading workers. If the number of unloading workers is decreased in the model to 7 workers, the high lifter is not able to operate anymore. This is not in line with reality (Project Manager & Vice president Dnata, 2018). In reality an aircraft can be unloaded with 7 workers, it only requires extra time. In reality the large discrete step occurs when less than 6 workers are available per high lifter. In the model this large discrete step is included but is simplified. This is a limitation of the model and policies that involve small changes in the number of workers can therefore not be implemented into this model.

9.1.2 Preferred validation

The preferred validation if the scope of this research was wider would consists of the following three validations tests: (1) a model validation to validate the output and conclusions, (2) a face validation to validate the assumptions and (3) a predictive validation to validate the assumptions, input parameter values and output values.

Model validation
A model validation is a good extra validation step to improve the validity of the model. The current discrete event model is based on multiple assumptions and simplification. If another study develops its own model, based on a separated literature study that has similar outcomes, the validity of both models increases. From a validity point of view, it would be interesting if the new model would also be a macroscopic analytical model instead of a simulation model. When different model approaches produce similar outcomes, it can be stated that both models have high change of being a good representation of reality.

Face validation
As stated in section 9.1.2 no final face validation is performed. It is preferred that a full-face validation on all the model assumptions is performed after the data was analyzed. The current face validation is performed by (humanitarian) aviation experts. These aviation experts are no modeling experts, this limits their ability to validate the model correctly. A preferred face validation would include multiple (humanitarian) aviation experts with modeling knowledge. This kind of people is very scarce, and it can be concluded that an accurate complete face validation would therefore be difficult to perform.

Predictive validation
The most preferred kind of validation is a predictive validation of a real situation. This test will validate the model on all three aspects of validation (assumptions validation, input parameter values and distributions validation and output values and conclusions validation). This can be accomplished by an on-site measuring of the real system during a disaster response and run the model parallel to the disaster and validate the model with the real world. To perform such validation there are multiple requirements. First the modeler should attend the air traffic coordination cell meeting. Second the modeler should have access to the data of the air traffic control, gate schedules, cargo handlers and air cargo organizations during the disaster response. If the model performs well on all three aspects of validation it can be stated that the model is a good representation of the real world. It can be concluded that this validation is the best kind of validation , but it requires a lot of preparation and resources.

9.2 Policy evaluation

In this section the policies are evaluated on three criteria: (1) their resilience score on the KPI's, (2) the implementation time and (3) the implementation effort. The resilience score on the KPI's of the different policies are discussed in section 8. The implementation time and the implementation effort are discussed in section 6.

The evaluation of section 8.6 shows that extra resources is the necessary policy and an early arrival of these resources is strongly preferred. The extra policies of temporary warehouse, extra holding capacity and prioritization are good add-ons on the extra resource policy, because they extend the absorption capacity of the system. However, the combined policy has two negative effects. Firstly, the combined policy scores low on implementation time. This is due to the long implementation time of the extra resources aspect of the combined policy. Secondly, the combined policy scores also low on the implementation effort. This is due the implementation of the extra responsibilities of the air traffic control. These are limitations of this policy. However, these implementation limitations are subordinate to the effect on the resilience of the system. Therefore, the combined policy is the preferred policy.

Together with the analyzes of the previous paragraph and the analyzes of section 8 the combined policy is stated as the preferred policy. The order of importance of the arrival of the extra resources is dependent on the scenario the airport system is facing. Scenarios where the percentage of workers that will not show up is high, are the worst scenarios followed by scenarios where the percentage of loose cargo is high. This makes the combined policy with extra resources arriving at the 9th day the most robust policy. The scenario where 0% of the workers will not show up and 0 % of the cargo during the response consists of loose boxes is the most robust scenario. These relations are visualized in table 21.

	30 % of worker will not show up 30 % of cargo are loose boxes	30 % of worker will not show up 0 % of cargo are loose boxes	0 % of worker will not show up 30 % of cargo are loose boxes	0 % of worker will not show up 0 % of cargo are loose boxes
Arrival at 9th day				
Arrival at 10th day				
Arrival at 11th day				

Table 21: Ability of airport system to recover from the influx when the combined policy is implemented under the four scenario's and three possible arrival times of the extra resources. Green means that the system can recover, orange means that the system can almost recover and red means the system cannot recover and gets overcrowded.

As a policy maker the combined policy should be implemented as soon as possible after the disaster occurs independent of the scenario the system is facing. This includes (ordered on level of importance): (1) ask aid organizations and/or the military for extra resources and emphasize the need for a quick arrival of these resources, (2) ask aid organizations for mobile storage units, (3) create extra holding capacity and (4) implement a prioritization policy on cargo type and aircraft size. By following these steps, the airport has the best change to stay operational.

The operations of the airport are influenced by two major external effect: (1) the percentage of loose cargo and (2) the percentage of workers that does not show up. The first effect can be minimized by emphasizing the negative effect of loose cargo to the humanitarian air cargo operators. If the humanitarian air cargo operators minimize the percentage of loose cargo, the airport can handle faster and more cargo. The second effect can be overcome by organizing upfront specialized extra workers that can act as a backup pool when the planned workers do not show up. These extra workers can come from the military as well from aid organizations like DHL. Theses extra workers minimize the performance loss of the airport and result in the effect that the airport can handle faster and more cargo.

9.3 Resilience measurement approach evaluation

To analyze the performances of the airport in the immediate post-disaster situation a new approach to measure resilience is used. This approach incorporates the bounce back and bounce up capacity of the airport instead of only measure the bounce back capacity.

The new approach helps to compare different policies by defining critical points in the outcome curves. By dividing resilience into three resilience aspects with timestamps, extra information about the system performance is gained. With the help of the values of the resilience aspects, curves with different behavior can be compared not only on their mean or maximum, but also on their behavior.

The extra information that this new approach provides is also a limitation of this framework. This framework does not provide one single score. The traditional resilience definition has a single score that can be calculated by measuring the surface of the triangle. This is not possible in the new bounce up measurement approach. A single score has two benefits: it communicates better and it is easier to compare policies.

This new approach can also be used in other situations if they face two similar system characteristics as an airport in the immediate post-disaster situation. These characteristics are: (1) dynamic required service levels over time and (2) internal system changes. Systems with these characteristics are for example seaport in humanitarian aid situations.

This framework is a useful approach to create insight in the resilience performance of a system. Policy makers can translate the results of the measurement approach into new policies. It is unknown how well policy makers are able to use this approach to create policies. This translation step by policy makers from resilience measurement to policy implementation is not studied in this study. A further study is needed to test if policy makers are able to translate a scientific approach to measure resilience into a practical policy on the ground.

In conclusion it, can be stated that this new approach is a good measurement technique to measure resilience in situations with the following characteristics: (1) dynamic required service levels over time and (2) internal system changes. With the help of the three different aspects of resilience extra information about the resilience behavior of the system is gained. This understanding will help policy makers to create better policies.

9.4 Limitations

The limitation section is divided into three subsections: (1) model validation limitations, (2) model verification limitations and (3) internal dependency of KPI. For every limitation the origin and implication are discussed.

Model validation limitations
The limitations of the validity of the model are categorized into two categories: limitations of the structural assumptions and limitations of the parametric assumptions.

The structural assumptions that are presented in table 5 are based on literature research and expert interviews. These assumption and simplification are made due to the scope and time constraint of this study. By making this assumption some parts of reality are out of the scope of this study. These assumptions are made due the mesoscopic scope of the model. This makes the model generalizable, which is a key aspect of this model. As mentioned in section 9.1 these assumptions are not fully validated by a humanitarian airport expert with modeling knowledge. This creates the possibility that some of these assumptions are wrong or too bold. Other model validations show that the model is valid. This shows that the implication of this limitation is limited.

The limitations of the parametric assumptions have one major cause and that is the lack of accurate data about airport operations in the immediate disaster response. A hypothetical case is created based of the Haiti and Nepal earthquakes to overcome the lack of data. This hypothetical case is hard to validate since it is hypothetical, and this limits the parametric validity of the model and the study. The historic output validation shows that although the case is hypothetical the conclusions are in line with reality. This shows that the implication of this limitation is limited.

Model verification limitations

The discrete event model is based on the conceptual model. The number of unloading workers to unload an aircraft is not implemented correctly according to the concept model and partly not in line with reality. This limitation is further discussed in appendix B.2.

High lifters require exactly 8 unloading workers, if the amount of unloading workers is decreased to 7, the high lifter is not able to operate anymore. In reality this large discrete step occurs when less than 6 workers are available per high lifter. In the model this large discrete step is included but is simplified. This is a limitation of the model and policies that involve small changes in the number of workers can therefore not be implemented into this model.

Internal dependency of KPI

The resilience of the airport is measured via three KPI (processed cargo, idle cargo and throughput time). These KPI's are chosen, because they provide insight in the capacity and operations of the airport. Based on these KPI's the effect of a policy on resilience level of the system is defined. The limitation of these KPI's are that they are strongly correlated. If the process capacity decreases the amount of idle cargo increases. When the amount of idle cargo increases, the throughput time increases as well. These correlations are schematically displayed in figure 34.

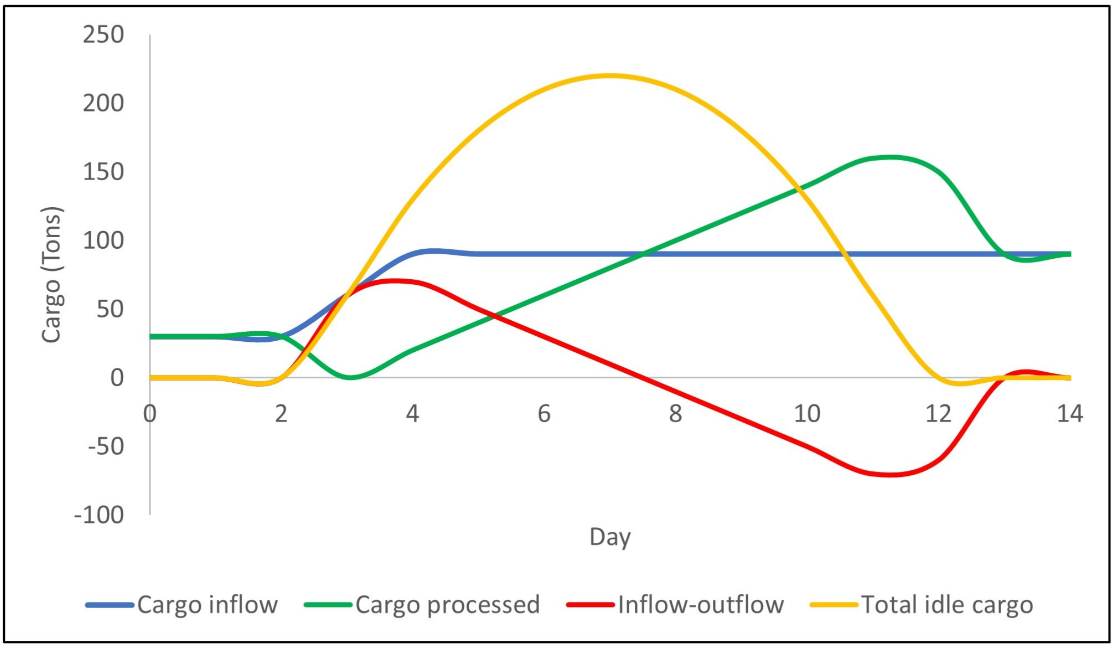


Figure 34: KPI correlations

As shown in section 4.3 all three KPI's are needed to provide sufficient insight about the resilience of the system. The processed cargo provides insight how much your capacity must increase. The idle cargo is needed to provide insight when the system reaches its critical level and the throughput time is needed to provide insight into which component of the system is under-performing. A policy maker should not be surprised that multiple KPI's perform badly in one situation. The policy maker should use all three KPI's to define which one is critical and adjust its policy on that critical KPI. Due to the strong internal correlation, one policy improvement on one KPI has effect on the other two. When this model is used these strong correlations should be taken into consideration.

10 Conclusions

In this section the conclusion of this study is presented. At first the research questions are answered, secondly the scientific and societal contribution are presented and at last the suggestions for further research are discussed.

10.1 Answering the research questions

The main research question in this research is presented below. This question is divided into four sub-questions which are answered subsequently.

How should airport services be improved to be more resilient during the immediate post-disaster response?

Sub-question Q1: How should the airport services be conceptualized?
With the help of the actor identification of section 4.1 all actors involved in the immediate disaster response at airports are mapped and categorized into core actors and serving parties. The four core actors in the immediate disaster response are: (1) humanitarian aid cargo organization, (2) air traffic control, (3) gate schedulers and (4) cargo handlers.

By decomposing the processes of these actors, a conceptual model of the operations is made in section 4.2. This conceptual model consists of three components displayed in figure 35: (1) gate selection, (2) aircraft unloading and (3) warehouse operations. This conceptual model is the answer to this research question and will act as the foundation for the quantitative model of sub-question 2.

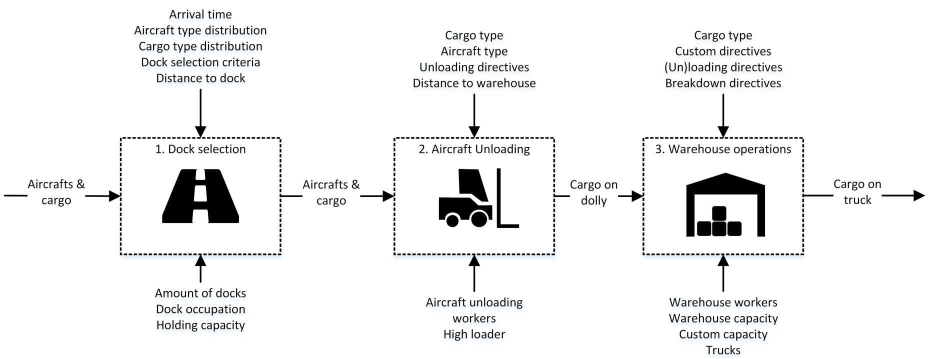


Figure 35: Meta model. Arrows from top to bottom represent the control factors of the operation. Arrows from bottom to top represent the resources needed. Horizontal arrows represent the inflow and outflow.

Sub-question Q2: How can an airport be captured in a quantitative model to model the effects of the immediate disaster response on airport operations?
In this research a mesoscopic model is build. This mesoscopic model splits the different processes of airports but keeps the interactions between them. This mesoscopic scope allows the conceptual model components to be incorporated into the quantitative model.

The mesoscopic scope requires simplifications and assumptions of the system. The simplifications and assumptions are based on literature reviews and expert interviews which are presented in section 5.3. Due to data limitation the model represents a hypothetical case which is based on the Nepal earthquake of 2015 and the Haiti earthquake of 2010. This is a limitation of the study. This quantitative mesoscopic discrete event model is the answer to research question 2.

Sub-question Q3: What policies make airport operations more resilient?
To know what polices make airports more resilience, resilience must be measured. The traditional bounce back resilience measurement approach does not apply for airports in an immediate post-disaster situation. A new bounce back and bounce up measurement approach is created in section 4.3 and displayed in figure 36. This approach divides resilience into three aspects: (1) absorption level, (2) adaptive level and (3) rapidity of the recovery. These aspects of resilience are measured for the three KPIs: (1) processed cargo, (2) idle cargo and (3) throughput time over all three model components.

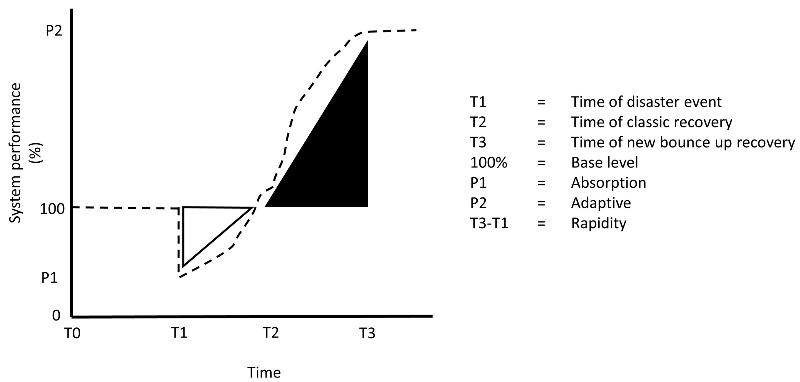


Figure 36: Redefined resilience triangle

The policies that are presented in chapter 6 and that are tested on their resilience are: extra resources, prioritize on aircraft size, prioritize on cargo type, extra warehouses, extra holding area and a combined policy. As stated in chapter 8 the extra resources policy is the necessary policy, because it is the only policy that can reach the necessary adaptive level of the processed cargo KPI. An early arrival of these resources is strongly preferred, because a late arrival time has a strong negative influence on the idle cargo KPI. The extra policies of temporary warehouse, extra holding capacity and prioritization are good add-ons on the extra resource policy, because they extend the absorption capacity of the system. Therefore, the combined policy is the preferred policy.

Sub-question Q4: In what way can this approach be generalized for similar airports?
There are two approaches in this study that can be generalized to other airports. First the approach of model-based decision making in the immediate post-disaster situation of airports and second the approach of resilience measurement.

The level of details of the mesoscopic model makes the model generalizable to other airports that are in the scope of this research defined in section 3.2. The model can be calibrated to a specific airport in an immediate natural sudden onset post-disaster response. This includes disasters like hurricanes and earthquakes. Firstly, the case specific parameters which are presented in section 5.3 should be adapted to another airport. Secondly, a scenario should be selected by changing the input parameters. This makes the model-based decision approach generalizable for similar airport and similar natural sudden onset disasters.

As stated in section 9.3 the new bounce back and bounce up measurement approach to measure resilience in situations can be generalized to other airports. This approach can also be used in other situations that require resilience measurements and face dynamic required service levels over time and internal system changes.

Main research question: How should airports services be improved to be more resilient during the immediate post-disaster response?
A policy maker should implement the combined policy as soon as possible after the disaster occurs independent of the scenario the system is facing. This includes (ordered on level of importance): (1) ask aid organizations and/or the military for extra resources and emphasize the need for a quick arrival of these resources, (2) ask aid organizations for mobile storage units, (3) create extra holding capacity and (4) implement a prioritization policy on cargo type and aircraft size. Scenarios were the percentage of workers that won't show up is high are the worst scenarios followed by scenarios were the percentage of loose cargo is high. Dependent on impact of the external effects and the arrival time of the extra resources the airport is able or not able to overcome the influx of aircraft.

The operations of the airport are influenced by two major external effects: (1) the percentage of loose cargo and (2) the percentage of workers that does not show up. The first effect can be minimized by emphasizing the negative effect of loose cargo to the humanitarian air cargo operators. The second effect can be overcome by organizing upfront specialized extra workers that can act as a backup pool when the planned workers do not show up.

10.2 Scientific and societal contribution

In section 2 the literature review is presented, and three knowledge gaps are identified. (1) Lack of academic research on the processes and problems within airports in humanitarian logistics in the immediate response phase. (2) Lack of academic research on airports modeling of humanitarian logistics in the immediate response phase. (3) Lack of academic research on approaches of resilience measurements for airports facing dynamic required service levels over time and internal system changes in the immediate response phase. This study makes three scientific contributions. The scientific contributions this study contribute are:

A new approach to measure resilience in situations of dynamic required service levels over time and internal system changes.
Resilience is a well discussed concept in scientific studies. The concept of resilience is used in different studies in different ways. The traditional measurement of resilience is focused on the bounce back capacity of the system and calculating the surface of the resilience triangle. There is a lack of academic research on methods of resilience measurements for systems with dynamic required service levels over time and internal system changes. This study adds to the traditional bounce back triangle a bounce up triangle. Together with this extra triangle the three aspects of resilience are redefined and a new measurement technique to measure resilience is created. This new measurement approach to measure resilience in situations of dynamic required service levels over time and internal system changes is a scientific contribution.

Insight into the intertwinement of in the processes and problems within airports in humanitarian logistics in the immediate response phase
Academic studies on operations within an airport in humanitarian logistics are new. This results into a lack of academic research on the processes and problems within airports in humanitarian logistics in the immediate response phase. The actor analysis of section 4.1 and the system decomposition of section 4.2 show that over 15 actors are involved, and that the processes and system component are strongly intertwined with each other. This intertwinement is also visible in the policy effects on the system. Further studies about airports in humanitarian logistics in the immediate response phase should take this intertwinement of the system into account and should study the airport system as a holistic whole. This insight of intertwinement and how different bottlenecks develop in the system is a scientific contribution that addresses this knowledge gap.

Insight in the level of detail that is needed to capture the airport system in humanitarian logistics in post-disasters response phase
The number of mesoscopic airport models are limited. There is also a lack of academic research on airport modeling of humanitarian logistics in the immediate response phase. This results in a lack of knowledge on the level of detail needed to model humanitarian logistics within the airport the immediate response phase. The mesoscopic model of section 5 is used to study the operations within the airport. It is created as a component-based structured

generic model that can be adapted to specific airport designs and specific natural sudden onset disasters. The system decomposition into the three components of gate selection, aircraft unloading and warehouse operations, are the lowest level of detail that is sufficient to perform analysis on. This insight of which level of detail is needed to capture the airport system in humanitarian logistics in post-disasters response phase is a scientific contribution.

Sudden onset disasters create social and economic damage to the community. Humanitarian aid minimizes this social and economic damage, but highly depends on pace of the logistics. The societal contribution of this study improves the immediate post-disaster airport logistics of humanitarian aid and so minimizes social and economic damage. The two societal contributions are:

A time line of policy implementations and how they improve the level of resilience of the airport in the immediate post-disaster response phase.
The policy maker that attends the air traffic coordination should implement the combined policy as soon as possible after the disaster occurs independent of the scenario the system is facing. This includes (ordered on level of importance): (1) ask aid organizations and/or the military for extra resources and emphasize the need for a quick arrival of these resources, (2) ask aid organizations for mobile storage units, (3) create extra holding capacity and (4) implement a prioritization policy on cargo type and aircraft size. By following these steps, the airport has the best chance to stay operational.

Insight in how the external effects on the operations at the airport in the immediate post-disaster response phase can be minimized.
The operations of the airport are influenced by two major external effect: (1) the percentage of loose cargo and (2) the percentage of workers that does not show up. The first effect can be minimized by emphasizing the negative effect of loose cargo to the humanitarian air cargo operators. If the humanitarian air cargo operators minimize the percentage of loose cargo, the airport can handle faster and more cargo. The second effect can be overcome by organizing upfront specialized extra workers that can act as a backup pool when the planned workers do not show up. These extra workers can come from the military as well from aid organizations like DHL. Theses extra workers minimize the performance loss of the airport and result in the effect that the airport can handle faster and more cargo.

10.3 Future research

During this study multiple direction for further studies are found. Together with the studies that improve the limitations this section provides five suggestions for further research.

The first suggested study is a model extension. The model used in this study can be extended in four ways. (1) By adding more cargo types like food, water, rescue teams, medicines etc. This will improve the insight into the prioritization policy. (2) The custom process can be modeled in more detail. This aspect of the model has a low level of detail but can have large impact on the operations based on previous disasters. (3) The cargo pick-up can be modeled in more detail. The problem of not collected aid is a big problem for airport. This aspect is due to lack of data simplified into one variable. This can be extended in more detail in a further study. (4) By adding physical damage caused by the disaster into the airport model, like a broken-down control tower or holes in the runway. This extension creates insight into how the physical damage by a disaster impacts the performances of the airport. The size of the extensions is determined by level of detail of the extension and the willingness to use real world data. The time needed to implement these extensions based on these aspects vary from weeks to months.

The second suggested study is an actual case study can be performed. The current research works with a hypothetical case which limits the validity and the societal contribution of the model. By performing multiple case studies with accurate data, the model can be better validated. Based on the case studies, the model can be stated as valid. After this validation, model-based decision making can be implemented in the immediate disaster response at airports. To model a case with accurate data the modeler should perform on sight measuring of the real system during a disaster response. First the modeler should attend the air traffic coordination cell meeting. Second the modeler should have access to the data of the air traffic control, gate schedules, cargo handlers, air cargo organizations during the disaster response. The size of such a study takes months of preparation and due the uncertainty of when a suitable disaster occurs this study can take years to complete.

The third study that can be conducted based on this research is a study that uses the new approach to measure resilience on another system that also faces dynamic required service levels over time and internal system changes. The size of such a study is dependent on the system that is analyzed. Such a study can vary from several months to a yearlong study. Possible systems that can be studied with the use of the new approach are sea ports, hospitals or telecoms networks in a post sudden onset disaster situation.

The fourth suggested study is a study about the role of the airport as part of the supply chain in the immediate post-disaster response can be performed. This study should be focused on resilience supply chains and study the capacity of the immediate post-disaster response transport system to recover from unusual conditions. This will be a large study of at least half a year and depending on the scope of the study it can take multiple years.

The fifth and last suggested study is about creating new creative policies that help improve the resilience of airports. In total six currently known policies are introduced in the current research. The created model environment of this research allows to experiment with new out-of-the-box policies without negative effects. Expert interviews and or brainstorms with field experts can be performed to develop these policies. A future study should develop new creative out of the box policies and test these policies in the model environment. Such a study can be performed within several months

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Appendix A Actor identification

In this appendix the different actors involved in the formulated problem will be identified and described. The actor identification creates the foundation to define the system boundaries. Based on the actor identification a selection is made of which actors will be part of the studied system. The actors can be distinguished in multiple ways. Firstly, on their time of presence. Local actors, who are present before a disaster occurs and humanitarian actors who arrive after a disaster occurs. Secondly, on the objective of actors. Help people in need, profit & continuity and high safety and security are the three different goals of the actors . Thirdly, the actors can be distinguished on their importance for the airport operations. The actors distinguished in core actors and serving parties. The core actors will be incorporated in the model.

- Core actors are actors that carry out a physical movement of the system elements or make decisions that have influence on the physical movement of the system elements.
- The serving parties are actors that do not carry out physical activities. The serving parties serve the core actors of the system and are not directly involved in operations.

The categorized actors with their interaction with each other are displayed in figure 37. The core presented with a gray background. The modeled system will involve the core actors and their interactions. The serving parties will be mentioned when needed. Some of them are involved in the implemented policies.

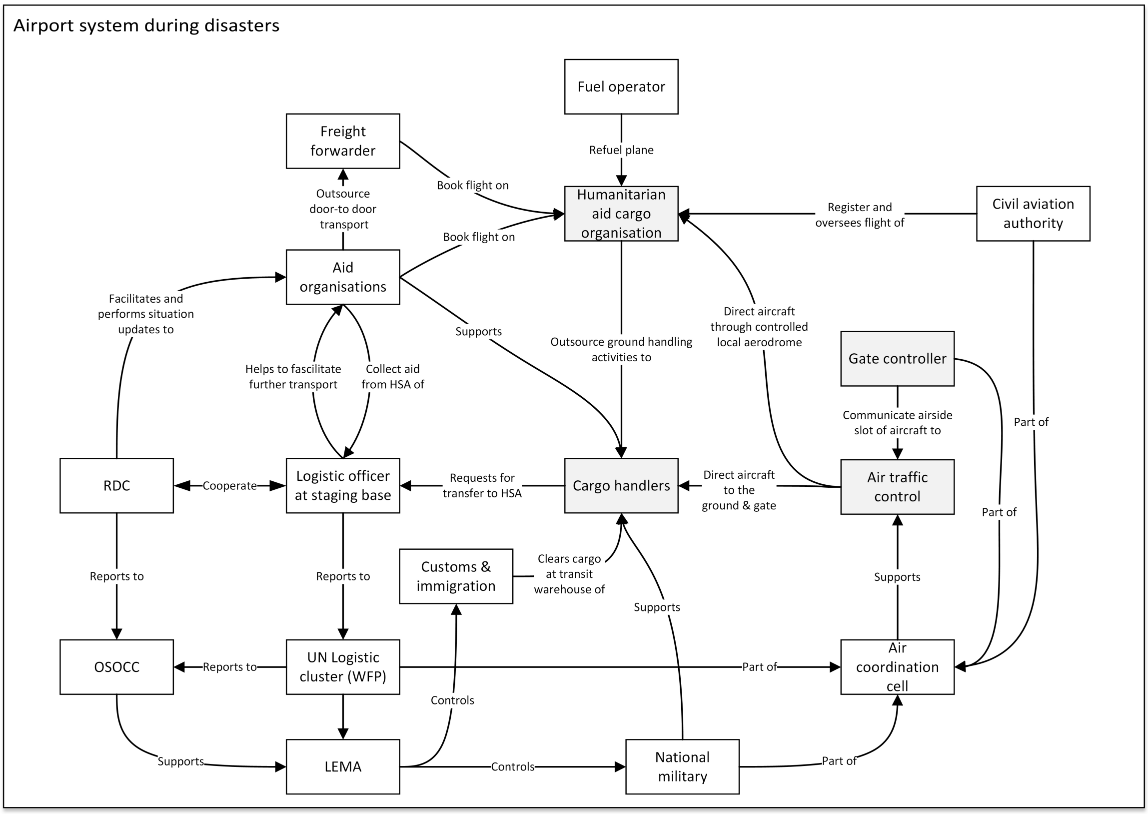

Figure 37: Actor interactions

A.1 Core actors

Humanitarian air cargo organizations

The humanitarian aircraft organizations own the aircraft that transport humanitarian cargo of aid organizations. These organization can be divided into aircraft charter companies like DHL and humanitarian organizations like United Nations Humanitarian Air Service and IFRC. These organizations own aircraft of different sizes and types. They fly goods to the airport. This group of actors are physically present at the airport and are considered a core actor (White, 2015).

Air traffic control

The air traffic control (ATC) is a critical factor in aircraft operations. The ATC is active in all phases of a flight. The goal of the ATC is to ensure a safe and efficient flow of aircraft through the airspace and airport. This includes separation assurance, communicate flight information, provide help in emergencies and congestion management. This last aspect is especially interesting in disaster situations. When congestion occurs, because the airport exceeds the operational acceptable level of traffic the ATC is responsible to manage the aircraft that want to land and take-off. The ATC can decide to reroute aircraft, delay aircraft via holding patterns or keep aircraft on the ground prior to departure (Hansman & Odoni, 2009).

Gate scheduler

The gate scheduler assigns aircraft to terminal or apron positions (gates). The assignment of aircraft to gates is communicated to the ATC. It is a key activity among airport operations. The goal of the gate scheduler is to ensure a safe and efficient usage of gates. Due to the fixed number of gates the gate scheduler should use the available gates in the best possible way. When congestion occurs the gate scheduler is responsible to manage the aircraft on the taxi lane (Dorndorf et al., 2008, 2012).

Ground handlers

The ground handlers are responsible for the unloading of the aircraft, the transport of the cargo of the transit warehouse and loading of the cargo for further transport to the humanitarian staging area. Ground handlers control the necessary manpower, equipment and buildings to facilitate these processes. (White, 2015; Fricke & Schultz, 2009; Han, Chung, & Liang, 2006).

A.2 Serving parties

Local Emergency Management Agency (LEMA)

The LEMA is responsible for the overall command, general coordination and management of the response operation. It also controls multiple local organization that work in different levels of the response like host nation support (HNS), national military, customs, local emergency responders and more. This actor is an overarching actor and is not physically active at the airport. Therefore this actor is considered a serving party (UNOCHA, 2014).

National military

The national military is always present in some way during the disaster logistic response. The military does not have one specific task, but can help several other actors by supplying personal, equipment and expertise. Extra personal and equipment can be used for ground handling, aircraft of the military can be used to deliver aid and the knowledge about aircraft coordination is used in the air coordination cell. The fact that the military doesn't have a specific task makes it a serving actor in the system (White, 2015; UNOCHA, 2014; Ludema & Roos, 2000; Assistant Professor, 2018).

Civil aviation authority

The civil aviation authority registers and oversees the approval and regulation of civil aviation. They are responsible for a safe and efficient use of the airspace. The civil aviation authority is also responsible that the controlled airports meet the safety standards (De Neufville, 2016).

Customs & immigration
The customs & immigration tries to conduct efficient accurate and fast security and safety checks. During a disaster the normal local customs laws apply. When cargo is being offloaded from an aircraft the cargo will be to to a holding area prior to being moved for further transportation. At this place the goods are checked by the custom authorities. Customs is strongly influenced by government authorities and varies strongly from country to country (White, 2015). In disaster situations a custom clearance for humanitarian aid is often installed, therefore this actor is considered a serving party (Project Manager & Vice president Dnata, 2018).

Commercial cargo airlines
Besides humanitarian flights also commercial flights are performed. These airlines have a different goal, they aim to create profit & continuity. The type of goods they supply is different from humanitarian goods. Commercial cargo flights have the lowest priority in the slot allocation and are often excluded from landing when the airport becomes more congested. Because of this this actor is excluded from the actor overview (USAID, 2015; Styles, 2010)

Freight forwarder
Freight forwarder arrange a full door to door transportation on behalf of shipper and/or consignee. Forwarders decide which airlines and aircraft are used. They influence the amount of cargo in a indirect way. This actor is not physically present and is considered a serving party.

Fuel operator
In a large-scale humanitarian emergency, the availability of aviation fuel is critical. Fuel and the operators have an important role in the success and concept design of the response. Several actors use fuel and the outcome of the fuel assessment influences all actors operating at the airport. If refueling can become a limiting factor the operators communicate this to the air coordination cell and aircraft operators should take possible shortages into account in their aircraft planning. The process of refueling is taken outside of the scope of this research, Since the process itself is often not a limiting factor, but only the availability of fuel (White, 2015).

On-Site Operations Coordination Centre
The On-Site Operations Coordination Centre (OSOCC) is a United Nation response tool that provides a platform for the coordination of international response activities in the immediate aftermath of a disaster. It acts as central hub for different organization like the reception and departure centre and is serving the the government of the affected country in their coordination. This actor doesn't have physical means on the airport operations, so it is considered a serving party (UNOCHA, 2014).

Reception & Departure Centre (RDC)
The Reception & Departure Centre (RDC) facilitates efficient arrival of international relief

teams & assists in coordinating of these teams into the country. The RDC serves as the central intake hub for international relief traffic and helps organizations to have an easy flow through the airport. This actor doesn't provide physical operations, it has a facilitating role. This makes this actor a serving party (UNOCHA, 2014).

UN logistic cluster (WFP)

The Logistics Cluster provides coordination and information to support transport related operational decision-making and improve the predictability, timeliness and efficiency of the humanitarian emergency response. They report to the OSOCC about the logistic operations of the response. The logistic cluster is active in at different levels during a response. At the airport the logistics officer at staging base (Log Off) controls the tasks of the logistic cluster. This overarching actor of logistic cluster does not have direct influence on the airport operation and is considered a serving party (White, 2015; Styles, 2017).

Logistics officer at staging base

At the airport the logistics officer at staging base (Log Off) controls the tasks of the logistic cluster. He/she monitors and facilitates the arrivals, handling, unloading transit storage and follow on transport. When cargo is cleared the cargo is moved from the transit storage of the airport to the humanitarian staging area (HSA) of the logistic cluster. The Log Off is in charge of this transport and controls the HSA. The transport from the transit storage to the staging area is not part of the system researched in this study. This actors serves the cargo handler in the outflow of cargo. Therefore this actor is not considered as a core actor, but a serving party (White, 2015; Styles, 2017).

Air Coordination Cell (ACC)

The air coordination cell manages the movement of aircraft into a (future) congested airport. By cooperating with the local military, ATC, gate schedulers, ground handlers, civil aviation authority and other parties it ensures adequate separation between flights, sufficient space to park, fuel supply and that there is adequate ground handling equipment and staff to perform these operations. It helps to prioritize requirement for air transport and provide information about air transport operations. The ACC is an important actor in disaster operations at airports, but it direct influence is limited. All the decisions are performed by other actors therefore this actor is not considered as a core actor, but a serving party (Tomasini & Van Wassenhove, 2009)

Aid organizations

There are multiple organizations that want to support the affected population: Nations institutions, governmental aid agencies, international non-governmental organizations (NGOs), members of the Red Cross and Red Crescent movements, and local NGOs based in the host nation. All these actors together create the supply of humanitarian aid and charter aircraft to fly to the affected region. These actors can also supply the airport with personal and equipment to create extra airport capacity (Smillie & Minear, 2004). These actors don't have physical operations on the airport, so they are considered a serving party.

Appendix B Verification

The model verification consists of two components. Verification checks and verification runs. The verification checks consist of: model correctness, balance checks, event tracking and run time visualizations. The verification runs consist of: degeneracy testing & continuity testing.

B.1 Verification checks

Model correctness
During the model implementation phase the model is continuously debugged and checked. Due to the component-based design of the model, building mistakes are contained to their own components. This improved the verification of correctness.

Balance checks
With the help of visualizations tools of Simio like labels balance checks are performed. The created entities are in line with the input values. The number of created entities match the number destroyed entities plus the number of entities in the system.

Event tracing
All different entities are tracked through the model with the help of the trace function of Simio. Every entity is tracked through its process through every server. With the help of this method it can be concluded that the logical process of the model matches the conceptual model.

Run time visualization
With the help of visualizations tools of Simio like labels, plots and counters the behavior of the model components and the complete model is checked if it matches the concept model.

B.2 Verification runs

Degeneracy testing
In this test the response of the model in extreme cases is verified. The following factors are set to zero or infinity: "Unloading time of aircraft", "number high lifter and workers" and the "number of cargo units per aircraft". Depending on the extreme case the systems get blocked in a specific component. If the other end of the spectrum is implemented the throughput time of that specific components gets abnormally high. These extreme cases don't structurally change the system and the model still behaves correctly.

Continuity testing
Several continuity tests are performed on different parameters. For almost all input parameters, a small change in input produced only a small change in the output. However, for the number of high lifters and number of unloading workers the effects of slight input changes produced a larger change in the output parameters. The reason for this is the large

discrete step of required workers to unload an aircraft.

One high lifter requires 8 unloading workers, if the number of unloading workers is decreased in the model to 7 workers, the high lifter is not able to operate anymore. This is not in line with reality (Project Manager & Vice president Dnata, 2018). In reality an aircraft can be unloaded with 7 workers, it only requires extra time. In reality the large discrete step of a not functioning high loader occurs when less than 6 workers are available per high lifter. In this model this large discrete step is included, but is simplified.

This results in the following system limitations. There are only 3 high lifters in the system a 1/8 decrease in number of workers results in a 1/3 decrease of unloading capacity and results in 47% less cargo processed by the system at the end of a full model run when no policy is implemented. This is a limitation of the model and policies that involve small changes in the number of workers can therefore not be implemented into this model.

Appendix C Validation

Several replications of the model are made to determine the amount of internal variability in the model results (Sargent, 2007). With 160 replications 95% of all model output values fall within an acceptable range of the mean output. The largest internal variability consist in the throughput time KPI of the aircraft unloading component during the first few days after the disaster. In figure 38 an overview of the validation runs is presented. In this figure the combined policy with the extra resources arriving at the 10th day (4th day after the disaster) in the scenario blue scenario (30% of the workers won't show up and 30 % of the cargo during the response consists of loose boxes) is displayed. 95% of all model output values fall within an acceptable range of the mean output this makes the model internally valid.

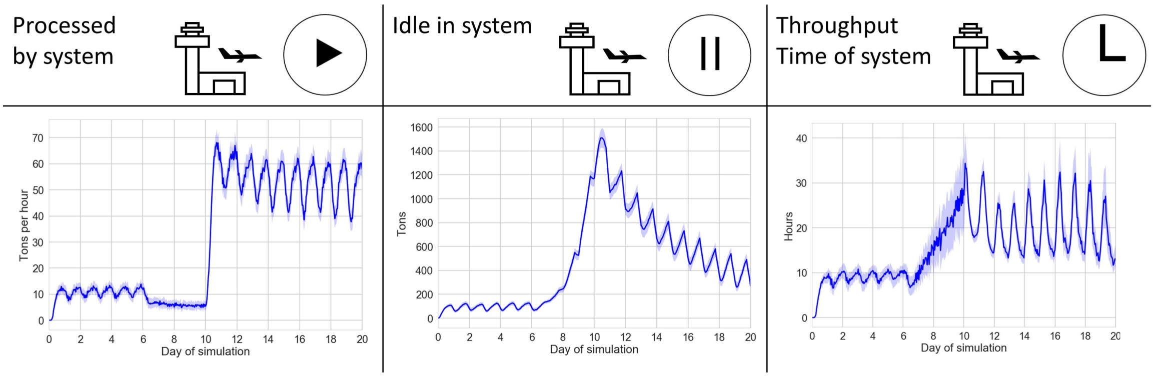

Figure 38: Internal validity of combined policy with the extra resources arriving at the 10th day in the blue scenario (30% of the workers won't show up and 30 % of the cargo during the response consists of loose boxes).

Appendix D Interview US Air Force Institute of Technology

Assistant Professor, Major Supply Chain Management US Air Force Institute of Technology 20-april-2018

What are your thoughts on resilience airport operations during immediate post-disaster response?
Scalability of airport demand in disaster situations is more about the level of flexibility. So maybe this concept is maybe more applicable.

What are your thoughts on airport operation in the immediate disaster response?
The US military was strongly involved in the Haiti response. I was only involved in the airports in Honduras. Honduras served as a strategic staging area. We supplied equipment (mostly helicopters) and medical personal. From Honduras it was only a 2-hour flight and the US was heavily deployed over there. Honduras was perfect for a strategic staging area. Aircraft went after they dropped their goods in Haiti to Honduras. They refueled and slept over there, before they made the flight back to the US. Crew rest and refueling are important aspects of a disaster response.

What were the key problems in the airport operations in Haiti?
(1) Security was a problem in Haiti. Humanitarian aid was looted from the airports. This was solved by employing local people to guard the cargo to decrease the incentive to steal cargo. (2)Last mile distribution was another problem. Vehicles (Trucks and helicopters) can not keep up with the output of the airport. This resulted in the pilling up of goods at the warehouse and ramp. Helicopters were flown in from Honduras, but helicopters can not take a lot of cargo. Trucks were unable to provide downstream logistics, due to the damaged roads. (3) Crew rest was a major concern. When airfield is congested. Pilot need to rest, but the facilities in the disaster area are limited. So, Honduras was used to rest the pilots.

What are other aspect of airport operations what you think are import for the throughput time?
(1) Capacity, there is limited space at the airport. The apron became crowded during the Haiti response. Parking aircraft and storage capacity was not sufficient. This increased the turnaround time. (2) Equipment, although this was not the problem in Haiti. An assessment was performed after 24 hours. The sight survey already foresaw limitations off insufficient equipment. The first military flight brought handling equipment with them. The fact that the military was strongly active in the response and they are self-sustaining organization made them less reliable on local equipment. Because of this the time to unload the aircraft was not critical. (3) Customs, but I am not aware of customs constrains in Haiti.

Appendix E Interview Dnata

Project Manager & Vice president air side Dnata 17-May-2018

What are your current resource planning methods?
We plan according to the flight schedule. Unfortunately they have to due different kind of reasons time delays. This makes scheduling quite hard. The type of aircraft and cargo defines what kind equipment and which persons are needed to handle this aircraft. This must be robust, so that the resources are available one hour after the expected arrival time. To overcome this problem workers are set on different projects in times of delays. Also, the use of flex workers can help. Currently this is 60-40% but goal is 70-30. Financial crisis resulted in a 60-40 distribution. Another problem we are facing is the slot scheduling of Schiphol. Schiphol can't provide slots to all freighters, this leads to irregular arrival times. Flex workers are planned on monthly basis. 95% work full time. It takes 2 years to be all-round worker and you can drive all vehicles.

What happens when you can't meet the demand for handling (due to no-show/breakdowns/increase of inflow)?
This happens every day. At peak times Dnata has 4 aircraft and in downtimes you have nothing. Due to the network system of freight aircraft one breakdown in the system leads to delays everywhere around the world. This means that sometimes you get an extra aircraft when you already on your max. A full freighter needs 7 persons, but in peak times of 5 aircraft. Workers are distributed and only 5 workers are used, who must work a harder, but it is still possible to meet acceptable throughput times.

How do you manage the assignment/prioritization of the right equipment when flight delay leads to an overload?
Normally aircraft that arrive on time will be handled first. Type of cargo can overrule this (for example flowers) also other social factors play a role like contract negotiation. So, no first come first serve. Normally 1-hour off-loading and 1.5 hours loading of wide body with half hour slack. Slack is used to overcome flight delays.

How do you manage the assignment/prioritization of the air side docks when flight delay leads to overload?
Currently Schiphol claims 1 air side dock/gate of Dnata for buffering. Dnata has now 7 air side docks. These 7 docks are a large overcapacity, because Dnata can only handle 4 aircraft simultaneously. So, there are almost always enough docks, when this is not the case the aircraft is parked on the taxi lane. Schiphol has holding position to park the aircraft. There is an option to park the aircraft at other handler, but this is not efficient because you must move all your equipment to this spot.

What are other aspect of airport operations what you think are import for

the throughput time?
The type of cargo. Disasters aircraft and military aircraft have often bulk cargo. Bulk takes longer to unload. Current trend is that military aircraft adapt to civil aviation standards.

What are possible policies for dealing with an increasing inflow
You go in a survival mode. This happens sometimes at RTHA when Schiphol can't handle aircraft. Possible options are:

- You switch to FIFO instead of the original schedule.
- You can ask for extra flex workers for the next day. You can ask to some degree for extra people, but this is very limited. What you not should do is ask random people to help unloading. A fire fighter will do more harm than good during unloading.
- You also divide equipment and not only people. For freight aircraft you switch your equipment from a plane between unloading and loading. You wait till the moment that all loaded cargo is ready. In this way you can divide your equipment over the aircraft.
- With limited warehouse space cargo is parked on the dolly or on the ground outside the warehouse.
- The airport takes control of the gate scheduler. The handler is not in charge. The contracts do not have value at that point.
- Is the right truck available to collect the cargo? You can prioritize on which truck is available.
- You can use extra workers in the warehouse. These workers don't need that much extra training.

How does the custom work in these extreme situations?
Custom is always in charge. They decide which cargo unit is checked. In crisis situations the crisis team will probably create a cargo clearance.

What is mostly the limiting factor in cargo processing (from most to least)?

1. Equipment
2. Workers
3. Warehouse capacity
4. Air side parking spots

Appendix F Interview DHL

Humanitarian Affairs Director and part of the Get Airports Ready for Disaster (GARD) program 18-May-2018

What are possible policies for dealing with an increasing inflow

(1) Prioritization

Prioritization is a good way. However, there is no official guideline about it. The hard part is that the ATC should be in charge of this, but they are not familiar with this responsibility. It can be implemented with the help of the Notice to Airmen (NOTAM) system. You can prioritize aircraft on the ground and in the air on different aspects:

- Cargo content (surge and rescue first)
- Easiness to unload cargo type (bulk/loose cargo vs BUP) Loose cargo can not easily off loaded because there are no rollers in the aircraft.

(2) Extra specialized handlers

The extra workers need to be experts. Aircraft and airport are dangerous places and small accidents can have major impact.

(3) Extra robust equipment

The extra equipment should be robust and easy to handle. You don't have people who are able to repair high-tech equipment.

(4) Extra temporary warehouse facility

90% of the time the consignee is not at the airport on time. The cargo has to be stored somewhere in the meantime. With the influx of cargo extra space is needed. This extra space can also be somewhere outside the airport. The only criterion is that it is not near the aircraft. The storage of the cargo should be done in a way you can access it when the consignee picks it up. It normally takes between 1 to 5 days before the consignee picks up the cargo.

These possible measures can be part of aircraft emergency plan. Which is mandatory by the ICAO Annex 14. This can help to formulate these plans.

What is the percentage of bulk cargo in humanitarian aid situations?

This mostly depends on the aircraft type. Old soviet aircraft (Ilyushin Il-76) are most of the time packet with bulk cargo. The amount of these type of aircraft depends on which countries and organization provide aid. The countries and organization helping is dependent on the location of the disaster. A disaster in South or North America like Haiti has almost no bulk cargo, but a disaster in Africa or Asia has more bulk cargo., due to the higher percentage of old soviet aircraft in that area.

What is the percentage workers don't show up after an disaster

This depends on multiple factors and there is not a general value for all disasters. Firstly, it depends on the location of the airport. If the airport is close to a city which is also affected by the disaster the impact is larger. Secondly, it depends on the accessible of the airport and thirdly, it depends on the size of the disaster. So in short multiple factors have large influence on this number and there is no single value.

What are the operations at the warehouse?

Cargo is unloaded from the dollies. Hereafter the pallet is broken down. This requires 3 people and 1 fork lift. This usually takes 15 to 30 minutes.

What is mostly the limiting factor in cargo processing (from most to least)?

1. Equipment (The most critical equipment is the high loader. Without this device you can't offload a wide body aircraft.)
2. Skilled workers
3. Warehouse capacity
4. Air side parking spots