Using an Automated Model to Develop Conceptual Designs:

Improving an Existing Model for the Conceptual Design of Baggage Handling Systems

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Preface

During my bachelor's program, my interest in aviation technology and management awakened. It all started with one small part of a course about the infrastructure of airports. The systems were so smart, easily adaptable and innovative, it immediately got my attention. Since then, every time I could choose a subject for a project, it had something to do with aviation. I did the minor 'Airport of the Future', that gave me all the ins and outs of airlines, airports and management. I applied this knowledge in my bachelor thesis, which was about KLM and Schiphol. For the specialization of my master program I went abroad to Omaha, Nebraska to learn everything about managing airline information systems. As I certainly have the desire to continue on this aviation path, it has been a great pleasure to end my journey as a student by researching all the ins and outs of baggage handling systems.

I am grateful that I had the chance to meet and collaborate with the Netherlands Airport Consultants, where I undertook an internship. The research was challenging since it continues on an initial model, setting the basis for my thesis which started with trying to fully understand the model. I would like to thank Laura van Noort for setting the groundwork for the model, and Mark Vijlbrief for developing the model and his endless support during my thesis. I would like to thank Taco Spoor for giving me the opportunity to perform the research at a company, with all the great discussions we had, and the freedom he gave me to perform the research just as I wanted to. Furthermore, I would like to thank my supervisors for their excellent guidance and support during this process. To my other colleagues at NACO, I would like to thank you for the wonderful cooperation. It was always helpful to have discussions about my research of how to continue or what is good to take into account. Especially I would like to thank the BHS team for always being supportive and answering all my questions.

In the past 6 months I have been challenged, amazed and surprised about what all happens behind the scenes of an airport. It has been great to figure out how all the different systems at an airport, and especially the baggage handling systems, need to fit together in order to have a working airport. I had great pleasure conducting the research and writing this thesis and I hope you will enjoy reading it as well!

Celine Carter
The Hague, September 2019

Executive Summary

Baggage handling systems (BHS) are unknown to most people, but play a vital role at airports. A BHS is a system that consists of different subsystems, each with its own functions. In a BHS, baggage is transported from the passengers to the aircraft and visa versa. The baggage is collected from multiple sources, sorted, if necessary stored, and redistributed to either the aircraft or back to the passenger. Integrating all different functions into one system, makes designing a BHS very complex.

The importance of a BHS is shown through the opening of Denver International Airport in 1994, in which failure of the BHS caused a 16 month delay, costing approximately 5 billion US dollar (Neufville, 1994). To prevent such BHS failures of happening, it is important to make well-informed decisions about the BHS as early as the conceptual design phase. The conceptual design is the part of the design where the basic solution, such as system configuration (the type and amount of equipment) and system layout (volume reservation for the system), is selected (Pahl, Beitz, Feldhusen, & Grote, 2007). The choices made in this phase influences the cost, performance, and reliability of the system. Even though the impact of the choices in the conceptual design phase is high, tools to guide the decisions are lacking (Wang, Shen, Xie, Neelamkavil, & Pardasani, 2002).

Previous research by Noort (2018) and Vijlbrief (2019) has led to an initial model that automates the conceptual design of a BHS. This model consists of five steps: (1) calculating the system demand, (2) calculating the ground equipment, (3) optimizing the ground equipment, (4) facility sizing, and (5) optimizing the transportation equipment. The BHS equipment is chosen based on a trade-off between the capital expenditure (CAPEX), operational expenditure (OPEX) and level of automation (LoA), which is restricted by the in system time (IST), redundancy, and terminal geometry.

This initial model still has major limitations which need to be resolved in order to finalize the model. For instance, the model has a long run time, it is only applicable to airports designed from scratch, it is too general, and has profound uncertainties. This thesis therefore explores how this initial model for the conceptual design of a BHS can be improved.

Thus, the goal of this research is to improve the model for the conceptual design of a BHS. How 'good' a model is can be assessed through the usability and the usefulness of the model. The usability of a model is how convenient it is to use (Nielsen, 1993). It describes the interaction between the user and the models features (Tsakonas & Papatheodorou, 2006). The usability of a model can be measured through the following four dimensions: learnability, efficiency, errors, and satisfaction. The usefulness of a model is the degree to which a model will provide the required

results to the user (Davis, 1989). It is the interaction between the user and the content of the model (Tsakonas & Papatheodorou, 2006). The usefulness can be measured by the following five dimensions: relevance, format, reliability, level, and timeliness.

The model is improved in several ways. First, an interactive dashboard is created to easily compare different scenarios. Second, the run time of the model is addressed by renewing the facility sizing step, in which the chosen equipment is placed at an optimal location inside a terminal. This decreased the run time of the model by 50% to 75% of the initial model, depending on the size of the airport. Furthermore, as transportation between subsystems often causes problems in the later stages, a detailed routing algorithm, namely A* (Hart & Raphael, 1968), is included in the conceptual design. In addition, the precision of the model is increased by conducting a sensitivity analysis, limiting the uncertainties in the model parameters. Also, the scope of the model is enlarged by adding features to customize designs, such as decentralizing subsystems, and extending the model for brownfield airports.

To evaluate if the model is improved, the usability and usefulness of the models (initial and improved) are evaluated. These two values are assessed through the 7-point Likert scale of acceptability. Figures 1 and 2 show the development of the model on each dimension. A score of a 5 or higher indicates that the model is acceptable. The mean usability increased from 3 to 5.3, indicating that usability of the improved model is just more than slightly acceptable. The mean usefulness increased from 5.4 to 6.2, demonstrating that the usefulness of the improved model is just more than acceptable.

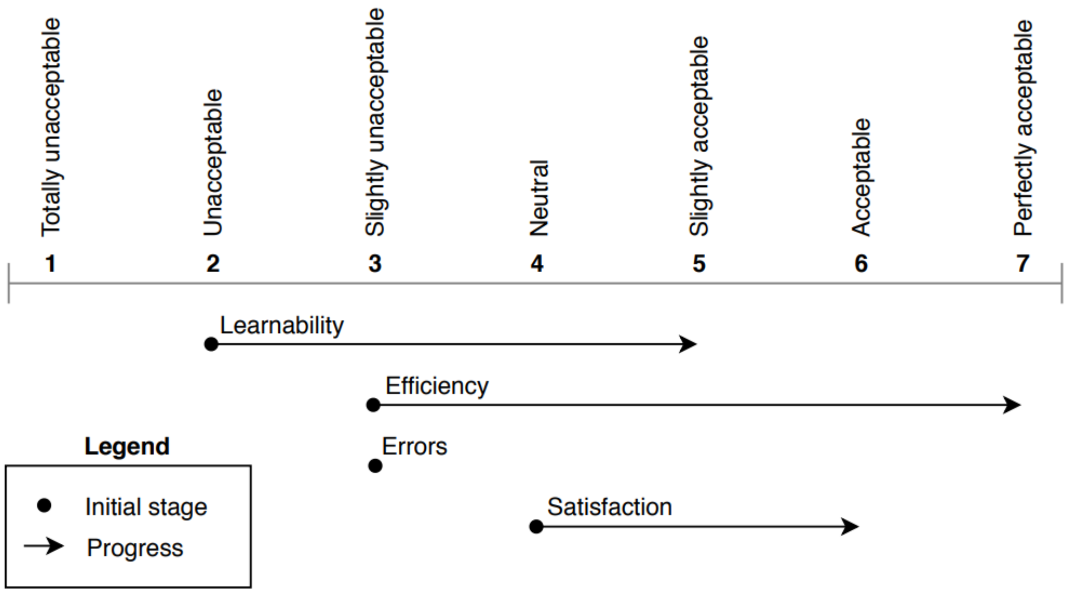

Figure 1: The progress of the usability of the model.

Based on the evaluated usability and usefulness of the model, it can be concluded that the model should be accepted by its users. However, not only the usability and usefulness of a model affect

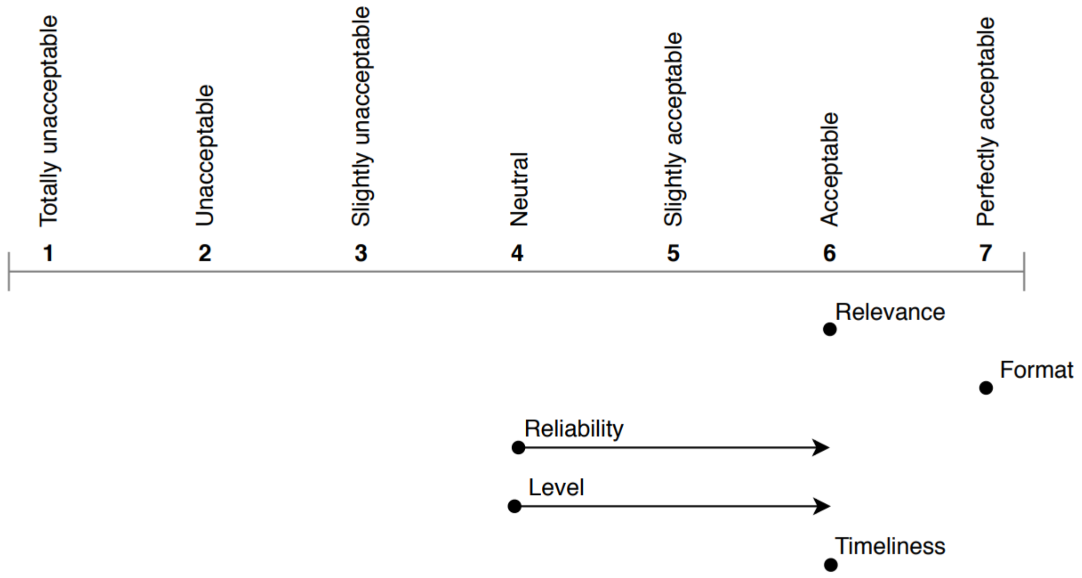

Figure 2: The progress of the usefulness of the model.

if the users will accept it, also the amount of trust they have in the model influences this. If a user does not trust a model, he will not use it. In order to increase trust in a model, the user should have regular positive interactions with the model. Only if a model is considered as good, e.g. high usability and usefulness, positive interactions can be created.

The initial goal of this research is to improve the model by increasing both the usability and usefulness of the initial model. Looking at the usability of the proposed model, adjustment have been made which increased the usability. Examples of improvements are decreasing the run time, writing a manual to motivate the learning of the model, and adding a dashboard to visualize the results. Furthermore, the other important factor of the model, the usefulness, has also increased. Examples of improvement targeting the usefulness of the model are expanding the scope of the model, increasing the model precision by limiting uncertainties, and adding levels of detail to the outcome. So, it can be concluded that since both facets of the model have been increased, the adjustments made to the initial model can be seen as improvements. It can therefore be said that the model proposed in this research can be seen as an improved model for the conceptual design of baggage handling systems.

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List of Abbreviations

AAS	Amsterdam Airport Schiphol
ALT	Automatic load unit transportation
AUA	Queen Beatrix International Airport
BAX	Baggage
BHS	Baggage handling system
CAPEX	Capital expenditure
CIA	Carter International Airport
DCT	Destination coded tray
DCV	Destination coded vehicle
DOH	Hamad International Airport
DSRM	Design science research methodology
EBS	Early baggage storage
EDS	Explosive detection system
EMA	Exploratory Modeling & Analysis
ETD	Explosives trace detection
FIA	Further Inspection Area
HBS	Hold baggage screening
IST	In system time
LAD	Luanda International Airport
LCC	Low cost carrier
LoA	Level of automation
LoS	Level of service

MUP	Make-up position
NACO	Netherlands Airport Consultants
NAICM	Nuevo Aeropuerto Internacional de la Ciudad de México
NB	Narrow-body aircraft
OPEX	Operational expenditure
OSR	On-screen resolution
RJ	Regional jet
ROA	Real Options Analysis
SA	Sensitivity Analysis
SAS	Special Airport Systems
STA	Scheduled time of arrival
STD	Scheduled time of departure
TPE	Taiwan Tayyuan International Airport
ULD	Unit load device
VLSI	Very large scale integration
WB	Wide-body aircraft

Chapter 1

Introduction

Aviation is an essential part of national economies. It provides for the transportation of people and goods throughout the world, greatly benefiting national and world economies (Belobaba, Odoni, & Barnhart, 2015). Aviation is one of the fastest, safest, and most far-reaching transportation modes. Over three billion people, which is nearly half of the global population, use the worlds airlines (Federal Aviation Administration, 2015). To be able to meet the needs of a growing economy and accommodate an expanding population, aviation will continue to grow.

Air travel forecasts expect aviation to continue to grow in the long term. Boeing (2015) predicted annual average growth of the number of passengers of 4.0 percent through 2034. Airbus (2014) forecasted an annual average growth of 4.4 percent over the next 20 years and doubling the air transportation in the next 15 years.

To manage the growth, airports will need to change and grow. New airports need to be built and existing airports need to expand. Infrastructure, including runways, terminals and air traffic control will need to both be more efficient and expand to handle the increasing number of passengers (IATA, 2016). However, airports are often built in or near big cities where space is scarce and building or expanding is very difficult. Among other things, the baggage handling system (BHS) is a critical element that determines the capacity of an airport (Cavada, Cortés, & Rey, 2017). As a BHS is often spread out over the entire airport, changing the system is not easy (Silven, 2018).

Furthermore, systems that are always in operation, such as most airport systems, are very critical to daily operations and are difficult to expand or enhance (Rengelink & Saanen, 2002). Optimal planning and testing is essential. The BHS is one of these critical systems. An example of a system gone wrong was the baggage system at the newly built Denver International Airport (Neufville, 1994). At the time the baggage handling system was supposed to be the world's largest automated airport BHS, cutting the turnaround time to just 30 minutes. However, the BHS had major issues delaying opening the Denver airport by 16 months and costing the airport approximately US$5 billion.

This chapter provides an introduction to this thesis. First the basic knowledge of baggage handling systems (BHS) is explained, which is needed to understand the rest of this thesis. In Section 1.2 the company for which the research is conducted is introduced. Section 1.3 explains the full design process of a BHS design at NACO. This is followed by discussing the aspects and importance of conceptual designs. Section 1.4 elaborates on the existing model that is built to generate a BHS concept designs. The research motivation, goal and research question and sub-questions are discussed in Section 1.5. The next section explains the approach that is used to tackle this thesis. At last, Section 1.7 describes the outline of the report.

1.1 What is a Baggage Handling System?

The baggage handling system (BHS) is a critical process in the landside or ground operations at airports, impacting both the airlines and their passengers (Cavada et al., 2017). If the BHS or a part of the BHS system is not well designed and managed, baggage can get damaged, delayed or lost, which increases costs and creates customer (passenger) frustration and dissatisfaction. This can be particularly relevant during peak hours and high season causing ripple effects throughout the airport and the airline.

As the BHS is a main subject in this thesis, it will be explained in more detail. Khosravi, Nahavandi, and Creighton (2009) defined a BHS as a system of sub-systems in which the different functions of the baggage handling system needs to be fulfilled. Figure 1.1 is a diagram of the typical subsystems. These complex baggage handling systems usually include three flows representing baggage moving through the airport: departing, arriving and transfer passengers. The departure flow handles baggage from departing passengers, from check-in to aircraft loading (the blue flow in Figure 1.1). The arriving flow handles baggage from the arriving passengers, from aircraft unloading to baggage reclaim where passengers collect their baggage (green flow). The transfer flow handles baggage that is unloaded from arriving aircraft, goes to screening so that it can be redirected to an outgoing flight through the departure flow (red flow).

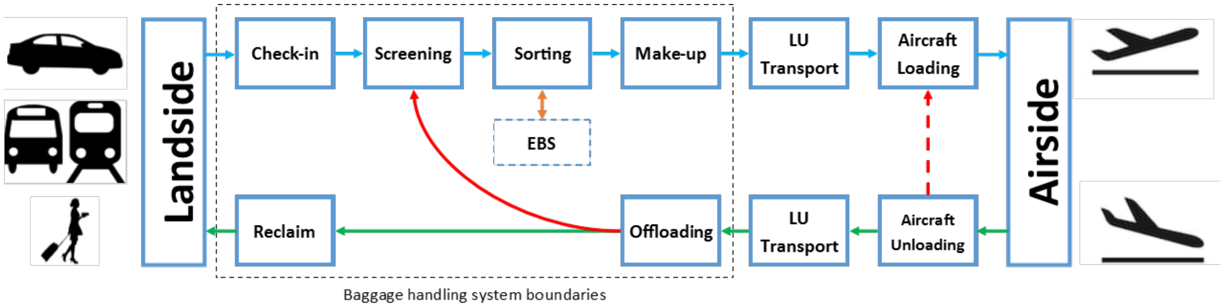


Figure 1.1: Baggage handling system boundaries (Vijlbrief, 2019).

NACO, the company for which this thesis is performed (see section 1.2), has defined the boundaries of a BHS from check-in to make-up, and from offloading to reclaim. This excludes odd-sized baggage and baggage which is checked-in during aircraft boarding (when there is not enough space for hand-luggage in the cabin). For the purpose of this thesis, a BHS consists of the following 7 subsystems:

1. **Check-in:** The departing passengers drop off their bags and the bags enter the BHS.
2. **Screening:** The baggage is screened for explosives. The baggage is screened in three levels. If the bag passes the first level (thus no sign of explosives), it goes straight to sorting. If

not, the bag goes to the next level and so on. If the bag does not pas the third test, it is taken out of the system.

3. **Sorting:** The baggage is sent to early baggage storage (EBS) or the right make-up position.
4. **EBS:** Baggage can be stored here. This is optional and used at airports that provide early check-in or for passengers that have a long lay-over between flights.
5. **Make-up:** Baggage is loaded on to unit load devices (ULD's) or carts.
6. **Offloading:** Baggage is offloaded from ULD's or carts on the reclaim belt. Offloading is usually divided into two systems: offloading for transfer baggage and offloading for arriving baggage (O&D).
7. **Reclaim:** Arriving passengers pick up their bags in the reclaim area.

Each subsystem is explained in more detail in Appendix B. Not always are the subsystems directly connected or next to each other. This creates the need for another subsystem: the transportation system. Transportation is needed when two subsystems are not directly linked and baggage needs to be transported between subsystems.

1.2 Netherlands Airport Consultants

The Netherlands Airport Consultants (NACO), is a world-leading independent airport consultancy and engineering firm. NACO is established in the aftermath of World War II, in 1949, by Dr. Albert Plesman. Plesman anticipated that the wish to travel would increase after the war and set up an organization that designs airports, with the combined knowledge of experts in airport design and construction. Today, NACO is part of Royal HaskoningDHV, which is one of the world's leading independent international project management and engineering consultancy service providers. In all these years, NACO has helped design and build over 600 airports around the world.

NACO aims to solve the increasingly complex situations and systems involved in developing world-class airports, that should be able to meet the requirements of the future. One of these systems is the design of baggage handling systems. NACO's Special Airport Systems (SAS) division specializes in optimizing baggage handling facilities to create a safe, compliant and efficient operation.

1.3 BHS design process

To be able to understand this research an elaborate explanation of the current BHS design process needs to be discussed. This section first briefly explains the full design process of a BHS design at NACO. This is followed by discussing the aspects and importance of conceptual designs.

1.3.1 Full BHS design process

The full design of the BHS consists of several phases. Figure 1.2 shows the entire design process for a baggage handling system. During the design process a lot of decisions are based on experience, rules of thumb and standards. Designing a BHS starts with a master plan, which is not done by the BHS team but the master planners. In the master plan the system requirements are set. These requirements are based on passenger data and baggage process equipment. The master planners decide on the basic size of the different facilities and the number of processors such as check-in desks and reclaim carousels. The work from the BHS-team starts from this point on. Based on the requirements from the master plan and the wishes from stakeholders, a functional design is made. During this phase the designers determine which functions are needed in the BHS. For instance, is an early baggage storage (EBS) required or not? The next phase is a combination of two tasks, the concept design and the material flow diagram. The concept design shows the BHS functions and the rough size of each BHS subsystem. The material flow diagram shows all the links between the different subsystems. These tasks are linked closely together. Often the designers go back and forth between these phases. These two designs are used to build the basic design. The design process is concluded with a detailed BHS design. During this stage the exact components are chosen and a 3D model of the design is made.

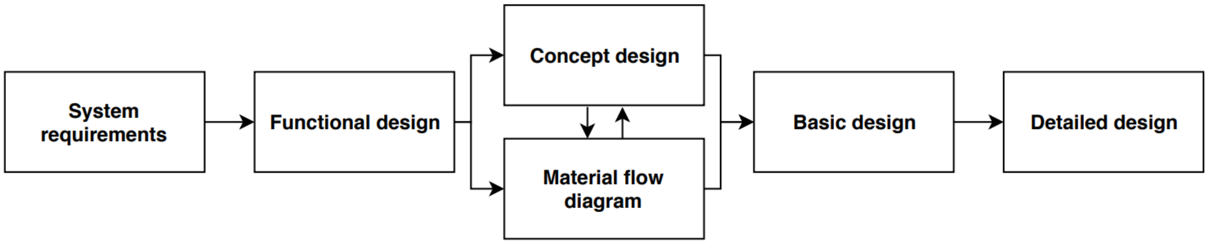


Figure 1.2: Full BHS design process.

A BHS-designer at NACO described the design process as follows: "the functional design is about 10% of the full design, the concept design and material flow diagram are about 30%, the basic design is about 70% and the detailed design is about 100% of the full BHS design." The full BHS design is the product that is the finished product that is tendered to the client. The BHS design process is often not fully (100%) completed. How many phases need to be designed depends on what the client has asked. As of phase 2, every phase can be delivered to the client as output.

1.3.2 Conceptual design phase

NACO's BHS model is a conceptual design model. As described by Pahl et al. (2007), "conceptual design is the part of the design process where the basic solution path is laid down through the elaboration of a solution principle." Wang et al. (2002) defines a concept design as combining working principles, selecting suitable combinations and creating solution variants. The outcome of a concept design is a 'basic' solution in which the broad outlines are provided, but the details still need to be filled in.

The conceptual design is a crucial stage in an engineering design, and influences the cost, performance, reliability, safety and environmental impact of a product (Hsu & Liu, 2000). While there are a lot of tools to guide the later phases in the full design, tools are lacking in the conceptual design phase (see Figure 1.3). However, this is the most important phase of the design. The impact of the decisions made during this stage are high and can account for more than 75% of the final product cost (Wang et al., 2002). The high impact of these decisions can be explained through two reasons. First, the decisions that are made in the subsequent stages are based on the decisions made in this stage. Second, it is the most difficult stage because parts selection, generic structures of the product, and topology (relative position between part) have to be designed according to the design requirements.

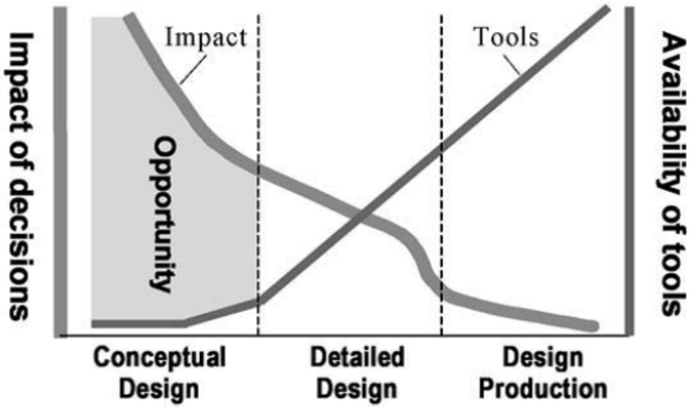


Figure 1.3: The impact of decisions versus the availability of tools in the design phases (Wang et al., 2002).

1.4 Existing model for the conceptual design of a BHS

At the moment, it takes NACO weeks to design each BHS scenario for an airport by hand. There can be many alternative scenarios as each BHS scenario includes the choice of specific equipment per subsystem (see Appendix B for all the equipment choices), the number of pieces of equipment for the required baggage capacity, and placement of the subsystems in the designated BHS area. As there are numerous potential scenarios, it is difficult and time consuming to determine the optimal scenario. Thus, only a few scenarios can be evaluated.

In the last two years, NACO has been exploring how to make the process more effective so that they can analyze more options in every BHS project. To improve NACO's BHS capabilities they are searching for an automated tool to facilitate the design of baggage handling systems. Two previous graduate students created a BHS concept design model to automatically generate and evaluate BHS concept designs (Noort, 2018; Vijlbrief, 2019). Criteria for the model are based on certain trade-offs, such as importance to the client of capital expenditures (CAPEX) or the level of automation (LoA). Every time the criteria change, the 'optimal' scenario will be revised.

The existing model is already an improvement of designing a BHS by hand, but it is not good enough for NACO to use in their daily operations. Therefore, this model needs to be improved. However, before the model can be improved, the existing model needs to be explored in more detail. This section will elaborate on this existing model. First the model framework will be discussed, which explains the principle behind the model. Section 1.4.2 shows the trade-offs that are used to optimize the conceptual designs. The next section explains the optimization algorithm that is used to choose the equipment in the conceptual designs. Last, in Section 1.4.4 the placement algorithm, which is used to search for the optimal location of a subsystem in a terminal, is described.

1.4.1 Model framework

Figure 1.4 shows the model framework of the existing conceptual design model for BHS. In stage one, the system capacity is defined using the inbound and outbound flows of an airport in conjunction with the input parameters, such as the level of service (LoS) and redundancy at the airport. Flight schedules and other operational requirements are used to determine the required BHS capacity. The flight schedule contains the scheduled time of departure or arrival (STD or STA), airline, flight direction (inbound or outbound), aircraft type, transfer passengers and origin- destination (OD) passengers. The capacity is calculated for each subsystem. The capacity of a subsystem per hour is based on the busiest 15 minutes of a day. This data is then used to define the system requirements.

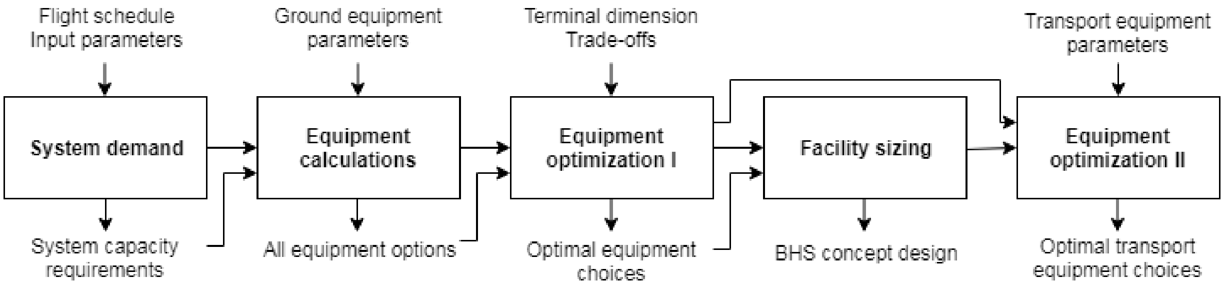


Figure 1.4: Model framework of the initial BHS conceptual design model.

The second stage analyses equipment data, with exception of the transportation and sorting equipment, to calculate the equipment that is needed for each possible type that can be used for the system or scenario. Appendix B describes all equipment types. For instance, for check-in there are three types of equipment. For each type, the number of machines that is needed to meet the system requirements, is calculated. This number can be adjusted according to the stated airport redundancy requirement. For each equipment type, the trade-offs are also analyzed, including the total amount of space needed, CAPEX, energy consumption, the number of operators and the in system time (IST).

In stage three, the type of equipment per subsystem is selected based on the available space in the terminal, the trade-off criteria and the system requirements. Certain equipment types can be eliminated by the available space or system requirements, for instance when a particular type of machine is too big or too high to fit into the available space. The trade-off criteria are then used to propose potential optimal solutions. At this point, the optimization of scenario's can occur. Optimization is discussed in more detail in Section 1.4.3. The outcome of this stage includes the choice of equipment per subsystem, capacity, redundancy, CAPEX, LoA, etc.

In the fourth stage, a program is used to plan how the equipment could be placed inside the space available in the terminal. The placement of each subsystem is chosen using the Droplet search model developed by Vijlbrief (2019), which is discussed in Section 1.4.4. The critical factor for placement is the capacity between the two subsystems. Preferably, the connection should be shorter when the capacity is higher. Even though the placement of the subsystems is based on the capacity between two subsystems (thus the transportation between the two subsystems), the transport equipment cannot be chosen yet because it depends on data that is only available after this fourth stage. So, at this point space is reserved for transportation lines to be added later.

In the fifth stage, transportation equipment is selected. Sorting and loading equipment is determined first. Since each type of transport equipment has specific loading and sorting equipment, there are 27 possible combinations. With just a few additional functions, transportation equipment is selected using the same optimization algorithm as the ground equipment (see Appendix 1.4.3). A 3D model of the equipment placement is created in a 3D Autodesk Revit program. The optimal scenario, equipment choice using the trade-off criteria, is provided in an Excel file.

1.4.2 Trade-offs

For each stakeholder and airport, different BHS characteristics are of importance. Therefore, trade-offs have to be made when choosing a conceptual design for a BHS. Table 1.1 shows the trade-offs that are used in the conceptual design model for BHS to calculate the optimal scenario. The values of these trade-offs are part of the output parameters of the conceptual design.

Table 1.1: Trade-offs in the model for the conceptual design.

BHS trade-off	**Explanation**
Capital expenditure (CAPEX)	Indicates the investment costs for the BHS.
Operational expenditure (OPEX)	The number of energy consumption of the machines versus the amount of operators needed.
In system time (IST)	The time a bag spends in the BHS.
Redundancy	The ability of the system to handle equipment malfunctions.
Level of automation (LoA)	How much automation is used in the BHS.

1.4.3 Equipment optimization

The optimization algorithm determines the best combination of equipment per subsystem. In total, there are 62,208 possible BHS configurations with the current types of equipment and input values. If more types of equipment or more input values are added in the model, this number increases even more. The model should narrow this to one optimal solution. The ground equipment is chosen (stage 3 in the Section 1.4.1) through a binary integer programming model which is based on Ölvander, Lundén, and Gavel (2009). This model consists of several parts which will be discussed in this section.

Decision variables

The binary decision variables represent the equipment choice for each type of equipment. If an equipment type j is chosen for subsystem i, the value of the decision variable is 1, otherwise 0. This function is shown in Equation 1.1.

$$x_{ij} = \begin{cases} 1 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is yes} \\ 0 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is no} \end{cases} \tag{1.1}$$

Objective function

An objective function is defined (see Equation 1.2), where a trade-off is made between the CAPEX (c_{ij}), the energy consumption (E_{ij}), the number of operators (Op_{ij}) and the level of automation (LoA_{ij}). Each trade-off has a weight (α, β, γ and δ), which is needed to make the trade-off. The sum of these weights needs to equal 1 (see Equation 1.3). To prevent the model from choosing a random option when two designs have the same objective solution, 0.01 is added to all trade-offs. This way, if two solutions have the same value, the model will choose the solution that has a better average over all the trade-offs.

Each trade-off is expressed in a different measuring unit. Since for the objective function all variables need to be expressed in the same unit, the sum of each trade-off is divided by the minimum possible sum of that trade-off.

Furthermore, if there is more automation of machines, less operators are needed and vice versa. So, the number of operators and the level of automation are negatively correlated to each other. This means that if one trade-off is minimized, the other should be maximized. This is done with μ (see Equation 1.4).

$$\begin{aligned} min \Bigg(\alpha * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} c_{ij} * x_{ij}}{\text{minimum value } CAPEX} + \beta * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} E_{ij} * x_{ij}}{\text{minimum value } Energy} + \\ \mu * \gamma * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} Op_{ij} * x_{ij}}{\text{minimum value } Operators} - \mu * \delta * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} LoA_{ij} * x_{ij}}{\text{minimum value } Automation} \Bigg) \end{aligned} \tag{1.2}$$

$$\alpha + \beta + \gamma + \delta = 1 \tag{1.3}$$

$$\mu = \begin{cases} -1 & \text{If the amount of operators should be maximized and the LoA minimized} \\ 1 & \text{If the amount of operators should be minimized and the LoA maximized} \end{cases} \tag{1.4}$$

Constraints

A constraint defines the rules to which the design solution should comply. The first constraint is that for each subsystem, only one equipment type can be chosen (see Equation 1.5). Furthermore, one important trade-off, the IST, is not included in the objective function. This is because the IST is rather a constraint, of which the system is not allowed to exceed the maximum IST. The maximum IST usually depends on the desired transfer time of an airport. Equation 1.6 shows this function. The next two constraints have to do with the terminal size. Equation 1.7 states that the area of the subsystems cannot exceed the available area in the terminal and Equation 1.8 states that height of the subsystems cannot exceed the maximum height in the terminal.

1. Only one equipment type per subsystem can be chosen.

$$\sum_{j=1}^{m} x_{ij} = 1 \quad \forall i \tag{1.5}$$

2. The IST boundary cannot be exceeded.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij} * x_{ij} \leq max_{IST} \tag{1.6}$$

3. The combined area of all subsystems cannot exceed the assigned area.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} * x_{ij} \leq max_{area} \tag{1.7}$$

4. The height of the equipment (h) cannot exceed the height of the terminal. For each subsystem this constraint is added separately.

$$\sum_{j=1}^{m} h_{ij} * x_{ij} < max_{height} \tag{1.8}$$

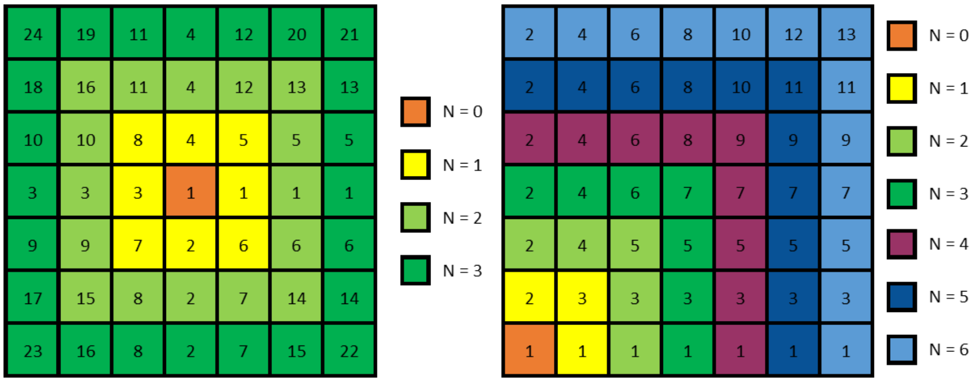
1.4.4 Placement model

The Droplet search model is one of the methods used in the initial (existing) model. This Droplet model is developed by Vijlbrief (2019) for the facility sizing of material handling systems, especially for facility sizing of a BHS. The model is based on a very large scale integration (VLSI) placement model. VLSI placement models aim at placing the subsystems while reducing the distance between connected subsystems (Lim, 2008). This is done by looking at the number of connections between subsystems. More specifically, the Droplet search model is based on the Gordian placement algorithm developed by Russell, Norvig, Canny, Malik, and Edwards (1991). This specific model is chosen by Vijlbrief because it is one of the algorithms which can handle fixed positions of some nodes and can assign weights to connections between subsystems.

The Droplet model is based on keeping the different subsystems as close to each other as possible, which minimizes the transportation distance. This is done by defining were the desired location of each subsystem is. The desired location can either be one single point, such as the end of the check-in hall (where the baggage enters the system), or the center between multiple points. After this, the actual placement is performed. For every subsystem the closest possible location for the equipment is defined and placed (in a sequence).

Vijlbrief's Droplet search model works as follows. First the starting point is defined. This is the desired location of the subsystem that will be placed. As previously mentioned, this can be the center of a previous subsystem or the midpoint between two subsystems. Next, the equipment can be placed. The placement is just like a drop falling into a puddle of water. The drop is the starting point, which sets off a wave and the wave keeps moving further and further away from the starting point. The model works with the same principle. It starts to check if there is space available at the starting point. If there is no space, the model will expand the search in all directions to the closest spaces nearby (just like a wave) to check if there is space available. If not, the wave will continue until there is space available.

Figure 1.5 shows this model. The actual model is an expanding square instead of a circle, which means that the distance between the points in the square and the starting point are not equal. This is solved by following a sequence within a wave (which is shown through the numbers in Figure 1.5). Thus, within every wave there is an order. For instance, in the second wave (yellow squares in the figure), the first place that is checked is square 1 and the last place is the highest numbered square in that wave (in this case 3 or 8 depending on the desired starting location). This process is repeated for each subsystem until they are all placed.



24	19	11	4	12	20	21
18	16	11	4	12	13	13
10	10	8	4	5	5	5
3	3	3	1	1	1	1
9	9	7	2	6	6	6
17	15	8	2	7	14	14
23	16	8	2	7	15	22

2	4	6	8	10	12	13
2	4	6	8	10	11	11
2	4	6	8	9	9	9
2	4	6	7	7	7	7
2	4	5	5	5	5	5
2	3	3	3	3	3	3
1	1	1	1	1	1	1

Figure 1.5: The Droplet search model by Vijlbrief (2019).

1.4.5 Shortcomings of the existing model

Now that the existing model is discussed, the model can be evaluated to find the shortcoming of the model. The model is still in the early stage. It is accelerating the design process, but a large BHS could still take hours or days to simulate. This is primarily due to the speed of the Droplet search model. In addition, the model can only be used for greenfield BHS, in which a project is built up from scratch. This means that no existing structures or equipment can be used in the designated BHS area. So, the model can only be used for new airports or airports that are completely redesigning their BHS (and terminal building/baggage hall/basement/etc.) from scratch or are adding a new building or facility. Furthermore, research is lacking about the effects of different airport layouts on the model. Another limitation is that the output of the model only contains the details (space, cost, etc.) of one specific scenario. The evaluation of each scenario is a manual process and can be very time consuming. Of course, a model is supposed to be a reflection of reality. However, there are always uncertainties, assumptions and aspects that are outside of the scope of the project. Although it is difficult to eliminate all assumptions and include everything in the scope, limiting as many uncertainties as possible can significantly increase the models' performance. Furthermore, the model still has a lot of rough edges and is difficult to use for outsiders. Finally, the model is not *fully* used yet by the NACO BHS designers. The capabilities of the model are high and have a lot of potential (if slightly upgraded). Thus, the model needs to be improved to reach the initial goal from NACO, to build a conceptual design model that will guide their decisions and will shorten the throughput time while increasing the level of detail.

1.5 Research definition

The aim of this research is to improve NACO's conceptual design model of a baggage handling system. This section begins by explaining the motivation for this research. The next section defines the goal of the research and states the research question. Section 1.5.3 explains the sub-questions.

1.5.1 Research motivation

Literature on BHS conceptual designs is lacking. Lemain (2002) focused on the business management side of BHS designs. Pielage (2005) researched a generic design method for airport freight transport systems, but not specifically BHS. Grigoras (2007) examined the transformation of a process flow diagram to a material flow diagram through route finding methods for BHS. However, no research has been done in studying the trade-offs and restrictions and providing insight in space reservation to build a concept design. Previous research by NACO (Noort, 2018; Vijlbrief, 2019) has led to the initial model (discussed in the previous section) to develop a BHS conceptual design. However, there are some important limitations (as addressed in Section 1.4.5). This research aims at addressing these limitations and improving the initial model.

1.5.2 Research goal

Using a model to build a conceptual design can be a difficult problem to tackle. As already mentioned, the conceptual design is the part of the design where the *basic* solution is selected. Though, a model provides an outcome which is based on precise calculations, explicit values, and particular relationships between parameters. Using a model to build basic solutions thus causes friction, because a model provides precise outcomes while only a basic solution is needed for during conceptual design phase.

As an initial model already exists, the research starts with that model. As shown in the previous section, this initial model from NACO works, but it still needs to be revised. The main research goal is to improve this model and to increase the use of this model in the future by the BHS designers at NACO. As Buchanan and Salako (2009); Tsakonas and Papatheodorou (2006) state, the quality of a model can be examined by assessing the usability and usefulness of the model. The *usability* of a model is how convenient it is to use (Nielsen, 1993), it is the interaction between the user and the models features (Tsakonas & Papatheodorou, 2006). The *usefulness* of a model covers the interaction between the user and the content of the model (Tsakonas & Papatheodorou, 2006), it is the degree to which a model will provide the required results to the user (Davis, 1989).

The focus of this thesis is on how a model can be developed in order to build plausible conceptual designs, that can be used to guide the early design decisions of baggage handling systems. A model builds plausible conceptual designs if the quality of the model is good, i.e. high usability and high usefulness. This leads to the following research question:

How can the model for conceptual designs of baggage handling systems be improved, in order to increase the usability and usefulness of the model?

As already mentioned, previous research by NACO has led to an initial model for conceptual designs of baggage handling systems. Though, the BHS designers at NACO, the users of the model, do not yet use the model in their decision making. In order for the BHS designers to use the model, it first needs to be improved. The term ‘improvement’ of a model is very broad. It can simply mean rectifying the model, increasing the speed, making it wider applicable, decreasing uncertainties, increasing precision or any other way the value of a model is increased.

This research will focus on multiple aspects of improvement. First, the model itself should be faster. For instance, the existing model uses an algorithm that can take a very long time (see Section 1.4.4) to place the subsystems. Changing this algorithm will increase the speed and usability of the model, as it can be used more often if it takes less time to compute.

Furthermore, when designing a scenario takes a long time, the designers often end up complying to stakeholders wishes, even if they think it might not be the best option. If the model can provide several scenarios in a shorter amount of time, these can be used to confirm or deny assumptions and to inform or convince stakeholders to make better decisions.

Third, the research will focus on limiting uncertainties to assist in making informed decisions. The results of the model are based on a set of predefined parameters. These parameters are often defined through experienced guesses and assumptions, and thus are open to uncertainty and error. As Kwakkel and Pruyt (2013) state "the use of models to make predictions can be seriously misleading if there are profound uncertainties." This limits the use of the BHS model for actual designs.

Last, often decision makers and stakeholders are not clear or cannot agree on goals or objectives for a project. As (Noyes, Cook, & Masakowski, 2007) state, automation and simulation has led to superior productivity, efficiency and quality control. Moreover, decision making on complex systems requires us to deal with high uncertainty, due to complex systems, a variety of stakeholders with different perspectives, and rapid change (Kwakkel & Haasnoot, 2018). Modeling these systems can illustrate or clarify scenarios and help stakeholders and decision makers come to an agreement and make informed decisions. On the other side, various researchers have shown that if a decision maker does not trust a model, he will not use it to guide his decision (Camp, 2003; Inagaki, 2008; Muir, 1987). Researchers have also shown that there is a balance between model complexity and trust (Astrup, Coates, & Hall, 2008; Chwif et al., 2000). These aspects need to be taken into account when developing a model that is designed to use for decision making.

1.5.3 Sub-questions

Several sub-questions are formulated from the research question. These sub-questions each address a shortcoming of the initial model. The sub-questions will be discussed in this section.

The first sub-question focuses on the evaluation of the outcome of the model. As the goal of the tool is to use the outcome to guide the early design decisions, the outcome needs to be evaluated in an efficient manner. Since the tool is developed for the conceptual design phase, which is early in the process where not all values and desires are fully known yet, it is necessary to develop several scenarios and compare them. The first sub-question addresses this problem.

Sub-question 1 *How can the model be developed in order to evaluate different scenarios for one airport?*

As already mentioned multiple times before, the run time of the model needs to be shortened. If the run time of the model exceeds the project throughput time for the conceptual design, the model is useless. Currently the model can take hours or days to generate just one scenario. In order to increase the usability of the model, the model run time needs to be decreased. This problem is tackled with the following sub-question:

Sub-question 2 *How can the run time of the model be improved, in order to increase the usability of the model?*

Transportation between subsystems is a vital aspect of a BHS. The transportation in BHS designs often causes the design to be insufficient or even impossible. It is therefore very important to take this transportation into account in the design as early as possible. At the moment, only a basic estimation of the transportation between two subsystems is added. To increase the usefulness of the model, more detailed transportation between subsystems needs to be added. This is addressed in the third sub-question:

Sub-question 3 *How can transportation between subsystems be included in the model, in order to increase the usefulness of the model?*

As already mentioned in Section 1.4.5, every model has uncertainties. A model can never be an exact representation of the real world. However, limiting these uncertainties improves the usability of the model (O'Connor, Yang, Tian, Chatterjee, & Lee, 2017). This leads to the following sub-question:

Sub-question 4 *How can the variation in the output of the model of the conceptual design of the baggage handling system be apportioned to different input parameters?*

Even though every airport is build up from the same subsystems, every airport is unique. This complicates the process of making a model that can design a BHS specific for one airport. However, there are certain airport aspects which have a lot of influence on the design of baggage handling systems. The following sub-question addresses how this can be taken into account in the design.

Sub-question 5 *Which criteria impact the design of baggage handling systems and how can these criteria be taken into account when modeling the conceptual design?*

Next, the model should be useful for all airports. The model can now only be used for a greenfield BHS (starting from scratch, renewing all systems) and not for a brownfield BHS (starting with something, partly renewing systems). Especially for airports that are already in use, systems are difficult to change and interruptions can be very costly (Rengelink & Saanen, 2002). Simulating and evaluating the system can limit costs and disruptions. This leads to the following sub-question:

Sub-question 6 *How can the model be adapted to be able to include brownfield baggage handling systems?*

When building a model to guide decision making, the use of this model needs to be considered. If a decision maker does not trust a model, he will not use it to guide his decision (Camp, 2003; Inagaki, 2008; Muir, 1987). Therefore, trust in the conceptual design model for BHS needs to be analyzed. This leads to the following sub-question:

Sub-question 7 *How can the use of the model of the conceptual design of the baggage handling system be improved, by increasing trust in the model?*

The last phase of this research is to test the model for different airports. If the model works, but it does not provide reliable results, it cannot be considered a 'good' model. This leads to the last sub-question:

Sub-question 8 *How does the outcome of the model compare to the manually developed conceptual BHS designs for different airports?*

1.6 Approach

To help structure this research, the Design Science Research Methodology, also known as DSRM, by Peffers, Tuunanen, Rothenberger, and Chatterjee (2007) is used. As Peffers et al. (2007, p. 6) state, 'this method is used for designed objects with an embedded solution to an understood research problem.' As this methodology can be applied to research new technologies within existing organizations (Asman & Srikanth, 2016), it suits this research. The methodology consists of six steps which are as follows:

1. **Problem identification and motivation.** Identifying the specific research problem and motivating why this problem is relevant to solve.

2. **Define the objectives for a solution.** The performance objectives of the solution need to be defined. The goal is to figure out what a possible and feasible solution is.

3. **Design and development.** Create the artifact that is used to create the solution, such as a model, method or instantiation.

4. **Demonstration.** Show the use of the artifact and how it operates. This can be done through experimentation, simulation, case study, or another activity.

5. **Evaluation.** Observe and measure, through the objectives defined in the second step, how well the created solution supports the problem.

6. **Communication.** Communicating the research problem by spreading the knowledge of the research.

1.7 Thesis outline

The report is structured is as shown in Figure 1.6. Chapters 2 and 3 explore the possibilities to increase the usability of the model. The usefulness of the model is tackled in Chapters 4 to 7. Two of those chapters focus on increasing the quality of the initial model, the other two broaden the scope of the model by increasing the number of options of the model. Chapters 8 and 9 attempt to demonstrate how well the model performs. In Chapter 10 the initial model is compared with the improved model based on the usability and usefulness of the models. Chapter 11 provides the conclusion and discussion of the research. As the method for this thesis differs for each sub-question and chapter, the methodology is at the beginning of each chapter.

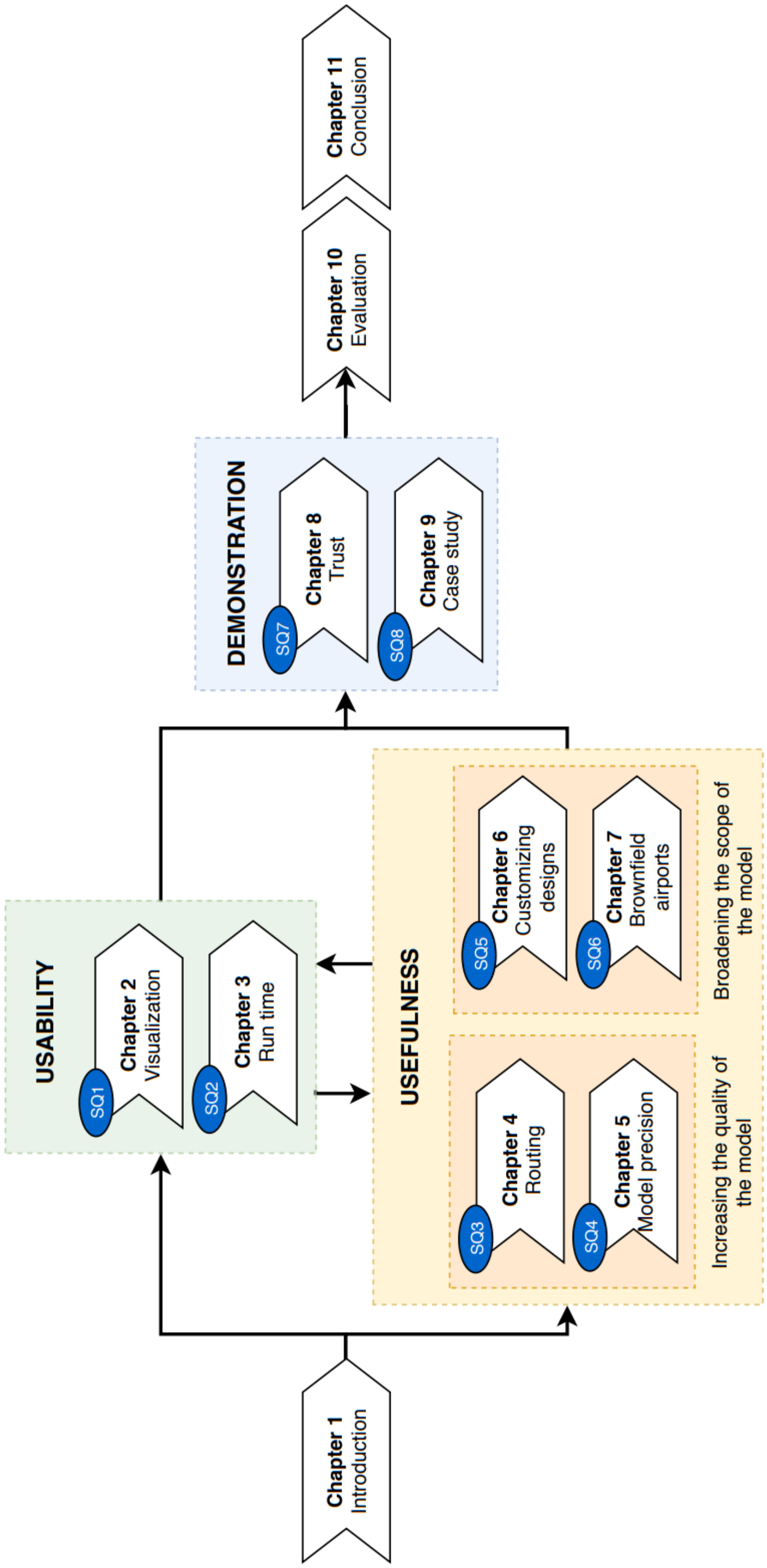


Figure 1.6: The structure of the thesis.

Chapter 2

Improving the visualization of a conceptual design

The model is developed for the BHS designers at NACO and therefore it needs to be developed in a manner that they can and will use it. As already mentioned, the conceptual design is the part of the design process where the basic solution path is laid down through the elaboration of a solution principle (Pahl et al., 2007). As the conceptual design is still early in the process, input parameters are not set in stone and choices in optimization need to be made. This decision can influence the model outcome. It is therefore necessary to be able to compare and evaluate different scenarios. This chapter addresses the first sub-question: *How can the model be developed in order to evaluate different scenarios for one airport?*

Scenarios differ due to altering input variables. For instance, scenarios can be run for different demands, optimization choices and/or design decisions (which are discussed in Chapter 6). Each set of input variables creates a different output, which is a possible scenario. An interactive dashboard is built to be able to compare these scenarios. The dashboard is split up in three parts. This chapter is structured as follows. In Section 2.2 is visualized how the input of the data per scenario is presented. In the next section an interactive dashboard is discussed, which allows the user of the model to compare different scenarios. Section 2.4 explains the last part of the dashboard that can be used to evaluate the results, namely a table with all the specific values for each subsystem. In the last section the findings of this chapter are summarized.

2.1 Visualization of the initial model

The visualization of the initial model is split up in two parts, a 3D drawing of the BHS terminal (see Figure 2.1) and a table representation of the specifics per subsystem (see Table 2.1). Every grey rectangle in the 3D drawing represents one floor, where the left rectangle is the lowest floor level, and every rectangle to the right is one level higher. So, in the 3D drawing in the figure below all subsystems are placed on floor level 0, and the first floor is empty. The visualization of the initial model shows the placement and values for one scenario. Though, comparing different scenarios needs to be done by hand and can be time consuming. Furthermore, a new Excel file is created for every scenario. In addition, as a lot of data is shown in the table, it can be difficult to see what the differences between the scenarios are. Moreover, to check the input values that are used to generate a scenario, one needs to go back into the model to find these values. So, even though it is possible to evaluate one scenario, and even to analyze two scenarios, the usability of the model due to visualization is not acceptable. To improve the usability of the model, this problem needs to be addressed, for which an interactive dashboard is build in order to improve the table representation. This dashboard is explained in the rest of this chapter.

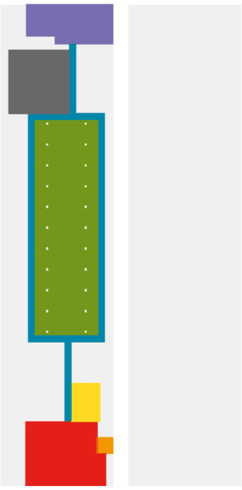
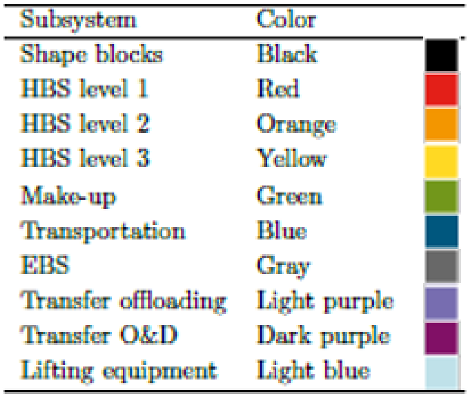


Figure 2.1: An example of a 3D drawing for a BHS.



Subsystem	Color	
Shape blocks	Black	⬛
HBS level 1	Red	🟥
HBS level 2	Orange	🟧
HBS level 3	Yellow	🟨
Make-up	Green	🟩
Transportation	Blue	🟦
EBS	Gray	◼
Transfer offloading	Light purple	🟪
Transfer O&D	Dark purple	🟪
Lifting equipment	Light blue	▫

Figure 2.2: Legend for the 3D drawing.

Table 2.1: An example for the table representation for a BHS (Vijlbrief, 2019).

	Check-in	HBS	Transportation	Total
Equipment type	Staffed counter	Medium speed EDS	DCT	-
Equipment amount	10	2	2	14
System area [m^2]	24	54	30	108
Capacity [bags/hr]	300	700	7200	4600
Redundancy [%]	75%	79%	100%	75%
CAPEX [Euro]	150,000	600,000	22,000	772,000
Energy consumption [kWh]	45	40	44	129
Operators	10	0	0	10
LoA	3	7	6	5.33
IST [min]	2	0.85	0.02	2.87

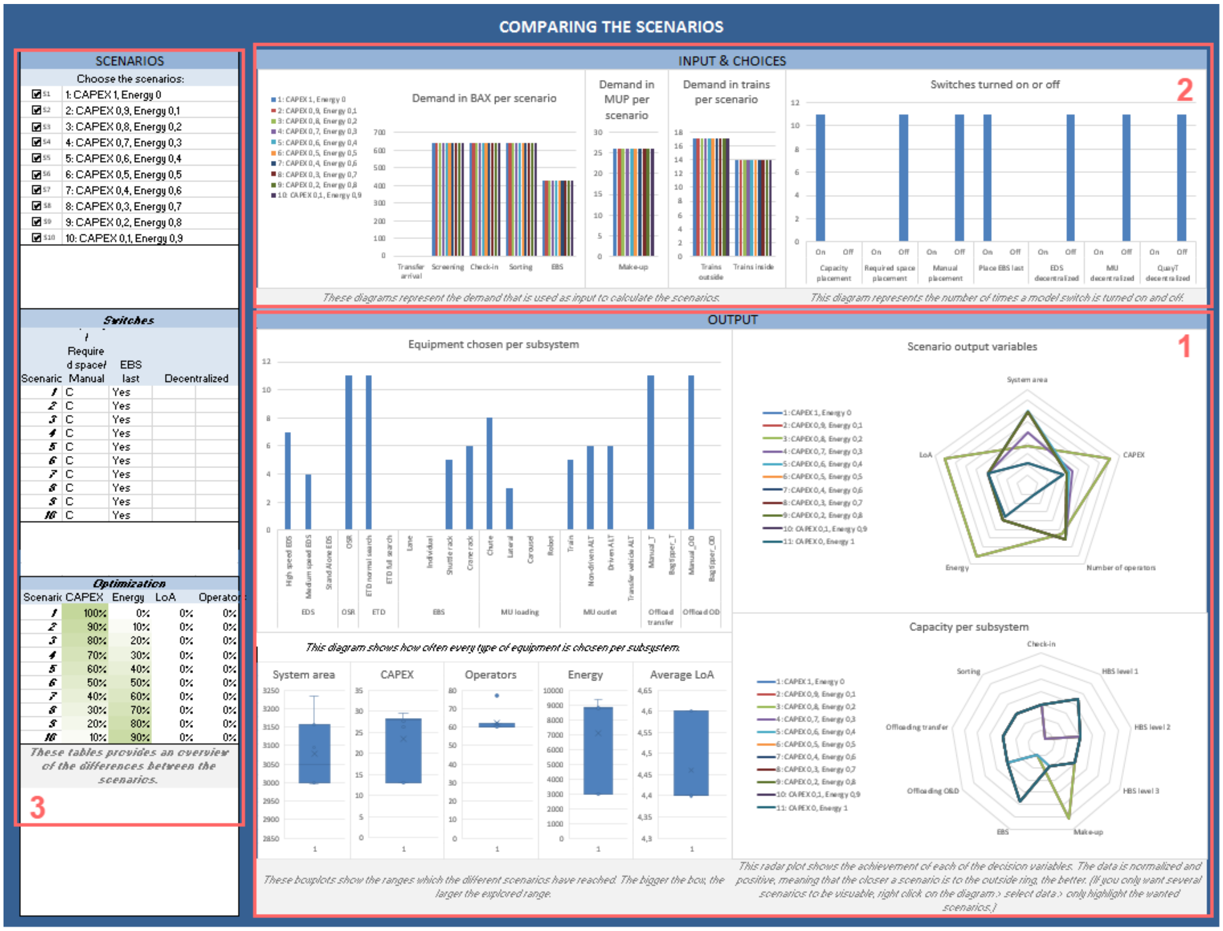
2.2 Scenario input dashboard

In the first dashboard, shown in Figure 2.7 at the end of this chapter, the information per scenario is showed next to each other. This makes it easy to see which input and choices you have evaluated and to which outcomes it has led. Every design choice or varying input variable is shown in the dashboard. Every row represents one scenario, which has a number and a name.

The dashboard is split up in input and choices, and output. On the input side, for every scenario the demand, switches (see Chapter 6), and optimization choices are shown. At the switches, if the block is green, that switch is turned on, otherwise it is turned off. The optimization parameters always have to add up to 100%. The darker green the block is, the more model is optimized on that optimization parameter. On the output side, the chosen subsystems and how many pieces are required are presented. In addition, also the value of the decision variables and the capacity of the subsystems is shown.

2.3 Scenario comparison dashboard

The second part of the dashboard, shown in Figure 2.3, gives the possibility to easily compare the different scenarios. It visualizes how large the scenario space is that you have analyzed, but most importantly which scenarios score well on the different decision variables compared to the other scenarios. The dashboard will be explained in three parts, which are indicated in the figure.



SCENARIOS

Choose the scenarios:

☑ S1 1: CAPEX 1, Energy 0
☑ S2 2: CAPEX 0,9, Energy 0,1
☑ S3 3: CAPEX 0,8, Energy 0,2
☑ S4 4: CAPEX 0,7, Energy 0,3
☑ S5 5: CAPEX 0,6, Energy 0,4
☑ S6 6: CAPEX 0,5, Energy 0,5
☑ S7 7: CAPEX 0,4, Energy 0,6
☑ S8 8: CAPEX 0,3, Energy 0,7
☑ S9 9: CAPEX 0,2, Energy 0,8
☑ S10 10: CAPEX 0,1, Energy 0,9

Switches

Scenaric	Require d space/ Manual	EBS last	Decentralized	
1	C	Yes		
2	C	Yes		
3	C	Yes		
4	C	Yes		
5	C	Yes		
6	C	Yes		
7	C	Yes		
8	C	Yes		
9	C	Yes		
10	C	Yes		

Optimization

Scenaric	CAPEX	Energy	LoA	Operator
1	100%	0%	0%	0%
2	90%	10%	0%	0%
3	80%	20%	0%	0%
4	70%	30%	0%	0%
5	60%	40%	0%	0%
6	50%	50%	0%	0%
7	40%	60%	0%	0%
8	30%	70%	0%	0%
9	20%	80%	0%	0%
10	10%	90%	0%	0%

These tables provides an overview of the differences between the scenarios.

These diagrams represent the demand that is used as input to calculate the scenarios.

This diagram represents the number of times a model switch is turned on and off.

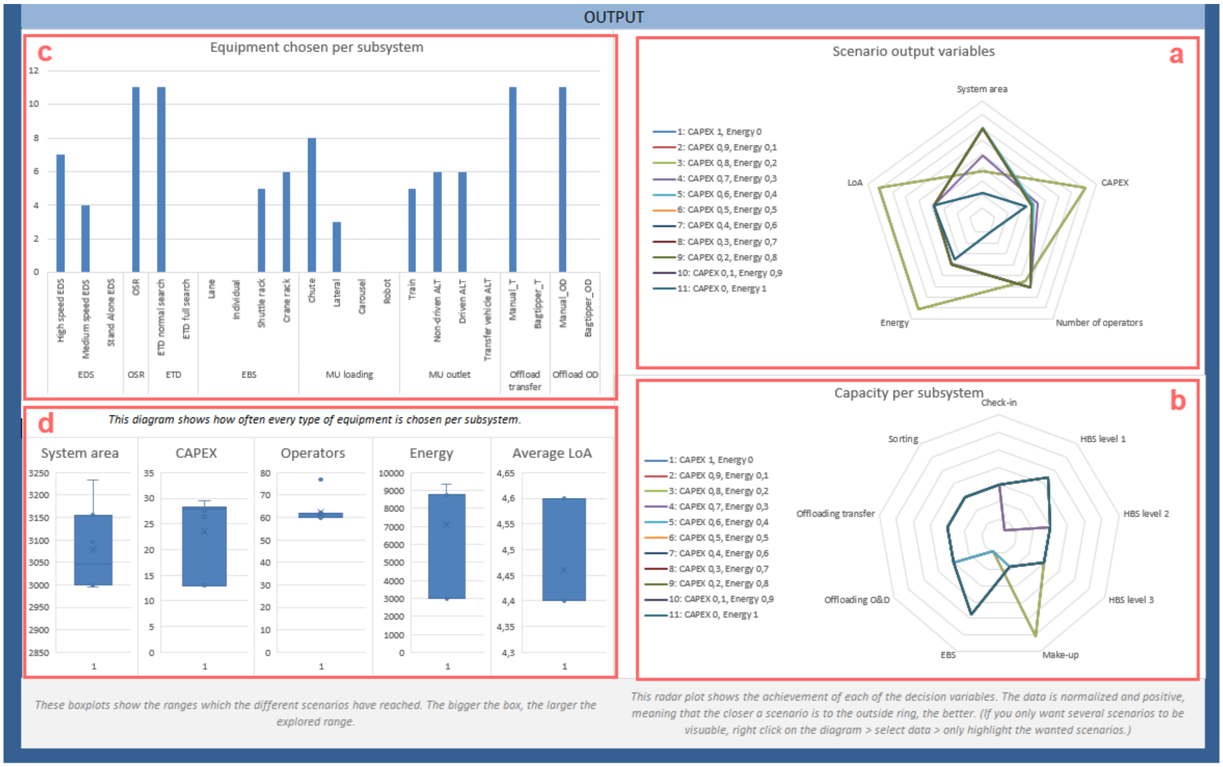
This diagram shows how often every type of equipment is chosen per subsystem.

These boxplots show the ranges which the different scenarios have reached. The bigger the box, the larger the explored range.

This radar plot shows the achievement of each of the decision variables. The data is normalized and positive, meaning that the closer a scenario is to the outside ring, the better. (If you only want several scenarios to be visuable, right click on the diagram > select data > only highlight the wanted scenarios.)

Figure 2.3: Scenario comparison dashboard.

Figure 2.4 shows part 1 of the dashboard. The top radar plot (a) shows the achievement of each of the decision variables. The data is normalized and positive, meaning that the closer a scenario is to the outside ring, the better. The next chart (b), shows the capacity of each subsystem per scenario. The capacity is a variable that needs to be considered different from the other decision variables. As every scenario meets the required subsystem capacity, every scenario is plausible. That said, the difference in size of the capacity depends on the switching points of the chosen equipment. At certain break points, the equipment choice changes, which sometimes results in a higher capacity than needed. However, when comparing scenarios, if the capacity of a subsystem for a scenario is high, this could accommodate future growth and can be a benefit. The equipment chart (c) shows how often a type of equipment per subsystem is chosen. If for several scenarios a type of equipment is never chosen, this could be an indication that that type of equipment is not very useful for that airport. The box plots in chart (d) show how much the scenarios differ from each other per decision variable, thus showing the range of the decision variables of the scenarios.



This diagram shows how often every type of equipment is chosen per subsystem.

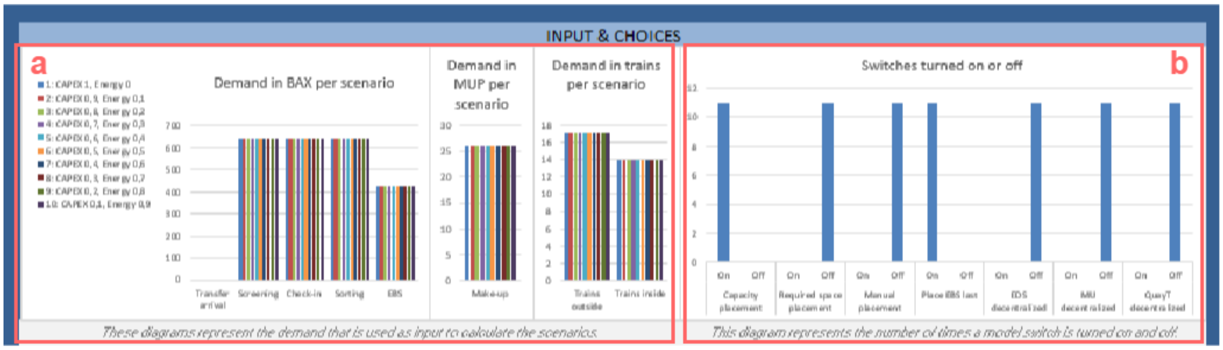
These boxplots show the ranges which the different scenarios have reached. The bigger the box, the larger the explored range.

This radar plot shows the achievement of each of the decision variables. The data is normalized and positive, meaning that the closer a scenario is to the outside ring, the better. (If you only want several scenarios to be visuable, right click on the diagram > select data > only highlight the wanted scenarios.)

Figure 2.4: Output part of the scenario comparison dashboard.

The bar chart (a) in Figure 2.5 shows the difference in demand. The higher the bar, the higher the demand in that scenario. The clustered chart (b) in Figure 2.5 shows how often each switch in the model was turned on or off.

Figure 2.6 shows the important scenario information. The box (a) shows the different scenarios through a scenario number and name. As it can be confusing to compare many scenarios at once, each scenario has a tick box which can be used to turn scenarios on or off. The second box (b) shows, in short, which switches are turned on in every scenario. This only shows the most important information. If more information is required, it can be found in the first part of the



These diagrams represent the demand that is used as input to calculate the scenarios.

This diagram represents the number of times a model switch is turned on and off.

Figure 2.5: Input & choices part of the scenario comparison dashboard.

dashboard. The last box (c) shows a quick overview of which optimization is used to generate the scenarios.

2.4 Detailed dashboard

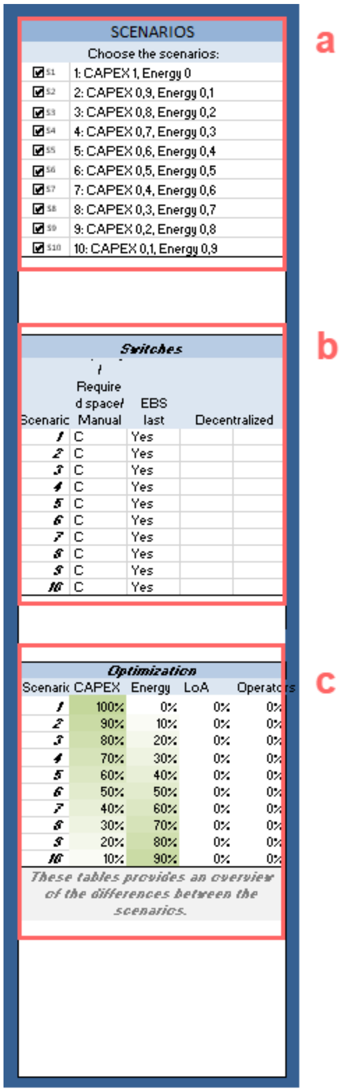
The previous two dashboards can be used to compare the scenarios in general. These are especially useful when comparing scenarios at first sight. They show the explored scenario space and make it easy to rate scenarios from best to worse. However, when actually choosing a concept design to further develop, more details need to be compared. To accommodate this, the last part of the dashboard provides details of each subsystem of each scenario (see Figure 2.8). For every subsystem the equipment type, amount, system area, capacity, CAPEX, number of operators, energy consumption, LoA, IST, and redundancy are shown.

Being able to compare scenarios in the early design phase can be very useful and save a lot of time. When a scenario does not look promising in the dashboard, it can right away be rejected, limiting the time spent on a insufficient solution.

The dashboard makes it possible to compare a maximum of 10 scenarios. As the dashboard has the ability to switch every scenario on and off, less scenarios can be compared as well. A choice has been made to limit the dashboard to 10 scenarios because comparing more scenarios can make it unclear. Seeing 10 scenarios at the same time can already be confusing, adding more will make it even more complicated. If it is necessary, more scenarios can be added manually or several sets of 10 scenario runs can be compared through several dashboards.

2.5 Chapter summary

In this chapter the first sub-question is addressed, namely: *How can the model be developed in order to evaluate different scenarios for one airport?* Being able to compare scenarios in the conceptual design phase, where not all input values and design choices are known or certain, adds value to the model as less time is spent on ineffective scenarios. As the conceptual design phase is in the beginning, decisions about input parameters can significantly influence the model



SCENARIOS

Choose the scenarios:

- ☑ S1 1: CAPEX 1, Energy 0
- ☑ S2 2: CAPEX 0,9, Energy 0,1
- ☑ S3 3: CAPEX 0,8, Energy 0,2
- ☑ S4 4: CAPEX 0,7, Energy 0,3
- ☑ S5 5: CAPEX 0,6, Energy 0,4
- ☑ S6 6: CAPEX 0,5, Energy 0,5
- ☑ S7 7: CAPEX 0,4, Energy 0,6
- ☑ S8 8: CAPEX 0,3, Energy 0,7
- ☑ S9 9: CAPEX 0,2, Energy 0,8
- ☑ S10 10: CAPEX 0,1, Energy 0,9

Switches

Scenari	Required space/ Manual	EBS last	Decentralized	
1	C	Yes		
2	C	Yes		
3	C	Yes		
4	C	Yes		
5	C	Yes		
6	C	Yes		
7	C	Yes		
8	C	Yes		
9	C	Yes		
10	C	Yes		

Optimization

Scenari	CAPEX	Energy	LoA	Operators
1	100%	0%	0%	0%
2	90%	10%	0%	0%
3	80%	20%	0%	0%
4	70%	30%	0%	0%
5	60%	40%	0%	0%
6	50%	50%	0%	0%
7	40%	60%	0%	0%
8	30%	70%	0%	0%
9	20%	80%	0%	0%
10	10%	90%	0%	0%

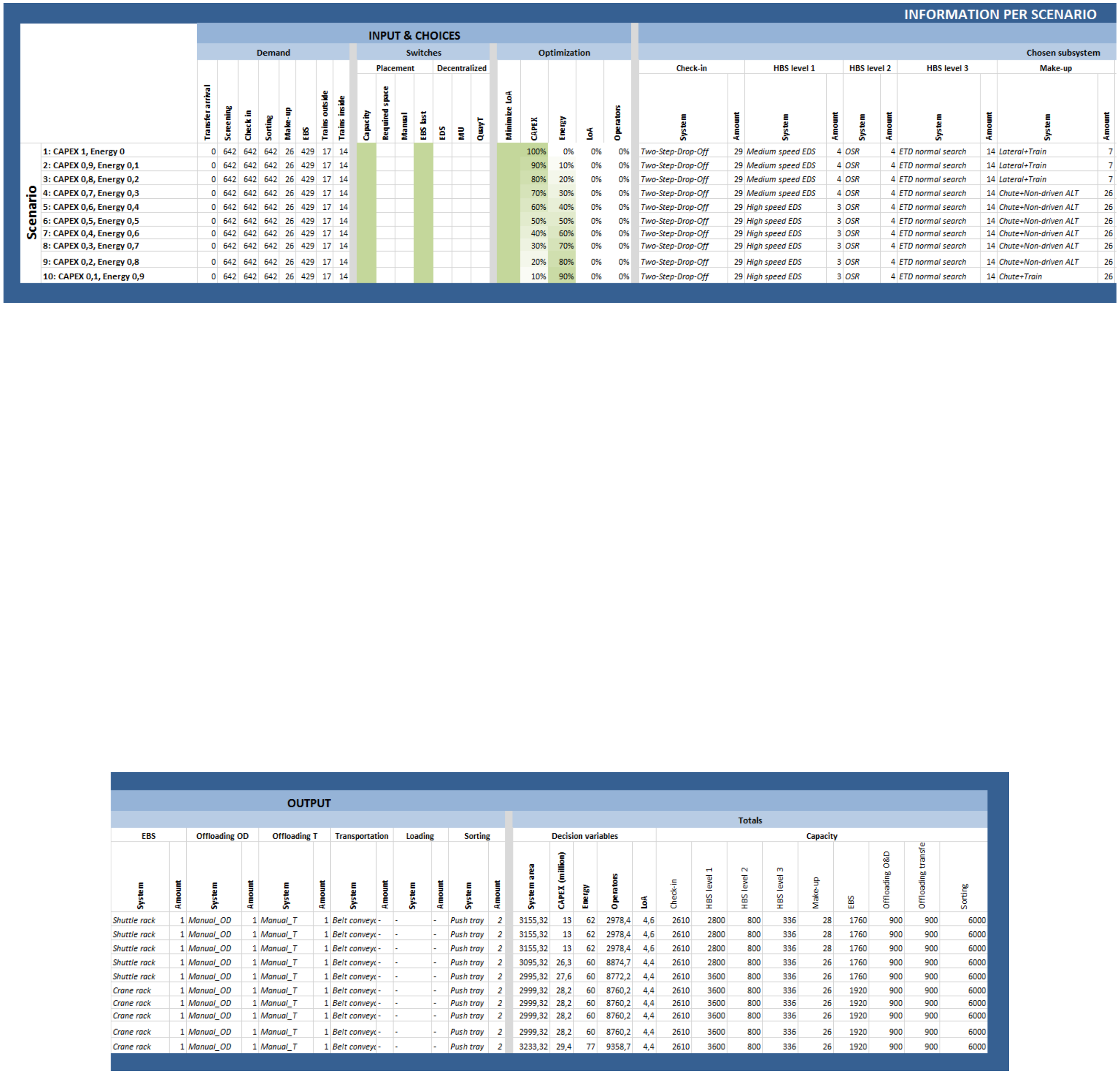
These tables provides an overview of the differences between the scenarios.

Figure 2.6: Scenario part of the scenario comparison dashboard.

outcome, removing uncertainties. If during this phase it can be shown that certain scenarios are insufficient, the designers can focus on other scenarios. So, if insufficient scenarios (either insufficient at all or insufficient compared to each other) can be identified as soon as possible, no extra time needs to be spent on these scenarios.

In order to compare different scenarios for one airport, an interactive dashboard is created. The dashboard makes it possible to visually display the results and more easily compare different scenarios. A maximum of 10 scenarios can be compared at once. This maximum of 10 scenarios is chosen as it becomes more confusing the more scenarios are visualized at once. The dashboard is split up into three parts: a scenario input dashboard, a comparison dashboard and a detailed dashboard. While the input dashboard shows the exact values and choices of each scenario, the comparison dashboard allows the user to visually see how 'good' a scenario rates compared to another. This makes it possible to quickly filter insufficient scenarios. However, the data is standardized. Due to this the figures do not show how big the differences between the scenarios are. This limitation is solved by adding the last dashboard, namely the detailed dashboard. This dashboard shows the specific values of each subsystem of each scenario.

In conclusion, using a combination of the three dashboards, allows the user to evaluate different scenarios for one airport. Each dashboard displays part of the information that is needed to make informed decisions about the scenarios. The initial model only visualized the specifics of one scenario, which makes it difficult to compare scenarios. A dashboard to compare the scenarios, not only improves the evaluation of a scenario, but it also limits the evaluation time as the scenarios can be compared more easily. Adding a dashboard such as shown in this chapter increases the usability of the model. How much a dashboard increases the usability will be evaluated later on during the case studies.

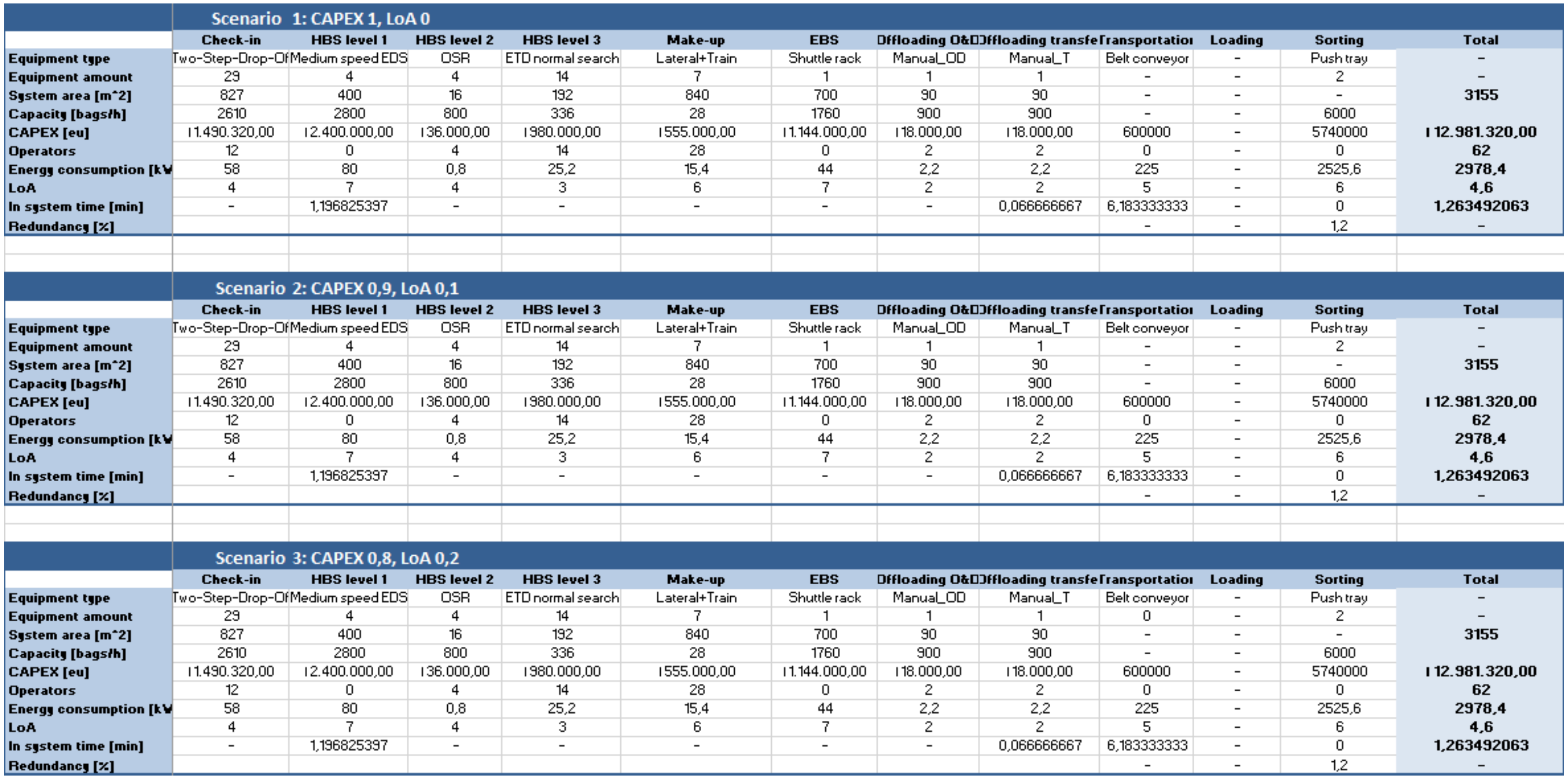


INFORMATION PER SCENARIO

	INPUT & CHOICES																													
	Demand								Switches							Optimization					Chosen subsystem									
									Placement				Decentralized								Check-in		HBS level 1		HBS level 2		HBS level 3		Make-up	
Scenario	Transfer arrival	Screening	Check in	Sorting	Make-up	EBS	Trains outside	Trains inside	Capacity	Required space	Manual	EBS last	EDS	MU	QuayT	Minimize LoA	CAPEX	Energy	LoA	Operators	System	Amount	System	Amount	System	Amount	System	Amount	System	Amount
1: CAPEX 1, Energy 0	0	642	642	642	26	429	17	14	🟩			🟩				🟩	100%	0%	0%	0%	Two-Step-Drop-Off	29	Medium speed EDS	4	OSR	4	ETD normal search	14	Lateral+Train	7
2: CAPEX 0,9, Energy 0,1	0	642	642	642	26	429	17	14	🟩			🟩				🟩	90%	10%	0%	0%	Two-Step-Drop-Off	29	Medium speed EDS	4	OSR	4	ETD normal search	14	Lateral+Train	7
3: CAPEX 0,8, Energy 0,2	0	642	642	642	26	429	17	14	🟩			🟩				🟩	80%	20%	0%	0%	Two-Step-Drop-Off	29	Medium speed EDS	4	OSR	4	ETD normal search	14	Lateral+Train	7
4: CAPEX 0,7, Energy 0,3	0	642	642	642	26	429	17	14	🟩			🟩				🟩	70%	30%	0%	0%	Two-Step-Drop-Off	29	Medium speed EDS	4	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
5: CAPEX 0,6, Energy 0,4	0	642	642	642	26	429	17	14	🟩			🟩				🟩	60%	40%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
6: CAPEX 0,5, Energy 0,5	0	642	642	642	26	429	17	14	🟩			🟩				🟩	50%	50%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
7: CAPEX 0,4, Energy 0,6	0	642	642	642	26	429	17	14	🟩			🟩				🟩	40%	60%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
8: CAPEX 0,3, Energy 0,7	0	642	642	642	26	429	17	14	🟩			🟩				🟩	30%	70%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
9: CAPEX 0,2, Energy 0,8	0	642	642	642	26	429	17	14	🟩			🟩				🟩	20%	80%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Non-driven ALT	26
10: CAPEX 0,1, Energy 0,9	0	642	642	642	26	429	17	14	🟩			🟩				🟩	10%	90%	0%	0%	Two-Step-Drop-Off	29	High speed EDS	3	OSR	4	ETD normal search	14	Chute+Train	26

OUTPUT																									
												Totals													
EBS		Offloading OD		Offloading T		Transportation		Loading		Sorting		Decision variables					Capacity								
System	Amount	System	Amount	System	Amount	System	Amount	System	Amount	System	Amount	System area	CAPEX (million)	Energy	Operators	LoA	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfe	Sorting
Shuttle rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	3155,32	13	62	2978,4	4,6	2610	2800	800	336	28	1760	900	900	6000
Shuttle rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	3155,32	13	62	2978,4	4,6	2610	2800	800	336	28	1760	900	900	6000
Shuttle rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	3155,32	13	62	2978,4	4,6	2610	2800	800	336	28	1760	900	900	6000
Shuttle rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	3095,32	26,3	60	8874,7	4,4	2610	2800	800	336	26	1760	900	900	6000
Shuttle rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	2995,32	27,6	60	8772,2	4,4	2610	3600	800	336	26	1760	900	900	6000
Crane rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	2999,32	28,2	60	8760,2	4,4	2610	3600	800	336	26	1920	900	900	6000
Crane rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	2999,32	28,2	60	8760,2	4,4	2610	3600	800	336	26	1920	900	900	6000
Crane rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	2999,32	28,2	60	8760,2	4,4	2610	3600	800	336	26	1920	900	900	6000
Crane rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	2999,32	28,2	60	8760,2	4,4	2610	3600	800	336	26	1920	900	900	6000
Crane rack	1	Manual_OD	1	Manual_T	1	Belt conveyc	-	-	-	Push tray	2	3233,32	29,4	77	9358,7	4,4	2610	3600	800	336	26	1920	900	900	6000

Figure 2.7: Information per scenario dashboard.



Scenario 1: CAPEX 1, LoA 0

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfe	Transportatio	Loading	Sorting	Total
Equipment type	Two-Step-Drop-Of	Medium speed EDS	OSR	ETD normal search	Lateral+Train	Shuttle rack	Manual_OD	Manual_T	Belt conveyor	-	Push tray	-
Equipment amount	29	4	4	14	7	1	1	1	-	-	2	-
System area [m^2]	827	400	16	192	840	700	90	90	-	-	-	3155
Capacity [bags/h]	2610	2800	800	336	28	1760	900	900	-	-	6000	
CAPEX [eu]	I1.490.320,00	I2.400.000,00	I36.000,00	I980.000,00	I555.000,00	I1.144.000,00	I18.000,00	I18.000,00	600000	-	5740000	I 12.981.320,00
Operators	12	0	4	14	28	0	2	2	0	-	0	62
Energy consumption [kW	58	80	0,8	25,2	15,4	44	2,2	2,2	225	-	2525,6	2978,4
LoA	4	7	4	3	6	7	2	2	5	-	6	4,6
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	6,183333333	-	0	1,263492063
Redundancy [%]									-	-	1,2	-

Scenario 2: CAPEX 0,9, LoA 0,1

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfe	Transportatio	Loading	Sorting	Total
Equipment type	Two-Step-Drop-Of	Medium speed EDS	OSR	ETD normal search	Lateral+Train	Shuttle rack	Manual_OD	Manual_T	Belt conveyor	-	Push tray	-
Equipment amount	29	4	4	14	7	1	1	1	-	-	2	-
System area [m^2]	827	400	16	192	840	700	90	90	-	-	-	3155
Capacity [bags/h]	2610	2800	800	336	28	1760	900	900	-	-	6000	
CAPEX [eu]	I1.490.320,00	I2.400.000,00	I36.000,00	I980.000,00	I555.000,00	I1.144.000,00	I18.000,00	I18.000,00	600000	-	5740000	I 12.981.320,00
Operators	12	0	4	14	28	0	2	2	0	-	0	62
Energy consumption [kW	58	80	0,8	25,2	15,4	44	2,2	2,2	225	-	2525,6	2978,4
LoA	4	7	4	3	6	7	2	2	5	-	6	4,6
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	6,183333333	-	0	1,263492063
Redundancy [%]									-	-	1,2	-

Scenario 3: CAPEX 0,8, LoA 0,2

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfe	Transportatio	Loading	Sorting	Total
Equipment type	Two-Step-Drop-Of	Medium speed EDS	OSR	ETD normal search	Lateral+Train	Shuttle rack	Manual_OD	Manual_T	Belt conveyor	-	Push tray	-
Equipment amount	29	4	4	14	7	1	1	1	0	-	2	-
System area [m^2]	827	400	16	192	840	700	90	90	-	-	-	3155
Capacity [bags/h]	2610	2800	800	336	28	1760	900	900	-	-	6000	
CAPEX [eu]	I1.490.320,00	I2.400.000,00	I36.000,00	I980.000,00	I555.000,00	I1.144.000,00	I18.000,00	I18.000,00	600000	-	5740000	I 12.981.320,00
Operators	12	0	4	14	28	0	2	2	0	-	0	62
Energy consumption [kW	58	80	0,8	25,2	15,4	44	2,2	2,2	225	-	2525,6	2978,4
LoA	4	7	4	3	6	7	2	2	5	-	6	4,6
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	6,183333333	-	0	1,263492063
Redundancy [%]									-	-	1,2	-

Figure 2.8: Detailed dashboard.

Chapter 3

Improving the model run time

The objective of this research is to improve and further develop the existing model for the conceptual design of a BHS. When manually designing a BHS, the conceptual design phase takes about 3 weeks to 1 month. Currently, the model can take hours or days to generate one specific scenario. The bigger the airport is, the longer the model needs to run. Until now the model has been run for small and medium airports. For bigger airports the model got interrupted because it took too long. As a goal of the model is to be applicable to all airports, the model run time needs to be improved.

So, the run time needs to decrease, especially for bigger airports. It is of course desired to have a run time that is as short as possible. However, the question that then arises is what is the maximum accepted run time? The previous chapter showed the importance of being able to compare different scenarios. As a small recap, the decisions made in the conceptual design phase can have a big impact on the final result. Being able to generate several scenarios for one airport and compare them, can help to choose the best conceptual design. So, while determining the maximum allowed run time, it needs to be taken into account that several scenarios need to be run for one airport. It needs to be noted that the scenarios can all be run at once by running the code. The scenarios are still executed after each other, but the user only has to start the process once, and the code will keep running during the night. Thus, the run time is not restrained by working hours.

Another restriction to the run time is that it should not exceed the time it takes to develop a BHS in the conceptual design phase. If the model takes just as long or longer than the manual process, the goal to speed up the project throughput time is not reached. This shows the next limitation. The model needs to shorten the total project throughput time, so not only should the model run faster than the manual time, also in combination with the evaluation of the model outcome the total throughput time should be shorter than three weeks. So, if the total project throughput time needs to be shorter than the manual process, let's say a maximum of 2 weeks time (which is 10 working days). It needs to be possible to run several scenarios, let's say at least 5 to be able to analyze different BHS aspects. As stated by one of the BHS designers at NACO, the evaluation of these scenarios and writing and reviewing the proposal for the client takes about 3 days. In addition, it might take 1 day to gather all airport input variables and convert the flight schedule. To keep some spare time in case sometime goes wrong it is good to keep 1 day reserve. This leaves 5 days to actually run the model (for 5 scenarios), which results in a maximum of 24 hours per scenario. So, the goal of this model is to reduce the run time to a maximum of 24 hours for one scenario.

This chapter thus explores the second sub-question: *How can the run time of the model be improved, in order to increase the usability of the model?* The run time of the model can be addressed in multiple ways. During this research the run time is approached through three different improvements: the subsystem placement algorithm, splitting up the model, and changing the order of the placement functions. Each section in this chapter elaborates on one of these improvements, of which the goal is to reduce the run time to a maximum of 24 hours. The last section will reflect on the effect of these improvements.

3.1 Subsystem placement

An element of the model that can be improved is the run time of the 'Droplet search model', which is used to determine the location of the subsystems. In short, the model works as follows. For each subsystem a starting point is defined based on specific requirements per subsystem. Next, the model searches for a location to place a subsystem. It begins at the starting point, if there is space available, it is placed there. If there is no space available, it searches the points closest to the starting point. The model continues searching until a space is available and the subsystem is placed. Section 1.4.4 explains this model in more detail.

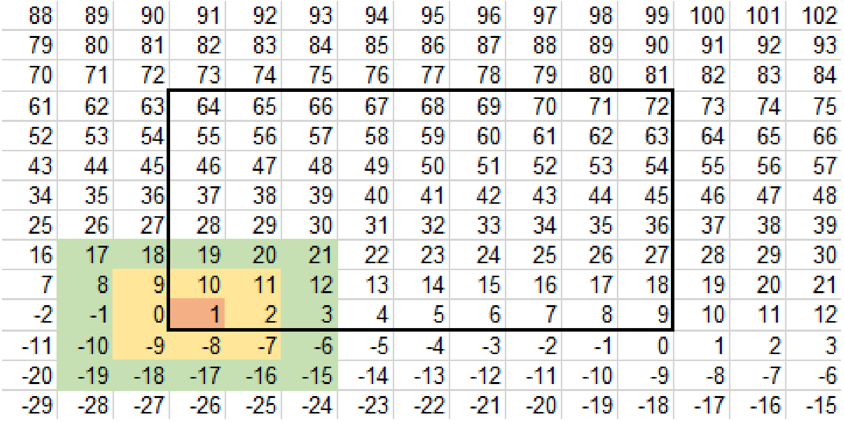
Unfortunately, the simulation for bigger airports takes hours or even days. This could be caused by the fact that for every subsystem, all potential locations are checked, even if a subsystem has already been placed in that location. In addition, due to the method used to number locations, the search algorithm also checks locations that are invalid, such as outside of the terminal. Thus, modifying the Droplet model could significantly decrease the simulation run time.

One reason why the placement algorithm developed by Vijlbrief (2019), the Droplet search model, takes time to compute, is due to the fact that it does not pre-determines or restricts certain places. For instance, every tile in the Droplet wave is evaluated even if that space is not available (anymore). A space could already be taken by another subsystem, be outside of the terminal, or not be available for baggage handling equipment.

A reason for these issues is the tile numbering system that Vijlbrief (2019) uses. The terminal is divided into squares of one by one meter, called tiles. The tiles are numbered from 1 to *'terminal width * terminal length'*, starting in the bottom left corner numbering to the right (and up if the side of the terminal is reached), increasing the number every tile until the top right corner of the terminal. For example, in a very small terminal of 9 by 8 meters, the tiles are numbered from 1 till 72 (see Figure 3.1). The algorithm that is used to place the subsystems cannot determine if a tile is outside the terminal, and thus evaluates all tiles in the wave. Figure 3.2 shows an example of this problem. If the starting point for a system is tile 1, but the subsystem cannot be placed there, the search moves on to the first wave (yellow tiles). As can be seen, five of the eight tiles lie outside the terminal and should not be evaluated, but are. This takes a lot of unnecessary time. Especially if many waves need to be evaluated and a lot of tiles fall outside of the terminal. To explain this inefficiency in a percentage, in the worst case scenario in this grid (which is starting in a corner and search until the very last tile is evaluated), only 24.9% (72/289) of the evaluated tiles are inside the terminal. This percentage changes for different terminal dimensions and starting points, but this indicates the placement search algorithm should be done differently. In addition to the tiles outside the terminal, also the tiles inside the terminal that are not available should not be evaluated. To decrease the run time of the model these issues need to be addressed.

64	65	66	67	68	69	70	71	72
55	56	57	58	59	60	61	62	63
46	47	48	49	50	51	52	53	54
37	38	39	40	41	42	43	44	45
28	29	30	31	32	33	34	35	36
19	20	21	22	23	24	25	26	27
10	11	12	13	14	15	16	17	18
1	2	3	4	5	6	7	8	9

Figure 3.1: Tile numbering system developed by Vijlbrief (2019).

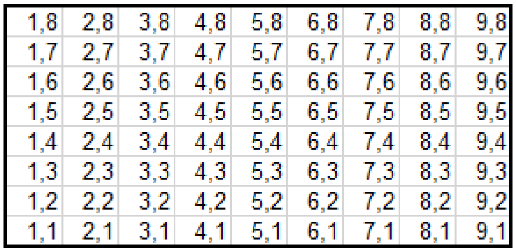


88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
79	80	81	82	83	84	85	86	87	88	89	90	91	92	93
70	71	72	73	74	75	76	77	78	79	80	81	82	83	84
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
43	44	45	46	47	48	49	50	51	52	53	54	55	56	57
34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12
-11	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3
-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6
-29	-28	-27	-26	-25	-24	-23	-22	-21	-20	-19	-18	-17	-16	-15

Figure 3.2: Inefficiency of the tile numbering system of the initial model. The orange tile is the first drop in the Droplet model (N=0), the yellow tiles are the first wave (N=1), and the green tiles are the second wave (N=2).

The first fix for this problem is to change the tile numbering system. In the new model the tiles are numbered with a 'x, y' value (see Figure 3.3). Due to this numbering system, no tile inside the terminal can have the same number as a tile outside of the terminal. This makes it possible for the model to differentiate between tiles inside and outside the terminal.

A disadvantage of changing the numbering system is that the placement algorithm by Vijlbrief (2019) is completely related to the tile numbering system he used. Therefore the entire placement algorithm of the previous model has been built again, this time based on the 'x, y'-numbering system. An advantage of changing the placement code, is that the algorithm could be improved in many ways. For instance, instead of searching every space inside the terminal, a pre-selection of only available spots is performed before the placement search. This again speeds up the search for a place.



1,8	2,8	3,8	4,8	5,8	6,8	7,8	8,8	9,8
1,7	2,7	3,7	4,7	5,7	6,7	7,7	8,7	9,7
1,6	2,6	3,6	4,6	5,6	6,6	7,6	8,6	9,6
1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5
1,4	2,4	3,4	4,4	5,4	6,4	7,4	8,4	9,4
1,3	2,3	3,3	4,3	5,3	6,3	7,3	8,3	9,3
1,2	2,2	3,2	4,2	5,2	6,2	7,2	8,2	9,2
1,1	2,1	3,1	4,1	5,1	6,1	7,1	8,1	9,1

Figure 3.3: New tile numbering system.

3.2 Splitting the model

The full BHS concept design model is built in Dynamo for Revit. Dynamo is a visual programming tool that works with Revit that allows users without a programming background to build algorithmic processes (Nezamaldin, 2019). Revit is a 3D modeling software, frequently used by NACO, where users can model different elements of a building. It allows engineers to visualize the structure of a building before it is placed in drawings.

During the development of the new placement algorithm, Jupyter Notebook was used rather than Dynamo as it is easier to use (e.g. run small parts of code, detailed error message, etc.). Noticeable is that there is a huge difference in the run time of the algorithm in Jupyter Notebook and Dynamo. Running the same placement problem in Jupyter notebook as in Dynamo, Jupyter's run time was often up to 2 times faster. A possible reason for this is that only the placement is run in Jupyter while the entire conceptual model is calculated in Dynamo. However, during further examination of this difference, the steps before and after the placement only take a couple of seconds. Therefore can be concluded that this decrease in run time in Jupyter cannot be explained by the fact that only a part of the model of the conceptual design is run.

There is no previous research that can explain this difference in run time. However, it is an additional benefit of developing the new placement model. It has led to another model improvement where the model is split up into three parts. Figure 3.4 shows this new model framework. In the first step the first three phases of the previous model framework are executed in Dynamo. The outcome of the Dynamo model (the optimal equipment choices) are exported to excel. This excel sheet is imported into Jupyter Notebook, which runs the placement algorithm (phase 4). This is again exported back to Dynamo to execute the last phase, optimize the transportation equipment. Furthermore, in the last step the placement data from Jupyter Notebook is used to visualize the placement of the subsystems in the terminal.

There are two advantages of this model split. The first and most important one is that it decreases the model run time. How much the run time decreases depends on the size of the BHS conceptual design problem. Second, even though it could be a disadvantage to perform several steps to execute the full problem, this is also an advantage. A concept design can now be executed in parts. Thus, to only figure out which equipment per subsystem is best with a certain optimization choice (e.g. optimize based on CAPEX, energy consumption, etc.), output is generated within a second. As a concept design is needed in the initial phases of a full BHS design, the optimal equipment choices already provide a lot of information for a client. Thus,

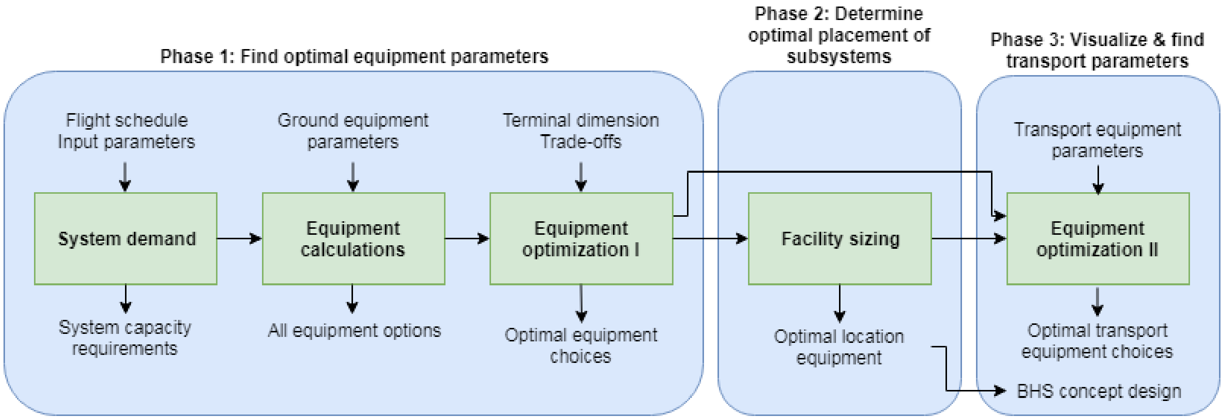


Figure 3.4: New model framework where the model is split into three modules.

the model can also be used for a different purpose now.

3.3 Changing the order of functions

In the previous placement model (developed by Vijlbrief (2019)), when a location for an equipment is searched the droplet algorithm is executed first. Only in the end is checked if that location is actually still available. In Section 3.1 is shown that it is necessary to change the numbering system behind the placement code. Even though this is a disadvantage (as it takes a long time to code it again), it is also an advantage as it provides room to write the code in a more efficient way. Figure 3.5 shows the structure of the new way the placement model is written. All the functions are described in Appendix C. The general structure of the new code is explained in this section.

The model is split up in three phases, of which each phase is executed for every scenario. The first is to create the grid (of the terminal). This is done by dividing the terminal surface area into squares of one square meter and giving it a rectangular form (for programming purposes). The actual shape of the terminal is created by using shapeblocks to block of the part(s) of the rectangle that are not part of the terminal. Figure 3.6 shows an examples of how this is done for Luanda International Airport (LAD) in Angola. A shapeblock can also be used if part of the terminal is not available for BHS equipment. The next function, to delete the spaces of the already placed subsystems, is added to be able to remove already used spaces from the grid. This function will make it possible to fix subsystems at certain locations, which is needed for sub-question 3. If no subsystem is fixed at a certain location this function has no effect. The next step in this phase is to determine in which direction the equipment should be placed. BHS-modelers have stated that it is often easier to expand a subsystem if the systems are placed modular (see Appendix D). The subsystems are thus placed in the other direction as the terminal. If the terminal length is larger than the width, the equipment is placed in the way where the width is larger than the length. The last step left to do is determine in which order the subsystems need to be placed. Chapter 6 explains the importance of the order of placement and how this is calculated.

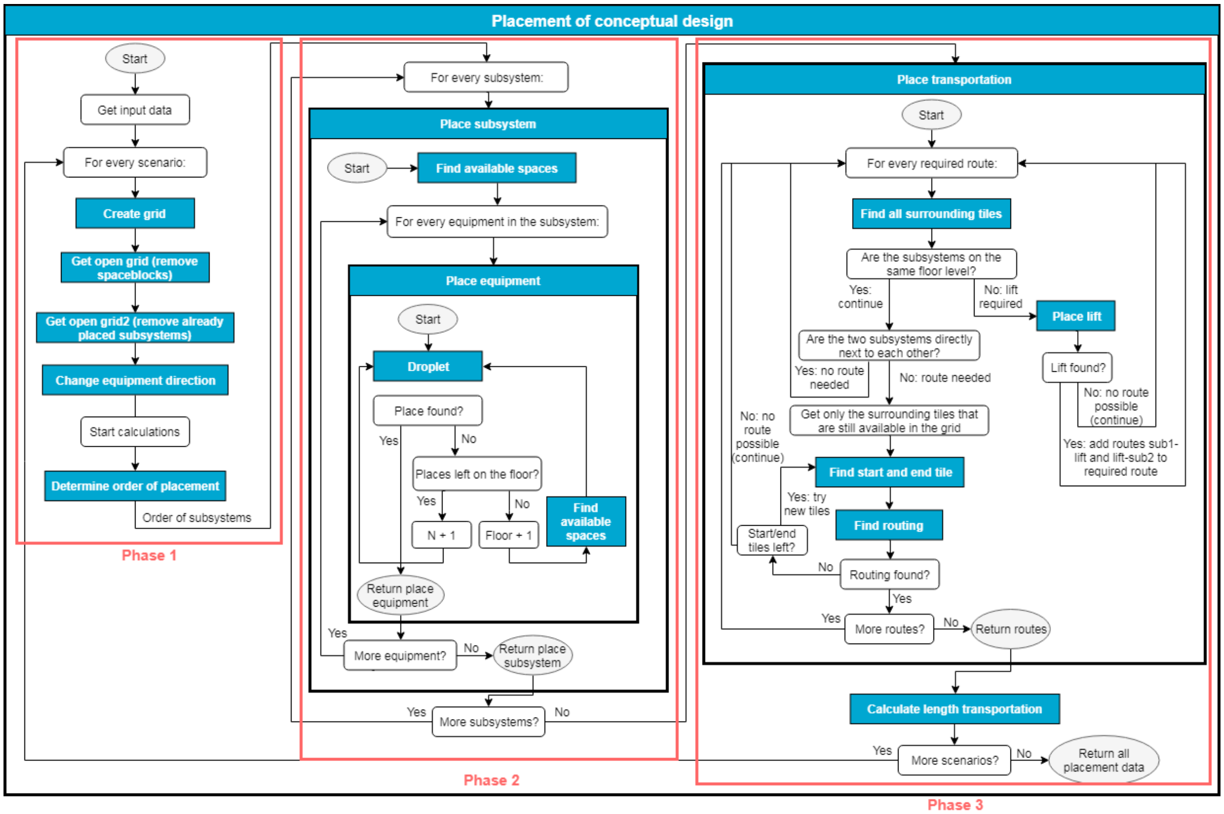


Figure 3.5: New order of functions of the facility sizing phase.

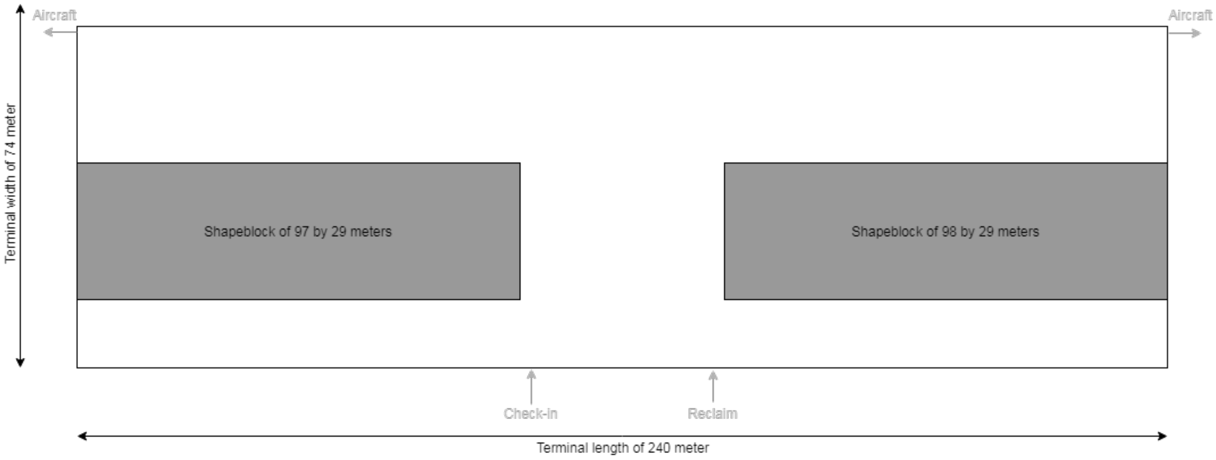


Figure 3.6: The use of shapeblocks to model the shape of LAD airport.

In the second phase, the placement of all the subsystems is executed. This is done for every subsystem in previously determined order. For every subsystem the available spaces on the optimal floor are found. This is followed by placing every equipment in the subsystem, using the Droplet model. The search continues until each equipment of each subsystem is placed.

Even though there are differences in structure between this model and the previous model, such as deleting the location of already placed subsystems and adding transportation in the end, the difference lies mainly in this phase. In this model first all the available spaces on a floor are found and only then the droplet model is used to find the optimal place. It takes time to find the available spaces up front, but time is saved because this process only has to be done once per subsystem. For instance, with a small airport such as Aruba, 7 pieces of make-up equipment need to be placed, but this function only has to be executed once. Furthermore, as this function takes the longest, the available spaces are only found on the optimal floor level. Only if there is no space available on the optimal floor level, the model will search the next level to find the available spaces. If there is also no space available on the next floor level, the model will search the next floor level and so on. This is especially an improvement for bigger airports (of which the time constraint was the biggest factor) because this process is only done once for all subsystems.

When all the subsystems are placed the last phase starts. This phase was only a small part in the model by Vijlbrief (2019), as an estimation was made to calculate the transportation distance between several subsystems and a route was placed from screening level 1 to make-up. One of the recommendations from Vijlbrief was to improve the transportation in the conceptual design phase. In this model, a more detailed transportation algorithm is added. For every transportation a (sub)optimal route is found through the transportation algorithm. The route is found through an algorithm, which is explained in the next section. When all routes are found, the total transportation length is calculated. This concludes the placement of one scenario and this process is repeated until all scenarios are run.

3.4 Chapter summary

This chapter elaborated about how the run time of the initial BHS model has been improved. The run time was improved in several aspects. The run time was shortened to approximately 50% of the previous model for small airports and 25% for big airports. This was accomplished by improving several components of the model. For example, the grid numbering system was changed enabling the model to differentiate between spaces inside and outside of the terminal. Only the spaces inside the terminal need to be evaluated, saving time. The placement algorithm was restructured. This led to the ability to pre-determine where subsystems could be placed. Especially for big airports this decreases the run time, as it only has to be performed once for all equipment in a subsystem. For big airports, the previous model was too slow to run the model due to the time constraint. This improvement enables the model to be run for big airports. In addition, the model is split up into three modules. The second module is now executed in Jupyter Notebook instead of Dynamo, decreasing the run time by 50% on this module. Moreover, splitting the model into three modules has two additional advantages. The model now has the ability to run individually. The first module can be used to limit the *useful* scenario space. If a specific scenario does not seem feasible in the first module, this scenario can be excluded from the rest of the analysis, saving time and effort. In addition, splitting the model enables several scenarios to be run in parallel.

So, this chapter partly answered the second sub-question: *How can the run time of the model be improved, in order to increase the usability of the model?* There are many ways to improve the run time of a model. For this research the run time is improved through multiple aspects, such as changing the tile numbering system, pre-determining places for subsystems, changing the order of the placement functions, and splitting the model in three modules. These are all examples of how the run time of the model can be improved. Of course there are also other possibilities to speed up the run time such as cloud computing (Zissis & Lekkas, 2012) or parallel computing (Kumar, 2002).

If the run time of the model exceeds the time of the manual process, the model is not usable. As stated in the introduction of this chapter, the maximum accepted run time is 24 hours. Small tests have shown that the run time of the model significantly decreased. However, to conclude on the exact run time, more case studies need to be conducted. So the run time of the model will be further analyzed in Chapter 9. Nonetheless, it can already be concluded that the run time decreased, which increases the usability of the model.

Chapter 4

Optimizing the routing between subsystems

Since baggage travels between subsystems, transportation between subsystems is a vital aspect of a BHS. It is important to find the shortest path between subsystems, not only because the equipment is expensive, as longer routes means higher CAPEX, but the transportation is also time critical. Furthermore, as BHS designers from NACO have mentioned, if the transportation of the BHS is not properly planned in advance, it often causes BHS designs to be insufficient, resulting in having to develop a new conceptual design.

In the existing model, transportation is only placed between baggage screening level 1 and make-up. The transportation is placed through reserving space by creating a path with a perpendicular angle between the center points of the two subsystems. Though, in reality there is more routing required. Figure 4.1 shows the how the baggage travels through a BHS.

As the transportation in BHS designs often causes problems, including a more detailed design in the conceptual design phase can be beneficial for the model. This chapter addresses this issue which explores the third sub-question: *How can transportation between subsystems be included in the model, in order to increase the usefulness of the model?* The chapter starts by exploring different routing algorithms. Next, Section 4.2 explains the algorithm that is used, and the last section elaborates on how this algorithm is implemented.

4.1 Routing algorithms

Finding the optimal transportation path is a complicated process. It can be a time consuming and computationally expensive process, that is solved by searching (Mapaila, 2012). The purpose of pathfinding is to find the shortest path between two points through a computer application. Generally, pathfinding can be solved through Exhaustive Search. Exhaustive search is generating and inspecting all data configurations in a large space where a desired solution is guaranteed (Nievergelt, 2000). Though, this takes up a lot of resources, has a long computation time, and is inefficient (Mapaila, 2012). The efficiency of path finding mainly depends on how complex the environment is. The complexity of the environment depends on how big it is, whether it is static or dynamic, and how many obstacles are in it. In the case of the BHS model, the environment

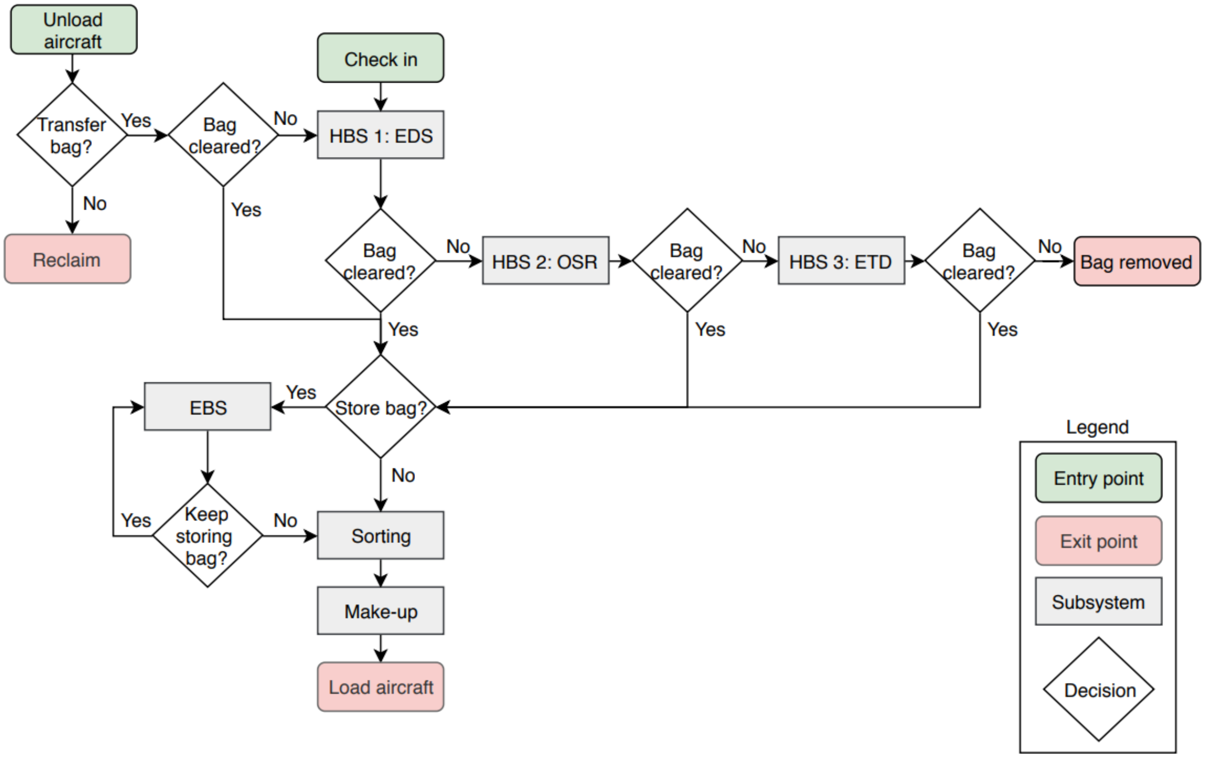


Figure 4.1: Routing of a BHS.

(e.g. the terminal size) ranges from small to large, the environment is static, and usually there are not a lot of obstacles.

As one of the goals of this thesis is to limit the model run time, using Exhaustive Search is not an option. Though, there are many pathfinding algorithms that can be used to find the shortest path. They are split up into two categories: uninformed and informed search algorithms (Russell, Norvig, Canny, Malik, & Edwards, 1995). Uninformed search is when the algorithm only uses the information that is available in the problem definition. The algorithms keep generating neighbouring nodes blindly until they find their goal. Drawbacks from uninformed search algorithms is that they require more memory and take long to compute, but with the benefit that they are simple to implement. Examples of uninformed search algorithms are breath first search, depth first search, and iterative deepening. The second category, informed search strategies, uses problem specific knowledge or heuristics to find an efficient solution. These algorithms contain information such as how far the goal is, what the path costs, how to reach the goal, etc. This information is used to limit the search space and find the goal in a more efficient way. The information is based on heuristics. A heuristic is a function that takes the current state of the node as its input and produces the estimation of how close that node is from the goal. Heuristics are thus an estimation of the current distance to the goal. Dijkstra's algorithm, the best first search algorithm, and A* are examples of informed search strategies.

As uninformed search algorithms are not fast enough for the BHS model, only the informed search algorithms are further explored. Dijkstra's algorithm is one of the oldest, but also one of the most famous algorithms (Dijkstra, 1959). The algorithm works by searching the nodes closest to the starting point, and repeatedly examining the nodes around it. It expands outwards, as a wave, until it reaches the goal. The algorithm is shown in (a) in Figure 4.2. The orange node is the start, the green the end, the blue nodes represent the outward wave.

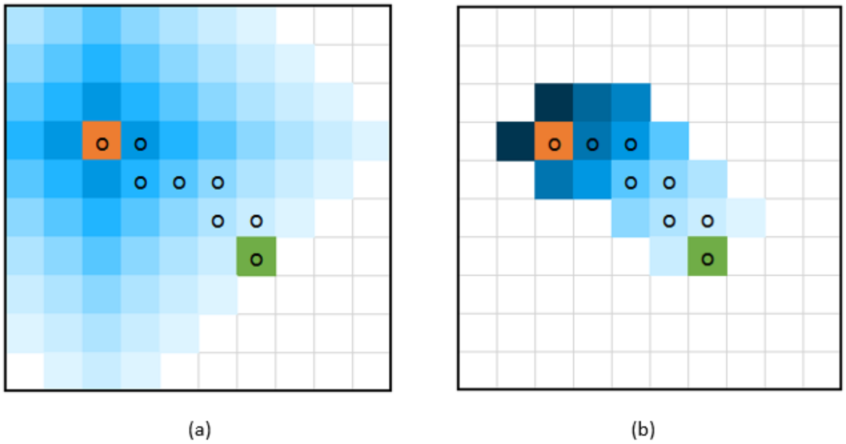


Figure 4.2: Two pathfinding algorithms visualized: (a) Dijkstra's algorithm, (b) best first search algorithm.

The best first search algorithm is similar to Dijkstra's algorithm, except it uses an evaluation function that estimates the desirability of each node (Reddy, 2013). A node is more desirable if it is closer to the goal. Instead of searching the nodes closest to the starting point which Dijkstra's algorithm does, the algorithm searches the nodes closest to the goal. The node with the highest desirability is chosen until the goal is reached. The second graph (b) in Figure 4.3 shows this algorithm. The lighter blue a node is, the lower the heuristic cost is. Best first search is a combination of the breadth and depth first search algorithms and combines both advantages (Potdar & Thool, 2014). With breath first search it is possible to find a solution without computing every node, and with depth first search it is ensured that the process does not get trapped. As best first search combines these two algorithm, it allows the search to switch between paths.

An advantage of the best first search algorithm over Dijkstra's is that it runs faster since less nodes are evaluated as it uses a heuristic function (Anbuselvi & Phil, 2013). However, the best first search algorithm does not perform well with obstacles, as it tries to move towards the goal even if it is not the right path (see Figure 4.3). This is due to the fact that the path is only based on the cost to get to the goal, and the cost of the path so far is ignored. Thus even though the algorithm works, it generates non-optimal paths. Dijkstra's algorithm does provide an optimal, but is still computationally expensive. Another algorithm, the A* algorithm, combines the best of these two path finding algorithms (Hart & Raphael, 1968). As Mapaila (2012) states, the A* algorithm guarantees the most efficient and shortest path. This is therefore the algorithm that is implemented for the transportation between subsystems.

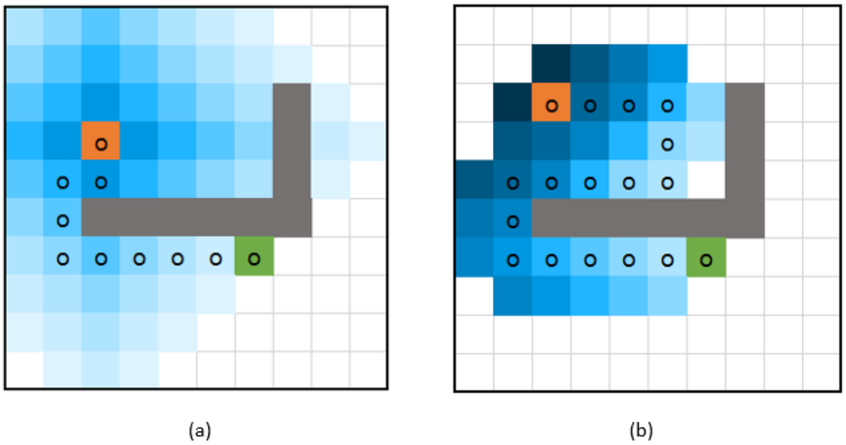

(a) (b)

Figure 4.3: Two pathfinding algorithms with obstacles visualized: (a) Dijkstra's algorithm, (b) best first search algorithm.

4.2 A* algorithm

The defining characteristic of the A* algorithm is that, as it searches for the shortest path, it evaluates two costs instead of one (Mathew, 2015). This is represented in Formula 4.1, where *g(n)* represents the cost of the starting node to node n, *h(n)* the estimated cost from node n to the goal, and *f(n)* the sum of these two costs, which represents the best guess for the cost when selecting node n.

$$f(n) = g(n) + h(n) \tag{4.1}$$

The A* algorithm repeatedly chooses the node which has the smallest f value until the goal is reached, while using two lists: an open list for unexamined nodes and a closed list for examined nodes (Anbuselvi & Phil, 2013). As the algorithm traverses the grid, it follows the nodes with the lowest known cost (see (a) in Figure 4.4). Every time a new node is chosen, if the surrounding nodes are not added to the closed list yet, they are added to the open list. At the same time, the algorithm keeps track, in sorted priority queue, of the nodes that were already added to the open list (and thus not evaluated yet). Every time a new node is chosen, the algorithm checks the open list to see if there is a node with a lower f value. If there is a node with a lower cost, it abandons the current path, and continues the path from the node with the lowest cost. This process continues until the goal is reached.

The difference with the previous two algorithms is that the algorithm is optimal *and* complete, and can solve very complex problems (Reddy, 2013). Although A* is one of the best search algorithm (Mapaila, 2012), it can led to a waste of resources. If the environment is large, thousands of nodes will be generated in the open and closed lists. This requires a lot of memory and a high processing time. Furthermore, the A* algorithm can be complex to implement. Moreover, the algorithm returns the path that occurs first, it does not continue to search for all remaining paths. A benefit of this is that it is fast. How efficient the algorithm is, depends on the quality of the heuristic. A bad heuristic can slow down the algorithm and give bad routes.

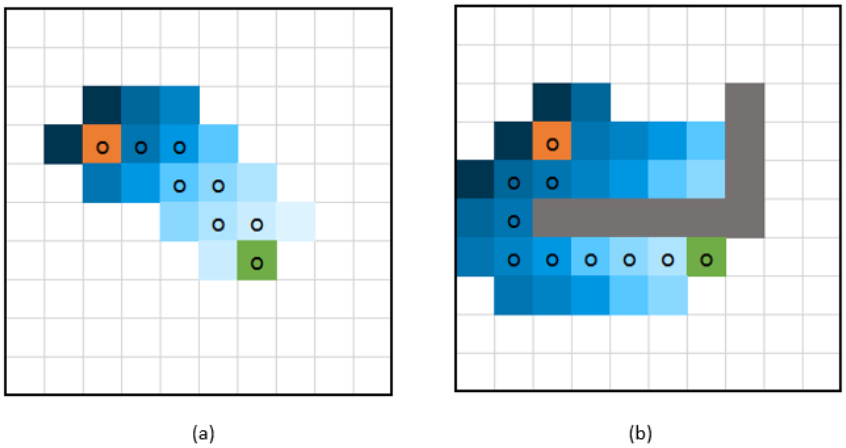
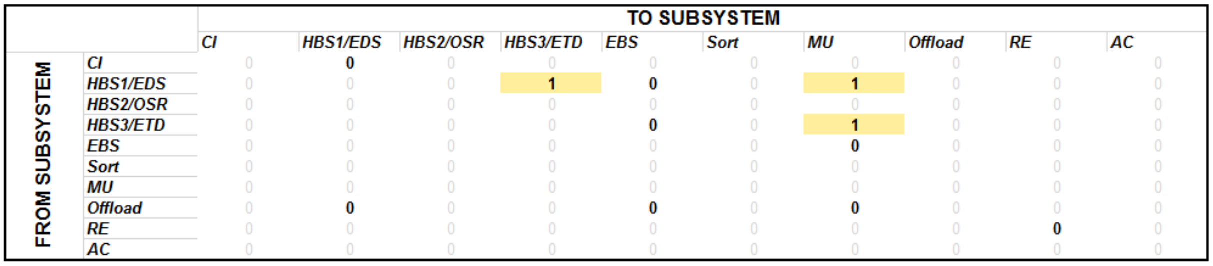


Figure 4.4: The A* algorithm without obstacles (a) and with obstacles (b).

As in many grid based A* algorithms, the heuristic in the model is based on the Manhattan distance. This is the minimum number of tiles that is needed to reach the goal tile.

4.3 Implementation of the A* routing algorithm

The A* algorithm is implemented in the placement code, as phase 3 (see Figure 3.5). Through one of the input sheets in Excel it is possible to add the transportation that is needed between two subsystems (see Figure 4.5). For instance, if this input shown in the figure is used, transportation at the airport is added between EDS and ETD, EDS and make-up, and ETD and make-up. Placing transportation is only possible on the subsystem pares that are bold in the Figure. Figure 4.6 shows these transportation pares. These routes are chosen based on the information provided by the BHS experts during the interviews (see Appendix D).



		TO SUBSYSTEM									
		CI	*HBS1/EDS*	*HBS2/OSR*	*HBS3/ETD*	*EBS*	*Sort*	*MU*	*Offload*	*RE*	*AC*
FROM SUBSYSTEM	*CI*	0	**0**	0	0	0	0	0	0	0	0
	HBS1/EDS	0	0	0	**1**	**0**	0	**1**	0	0	0
	HBS2/OSR	0	0	0	0	0	0	0	0	0	0
	HBS3/ETD	0	0	0	0	**0**	0	**1**	0	0	0
	EBS	0	0	0	0	0	0	**0**	0	0	0
	Sort	0	0	0	0	0	0	0	0	0	0
	MU	0	0	0	0	0	0	0	0	0	0
	Offload	0	**0**	0	0	**0**	0	**0**	0	0	0
	RE	0	0	0	0	0	0	0	0	**0**	0
	AC	0	0	0	0	0	0	0	0	0	0

Figure 4.5: The added function to place transportation between subsystems.

For every required route, the algorithm executes the following process. It start with some checks to see if routing is actually needed and how it is needed. It first finds the tiles that are next to the subsystem. If the two subsystems that require routing are not on the same floor level, a lift is added in between the two subsystems. The required routing list changes from subsystem A to B, to subsystem A to the lift and the lift to subsystem B, and the process restarts. If the subsystems are on the same level, the next check is to verify if they are directly next to

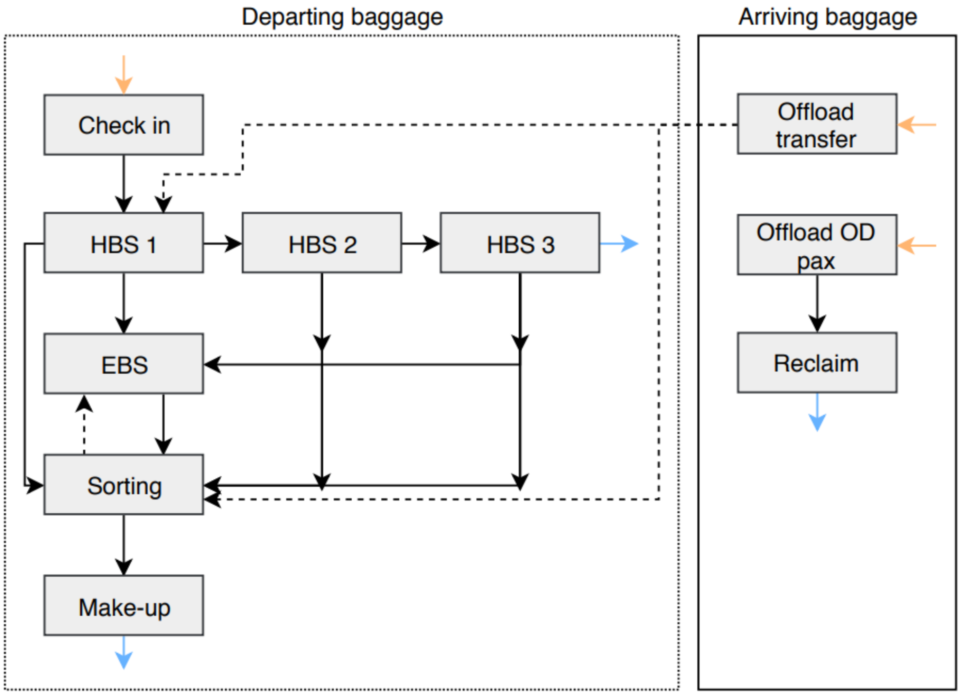


Figure 4.6: Routing between subsystems of a BHS.

each other. If so, routing is not needed and the algorithm continues with the next required transportation. If routing is needed, the algorithm continues by searching for the optimal begin and end tiles, which minimizes the transportation length needed. For these two tiles, the A* algorithm is executed. If no route between these two tiles is possible, the next best start and end tiles are searched, and the A* algorithm is executed again. This process continues until either a route is found or routes between all start and end tiles could not be found.

The transportation algorithm thus searches for routes until all possible routes are checked. However, if no route is found, the model does not change the placement of the subsystems until this is possible. As the subsystems are placed as close as possible to each other, and transportation is only added afterwards, there is sometimes no route possible. However, if the algorithm cannot find a route, it does not necessarily mean that there in no route possible in reality. The blocks of the equipment represent the *entire* space reservation of each equipment unit. The blocks also reserve space for additional transport equipment and maintenance area (see Figure 4.7). Thus, as there is extra space reserved which is not actually needed for the equipment, if the algorithm cannot find a route, it can still be possible to add transportation while using this space reserved.

4.4 Chapter summary

This chapter elaborated about how the routing between subsystems can be optimized from the initial model where transportation is only placed by reserving space between two subsystems. Since the transportation between these systems can cause problems in the later phases of a BHS

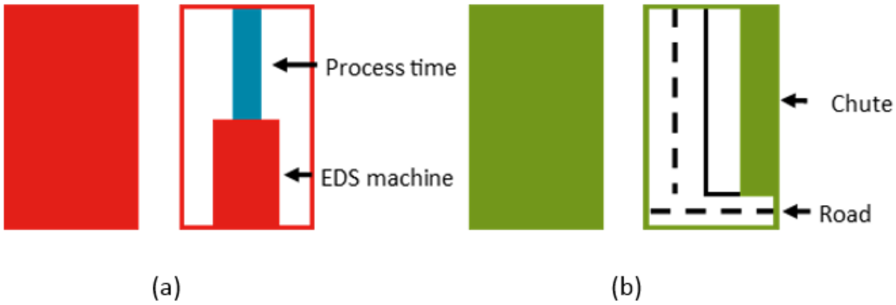


Figure 4.7: A graphical representation of what is inside the 3D space reservation blocks of (a) screening level 1 and (b) make-up.

design, it is important to take it into account as early as the conceptual design phase. This is beneficial as less time is spent on scenarios that BHS designers later learn are ineffective.

So, actual routing between subsystems is desired. Due to this, a more detailed design of the transportation between subsystems has been added to the model. The A* algorithm is used to search for the optimal route between subsystems. This algorithm is chosen because it guarantees the most efficient and shortest path. In conclusion, this chapter addressed the third sub-question: *How can transportation between subsystems be included in the model, in order to increase the usefulness of the model?* A grid based A* algorithm is implemented to determine the optimal routes between subsystems, for all requested subsystem pares.

Chapter 5

Increasing the model precision

One of the research objectives is to limit uncertainties in the model. The outcome of the model depends on a set of predefined input parameters. These parameters are often defined through experience and assumptions of the BHS designers at NACO. This leaves the model open to uncertainty and potential errors. This chapter explores if, or how, the outcome of the model changes when the input parameters are altered.

The following sub-question is addressed: *How can the variation in the output of the model of the conceptual design of the baggage handling system be apportioned to different input parameters?* In other words, how do changes to the input parameters change the output. This chapter is structured as follows. Section 5.1 explains the method, Sensitivity Analysis, which is used to analyze the variations in output. Section 5.2 evaluates the model, using three input categories, by applying the method for the Aruba Airport. The analysis led to an improvement to the model, which is discussed in Section 5.3.

5.1 Sensitivity Analysis

Sensitivity Analysis (SA) can be a great method when building a simulation tool. With SA, uncertainty in the output of a model can be allocated to different sources of uncertainty in the input of the model (Saltelli, Chan, & Scott, 2009). It can be used to determine the input variables that have the most influence to an output behaviour, but also the input variables that are the least-influential inputs (Iooss & Lemaître, 2015). SA is typically performed to check the robustness of the results of a model (Chin & Lee, 2008). If there is uncertainty about a parameter estimate, SA can be used to evaluate this uncertainty. SA can significantly impact the predictive qualities of a model because it can identify uncertain model parameters (O'Connor et al., 2017). SA can be used as feedback to the development of the process model by identifying uncertain model parameters that can have a significant impact on the prediction of attributes. With this analysis it can be determined if the parameter estimates are sufficiently precise to produce reliable outputs. If the analysis shows that the estimates are not precise enough and these are not improved, the model can be very uncertain.

There are several SA methods that can be used to determine parameter uncertainty. Local SA focuses on the local impact of variables on the model (Saltelli et al., 2009). With this method, the model is repeatedly run for different values of a parameter, while holding all other parameters fixed at the same values. It can be seen as a one-variable-at-a-time approach. If local SA is executed, the model input is explored over a small range around the tested value. This is a great method to determine which parameters should be modified to produce a desired outcome (Hoops et al., 2016).

A different method can be used when it is necessary to explore a wider input space, namely global SA. With global SA all model inputs are varied simultaneously, calculating the entire range of each model input (Saltelli et al., 2009). Global SA can be used to reduce the number of parameters, because the analysis can show the parameters that hardly influence the outcome (Hoops et al., 2016). If it is possible global SA is preferred as it provides greater detail. However, for a large systems it can be very computationally expensive. In these cases local SA can be preferred as it requires less computational power.

5.2 Results of the sensitivity analysis

Since the run time of the model is long and the time to write the thesis short, performing global SA is not realistic. Local SA is a relatively simple method that is easily applied (Frey & Patil, 2002). It is done by repeatedly running the model for different values of a parameter, while holding all other parameters fixed at the same values. However, performing local SA has a disadvantage. As Yang et al. (2016) state, local SA only analysis the relationship around the input variables, without considering the interactions among the inputs. The parameters that are evaluated are the demand (which is based on a flight schedule), the airport specific input parameters, and the optimization parameters. The execution of the SA is split up per parameter group.

5.2.1 Aruba Airport

The sensitivity analysis is executed for Queen Beatrix International Airport, also known as AUA. It is the main and only airport on the Caribbean island of Aruba (Aruba Airport Authority N.V., 2019). As part of a terminal expansion, a new BHS needs to be designed. The new building is shown in Figure 5.1. The airport has 1 runway and currently transports 2.5 million passengers per year. At the moment the airport has 8 gates, which will be expanded to 10. AUA transports nearly no transfer passengers. The layout of the new BHS terminal is shown in Figure 5.2.

5.2.2 Model sensitivity of the demand parameters

The demand parameters are the minimum operational values that the BHS design has to meet. The demand for the BHS system is calculated through the peak hour of a flight schedule, which is read into the model. In the model each demand can be changed manually. This is often needed when only a historical flight schedule is available, but the design needs to be created for a scenario in the future with higher demand. The sensitivity analysis will be executed by changing the demand 10% and analyzing if the effect of this change is also in the same order of magnitude.

Figure 5.3 shows these values for Aruba Airport. Scenario 1 is the demand calculated through the flight schedule (base case), scenario 2 is the base case -10% and scenario 3 is the base

Figure 5.1: AUA airport layout.

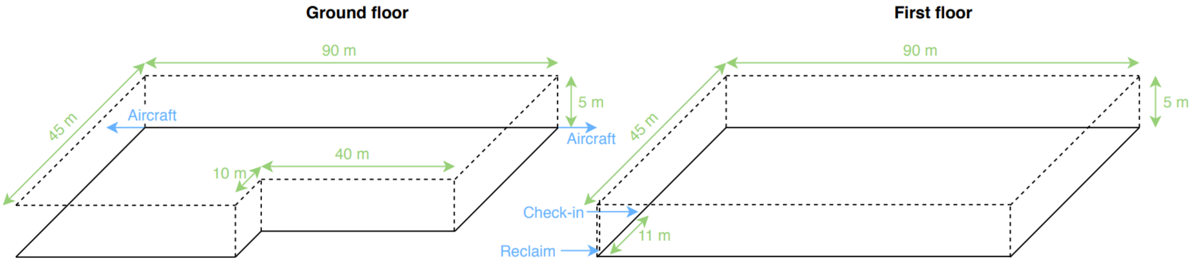


Figure 5.2: AUA terminal layout.

case +10%. All scenarios are generated with the standard settings, keeping all other variables constant.

It is remarkable that all equipment for the three scenarios stayed the same except for two cases. In scenario 2 (-10%), the sorting equipment changed from 'push tray' to 'pusher low speed'. In scenario 3 (+10%), the make-up loading equipment changed from 'lateral' to 'carousel'. Both can be explained by the change in demand. The former changed because the pusher low speed equipment has a lower CAPEX (and the scenario's are optimized on CAPEX) than the push tray, and with the reduced demand it is possible to choose this cheaper option. It is remarkable though that the capacity of the pusher equipment is almost double that of the tray equipment, while you would expect it the other way around. However, this is explained by the fact that if the pusher low speed equipment is chosen, for every lateral in make-up, one pusher is needed even if it is not needed for the capacity. As there are six laterals in make-up, also six pushers

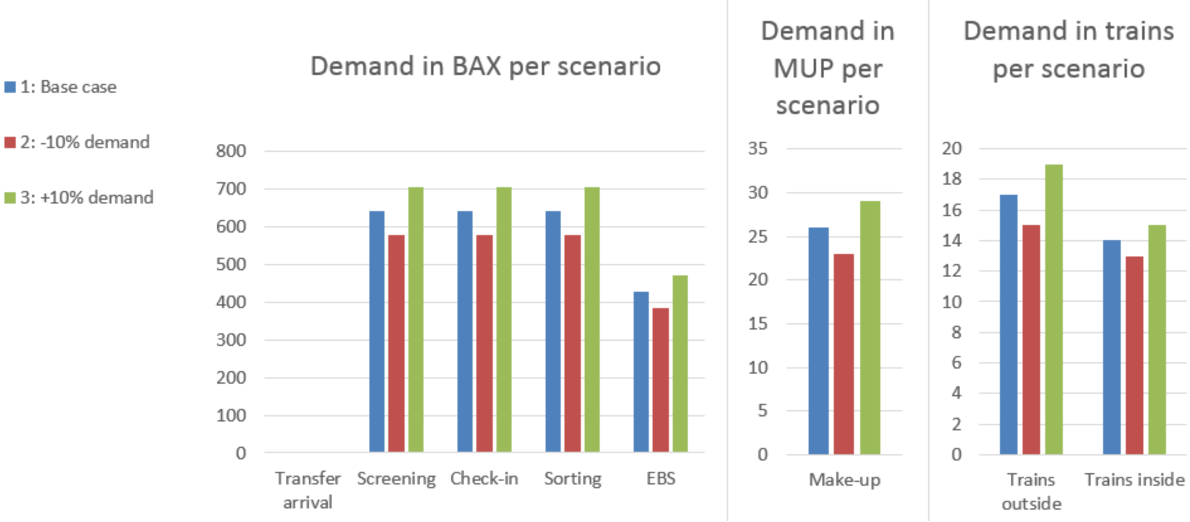


Figure 5.3: Demand changes in the SA for AUA.

need to be installed. The latter change in equipment can probably be explained by the fact that the capacity of a carousel is three times that of a lateral. This 10% increase was probably the switching point between the two, making the carousel more attractive than the lateral.

The changes in equipment also effects the other results. Figure 5.4 shows some of these results. This chart shows the achievement of each of the decision variables. The data is standardized and adapted in a way that the closer a scenario is to the outer ring, the better. Of course, with a changing demand this does not always show comparable results for all decision variables. For instance, the total system area of scenario 2 (-10%) is, as expected, lower than the base case (scenario 1), etc. However, the CAPEX of scenario 3 (+10%) is surprisingly better than of the other two. This is explained by the change in make-up equipment, which effected the CAPEX of the sorting equipment. With the carousel equipment the sorting loop is smaller, reducing the total CAPEX and the energy consumption. This change in equipment even makes scenario 3 (+10%) cheaper than the other two scenario's, while meeting a higher demand. However, scenario 3 does require slightly more operators and a bigger system area. As there are differences in the achievement of the different scenarios, it is up to the decision maker to choose the scenario he wants to implement based on what he values more. However, in this case, scenario 1 does not rate better in any of the decision variables, scenario 2 does not meet the system demand, which will probably result in choosing scenario 3 or running more scenarios.

On a side note, the reason why the CAPEX of scenario 3 can be cheaper than the other scenario's, while optimizing based on CAPEX, is that the optimization is split up into two parts. First the BHS equipment is chosen, and only after this is placed inside the BHS terminal, the transportation equipment can be chosen. There are a lot of rules and restrictions when choosing the transportation equipment, such as needing a pusher for every lateral. This causes big differences in the CAPEX (and also other decision variables) of the transportation equipment, resulting in strange outcomes such as cheaper solutions for the higher demand. A solution to this problem is to change the five step design framework (see Chapter 1.3) to a four step frame-

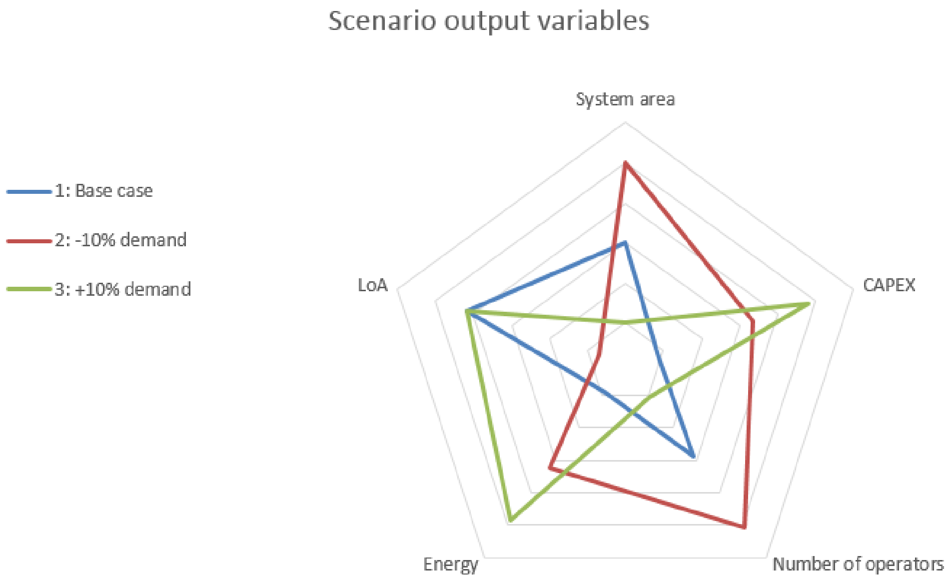


Figure 5.4: Radar chart of the decision variables of SA demand scenarios of AUA (more outward is better).

work, including the transportation optimization in the equipment optimization. However, the reason why the five step framework is used is due to the optimization software 'Windows Solver Foundation', which does not allows to include both optimization's in step 3 (Vijlbrief, 2019).

Concluded from this sensitivity analysis is that the model is sensitive to changes in demand. Yet, all changes can be explored and explained. The model behaves as expected. Though, which type of equipment is chosen is the determining factor for the height of the decision variables. Moreover, the model responds the same until certain 'break points'. For instance, the higher demand has a lower CAPEX than the other two scenario's. It would be interesting to figure out when these break points occur.

5.2.3 Model sensitivity of the airport specific input parameters

The BHS design is based on airport specific input parameters. This section will explore the sensitivity of these input parameters on the outcome. For every parameter a SA is executed. As every parameter is different, various SA's are executed depending on the variable. Table 5.1 shows which values are used for the SA's.

The number of check-in systems represents the number of check-in-systems. If check-in is centralized, this value is 1. If check-in is decentralized, this value is 2 or higher and represents over how many areas it is decentralized. The redundancy is the redundancy of the entire BHS. The number of check-in desks per side is the number of check-in desks that are in a row next to each other, thus the desks per island side. The distance between the check-in sides is the distance between the different check-in islands. The HBS level 1 rejection rate is the fraction of bags which get send from level 1 baggage screening (EDS) to level 2 screening (OSR). The HBS level

Table 5.1: SA scenarios for the airport specific input parameters.

SA	**Parameter**	**Unit**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario selection**
A	Number of check-in systems	-	1	2	3	1 or more
B	Redundancy	%	75	67,5	82,5	-+10%
C	Check-in desks per side	-	7	6	8	-+10%
D	Distance between check-in sides	Meter	26	23	29	-+10%
E	HBS level 1 rejection rate	Fraction	0,25	0,225	0,275	-+10%
F	HBS level 2 rejection rate	Fraction	0,5	0,45	0,55	-+10%
G	Road width	Meter	3	2,7	3,3	-+10%
H	Average number of bags in a NB cart and WB ULD	Bags	35	31	39	-+10%
I	Loop sorting	-	yes	no	-	yes or no

2 rejection rate is the fraction of bags which get send to from level 2 baggage screening (OSR) to level 3 screening (ETD). The road with is the width of the road that is needed at make-up to transport the trains or carts. If ALT is not used, space for a road (with this width) is reserved. The average number of bags in a NB cart and WB ULD represents the average number of bags that goes into a baggage cart or ULD. Loop sorting refers to if there is a make-up loop or not. The number of MUP's per subloop refers to if all make-up equipment is directly connected to the loop, then the value (N) equals 1, or if there are any subloops. Figure 5.5 shows this difference.

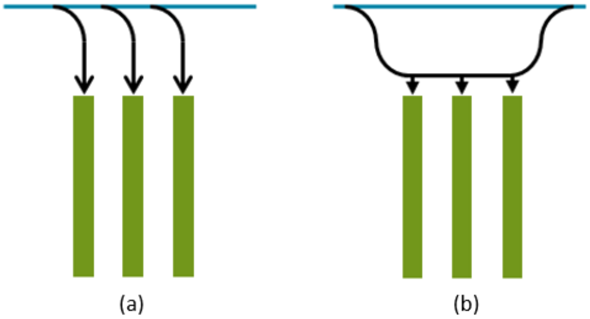


Figure 5.5: The difference between a make-up loop where N = 1 (a) and a make-up subloop where N = 3 (b).

As the model is run 29 times to obtain the SA results, only the important results will be discussed. The number of check-in systems (SA A) only slightly changed the pieces of equipment per scenario, not impacting the subsequent calculations. The number of check-in desks per side (SA C) slightly changed the system area and CAPEX of check-in, again not impacting the following calculations. The distance between check-in sides (SA D) only affects the system area of check-in. The road width (SA G) only affects the system area of make-up. As expected, the SA of the average number of bags in a NB cart and WB ULD (SA H) showed slight changes in make-up capacity.

The reduced redundancy (SA B2) caused the sorting equipment to change from push tray to pusher low speed. As explained in Section 5.2.2, this caused the capacity of the sorting equipment of scenario B2 (-10% redundancy) to double and a slight decrease in CAPEX of 8%. The increase in redundancy, scenario B3, requires the BHS to add a HBS level 1 equipment, resulting in a small change in CAPEX, system area and energy consumption. Figure 5.6 shows these outcomes. This also affected the placement. Since HBS level 1 is one of the first subsystems to be placed, the other subsystems placed later on had another optimal location. Also the SA of loop sorting (SA I) resulted in the same alteration of sorting equipment.

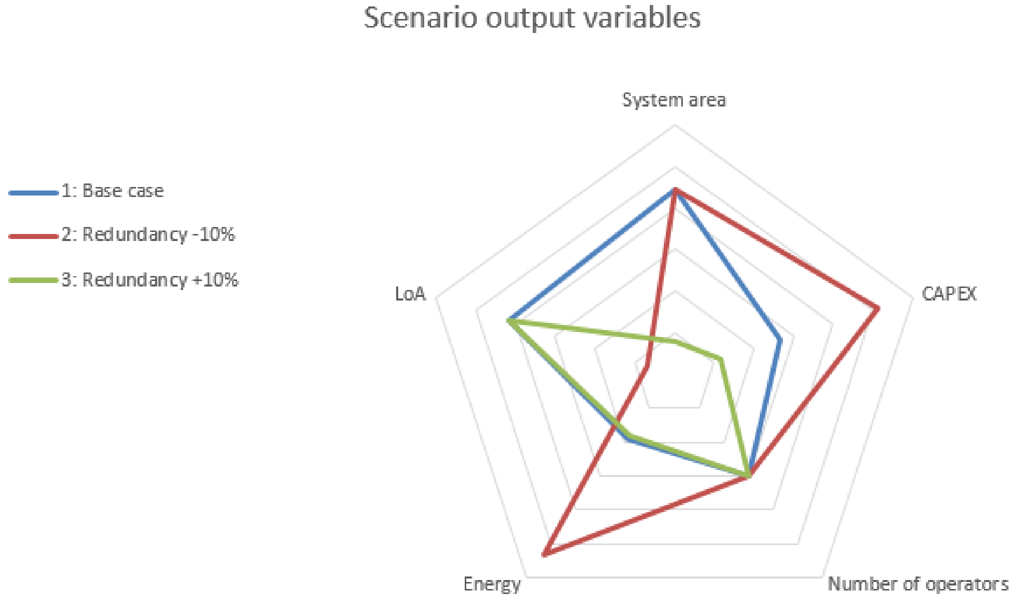


Figure 5.6: Change in decision variables due to the SA of redundancy for AUA (more outward is better).

The HBS rejection rates (SA E and SA F) both altered the number of HBS equipment by one, affecting the CAPEX, number of operators and energy consumption (see Figure 5.7). The LoA stays the same as the type of equipment does not change. These results are all as expects. However, the system area stays the same. This is explained by the fact that HBS level 2 and 3, the subsystem affected by the rejection rates, are designed to give rectangular rooms where operators can walk around. For instance, between 9 and 16 OSR machines, the area is 12 by 16 meter. Thus, only if the number of equipment changes outside these regions, the system area is affected.

5.2.4 Model sensitivity of the optimization parameters

The ground and transportation equipment for the BHS is chosen through an optimization algorithm. The optimization algorithm is a binary integer programming model that is based on Ölvander et al. (2009). Section 1.4.3 explains in detail how the optimization works. In short, there are four parameters that, by itself or in combination with the other parameters, decide which equipment for that scenario is optimal. These parameters represent the stakeholders interests and trade-offs. The four parameters are the CAPEX, energy consumption, number of operators and LoA. The CAPEX and energy consumption can be minimized, the number of operators and LoA can be minimized or maximized. The model is tested to see how large the

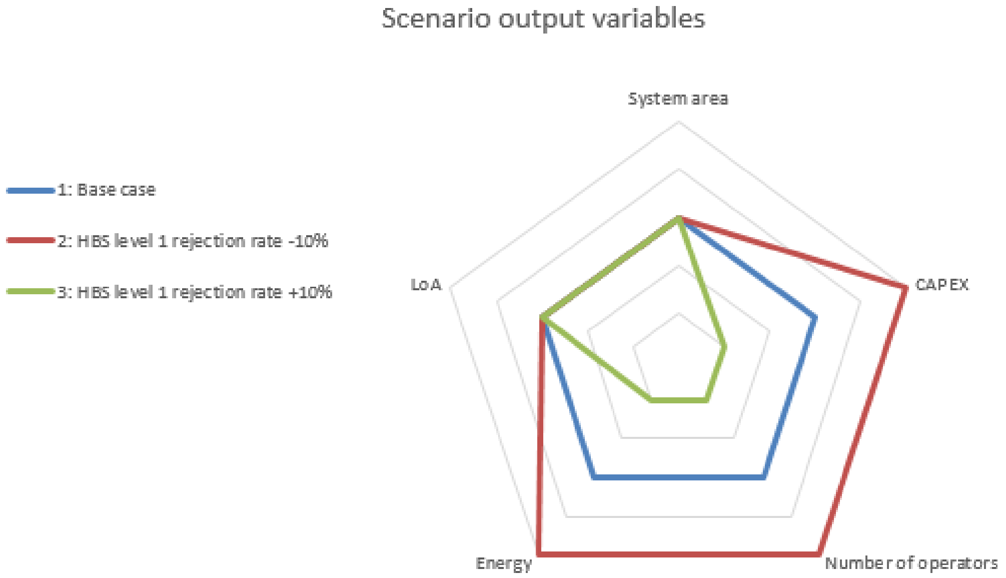


Figure 5.7: Change in decision variables due to the SA of the HBS rejection rate for AUA (more outward is better).

effect of these parameters is.

The first SA is to minimize or maximize each of these parameters. Figure 5.8 shows the radar plot of the decision variable of these six scenario's. The figure shows that each scenario scores as expected for the decision variable it was optimized, except for the minimized energy consumption optimization (scenario 2). This is due to the fact that the transport can only be chosen in the end and in this case is 97% of the total energy consumption. This issue has arisen several times already in the previous SA's and can maybe be solved by including the transportation optimization into the ground equipment optimization. Furthermore, scenario 1 (minimize CAPEX) is the cheapest of these scenarios as it has a much lower CAPEX and also a lower energy consumption. Surprisingly scenario 4 (maximize LoA) scores high on all decision variables, while it would be expected that it would be an expensive scenario with the new expensive technology needed. However, the equipment with a high LoA has a high capacity, which results is less equipment needed. Other than the CAPEX, also scenario 6 (maximize the number of operators) scores well on the decision variables. Scenario 3 (minimize LoA) and scenario 5 (minimize the number of operators) do not score well on any of the decision variables. It can be concluded from this chart that for Aruba Airport scenarios 1, 4 and 6 can be good solutions, scenarios 3 and 5 not, and the model is not reliable regarding the optimization on the energy consumption.

The CAPEX versus the energy consumption, the second SA, is tested by performing 11 runs ranging the two optimization parameters between 0 and 1. Some combinations have the same solution, as the change in parameter did not change the equipment chosen. Just as scenario 2 (minimize energy) in the first SA, this SA also shows that the energy consumption as an optimization parameter is not able to provide reliable solutions. Even more, the higher the energy optimization parameter is, which is supposed to result in a lower energy consumption, the higher

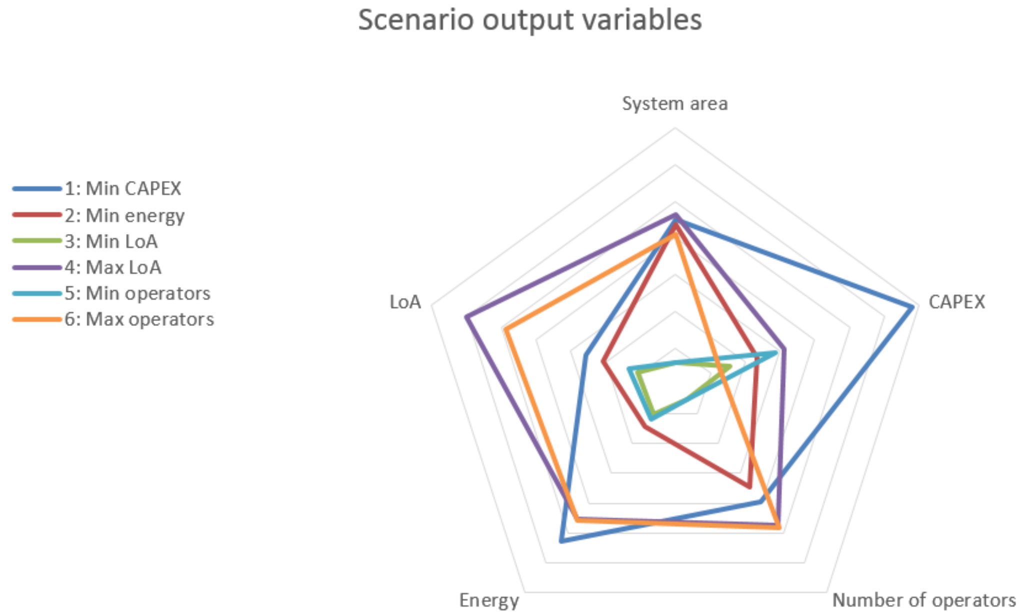


Figure 5.8: Radar chart of the decision variables of the first SA of the optimization parameters for AUA (more outward is better).

the total energy consumption. Figure 5.9 shows this impact in a scatter plot. The plot shows that a low CAPEX is related to a low energy consumption and a high CAPEX to a high energy consumption. However, as the optimization ability of the energy consumption does not have the desired effect, this can be a coincidental. These results are in line with the research of Vijlbrief (2019).

In the third SA, 22 runs ranging the CAPEX versus number of operators is performed. Half of the runs test the CAPEX versus *minimizing* the number of operators, the other half the CAPEX versus *maximizing* the number of operators. Figure 5.10 shows the relationship between the two parameters. There is a non-linear relationship which is negative when the number of operators is minimized and positive when the number of operators is maximized. When minimizing the number of operators, the CAPEX goes up. This is as expected since equipment where less operators are needed is generally more expensive. Nonetheless, the range in which the CAPEX differs is big, while the range between the number of operators is small. When the number of operators is maximized with 0.1, the number of operators doubles compared to 0. If this parameter is 0.2 or higher, the number of operators almost triples and the CAPEX doubles. This is explained through if a high number of operators is desired, chutes are chosen for make-up. If chutes are used, for the sorting equipment a conveyor belt and pushers is replaced by a push tray belt, which costs 1000 €/meter more. The increase in CAPEX is explained even more by the placement of these scenarios compared to the previous, where the transportation length of make-up is higher, increasing the cost even more (see Figure 5.11). Another reason for the difference in range between the CAPEX and number of operators is that AUA is a small airport. If the equipment type at an airport changes, the effect of this change gets multiplied by the number of equipment. At small airports the number of equipment is also limited, resulting in

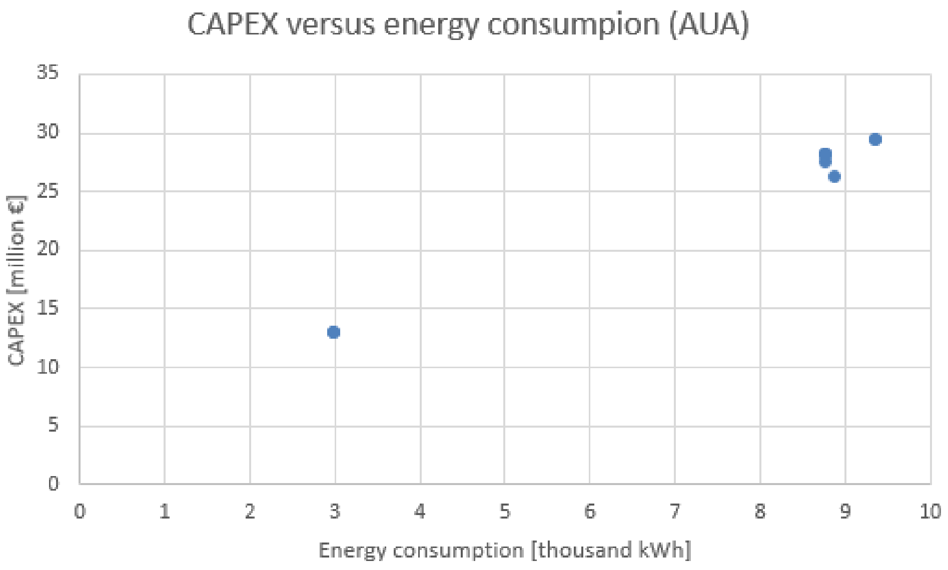


Figure 5.9: The relation between the CAPEX and energy consumption for AUA.

small changes in operators.

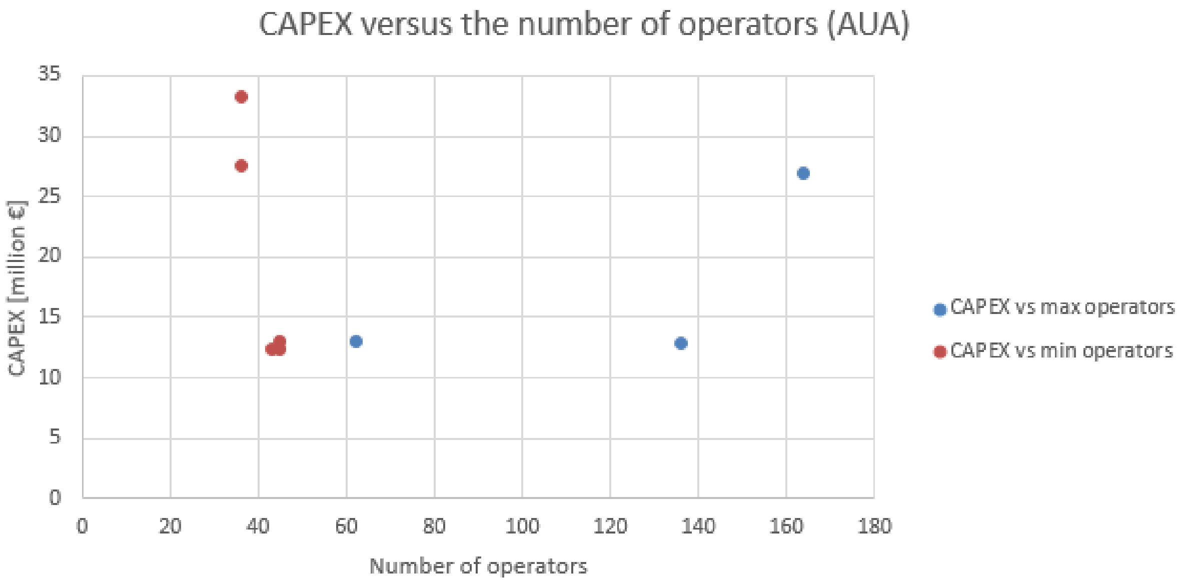


Figure 5.10: The relation between the CAPEX and the number of operators for AUA.

Furthermore, this SA shows the switching points between the trade-off of the two parameters (when maximizing the number of operators), which are visible in the radar plot in Figure 5.12. Scenario 1 (minimizing CAPEX) scores the highest on all variables except for the maximum number of operators. Scenario 2 (minimizing CAPEX 0.9 and maximizing the number of operators 0.1) scores slightly lower on these decision variables, but higher on the number of

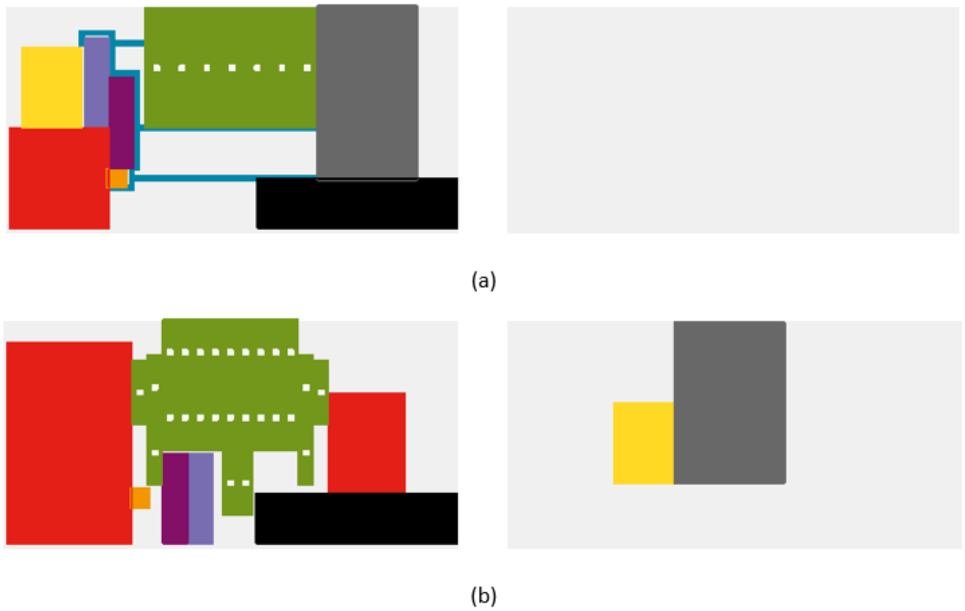


Figure 5.11: Placement of the scenarios of the CAPEX versus the maximum number of operators for AUA. The top figure (a) shows scenarios 1-2 and the bottom figure (b) shows scenarios 3-11.

operators. Scenarios 3 to 11 (minimizing the CAPEX ranging from 0.8 to 0 and maximizing the number of operators ranging from 0.2 to 1), all score approximately the same, a little higher on the number of operators, but lower on the others. Also, the switching points when minimizing the number of operators are clear in the radar plot in Figure 5.13. Scenarios 2 to 5 (minimizing CAPEX ranging from 0.9 to 0.6 and minimizing the number of operators ranging from 0.1 to 0.4) score higher or the same for all decision variable than scenario 1 (minimizing CAPEX 1 and minimizing the number of operators 0). Scenarios 6 to 9 (minimizing CAPEX ranging from 0.5 to 0.2 and minimizing the number of operators ranging from 0.5 to 0.8) score average in all categories. As soon as the CAPEX is minimized with 0.1 or less and the operators are minimized with 0.9 or more, the scenarios score higher on the LoA and number of operators, but lower on the other decision variables.

The last SA that is performed is the CAPEX versus the LoA, again 22 runs ranging the two parameters, half minimizing and half maximizing the LoA. Figure 5.14 shows the relationship between the two parameters. Similar to the previous SA, there is a non-linear relationship between the two parameters. Even though the equipment with a lower LoA usually costs less, the capacity of these equipment's is also lower, resulting in a higher number of equipment. Thus, although the equipment is cheaper, the total CAPEX is higher as more of it is needed. Equipment with a high LoA generally costs more, increasing the CAPEX in these scenarios.

The lines 'Minimum LoA' and 'Maximum LoA' show the theoretical minimum and maximum LoA values. They are calculated by combining the types of equipment with the lowest and highest LoA. These values are theoretical because certain types of equipment require other types of equipment with a higher or lower LoA value. Thus, the actual minimum achievable LoA is 4.00 and the maximum is 6.00.

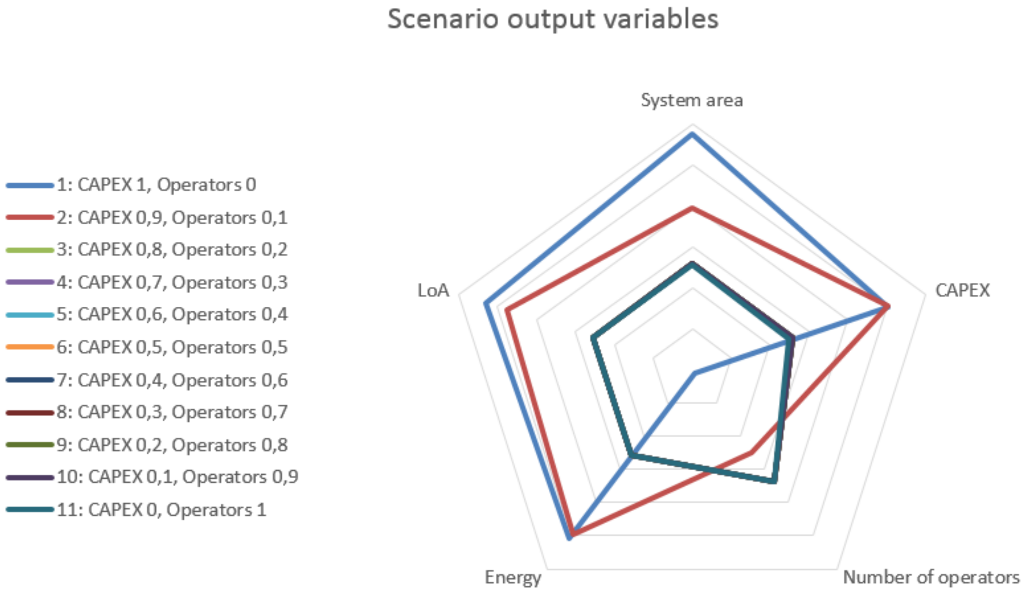


Figure 5.12: Radar chart of the SA testing the CAPEX versus the maximum number of operators for AUA (more outward is better). *Note that in contrast to the other radar charts in this thesis, the number of operators is maximized, meaning the closer the scenarios are to the outer ring, the more operators are needed.*

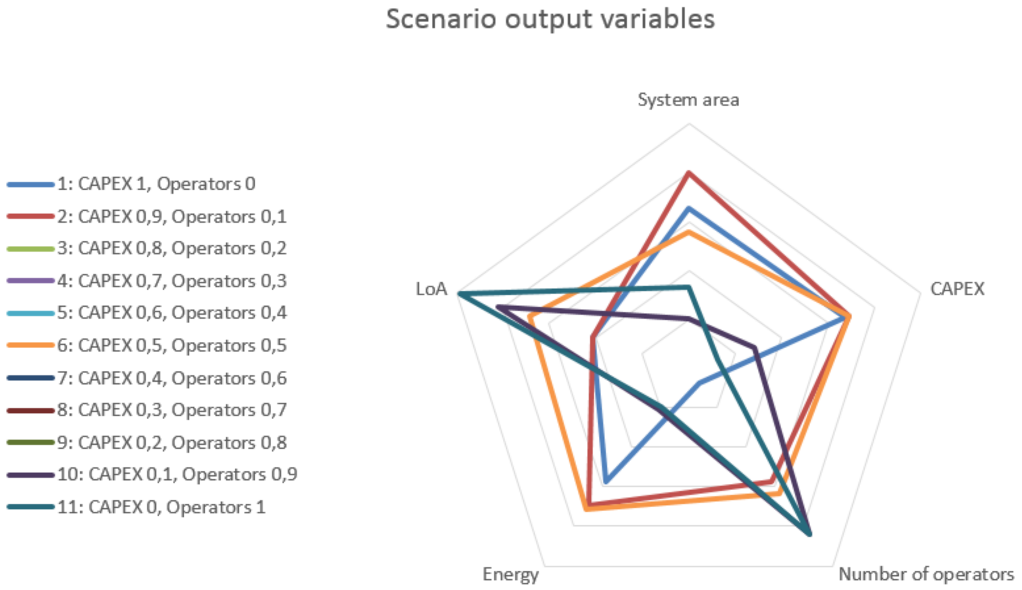


Figure 5.13: Radar chart of the SA testing the CAPEX versus the minimum number of operators for AUA (more outward is better).

Two clear switch points can be determined from the last SA. When maximizing the LoA, as of

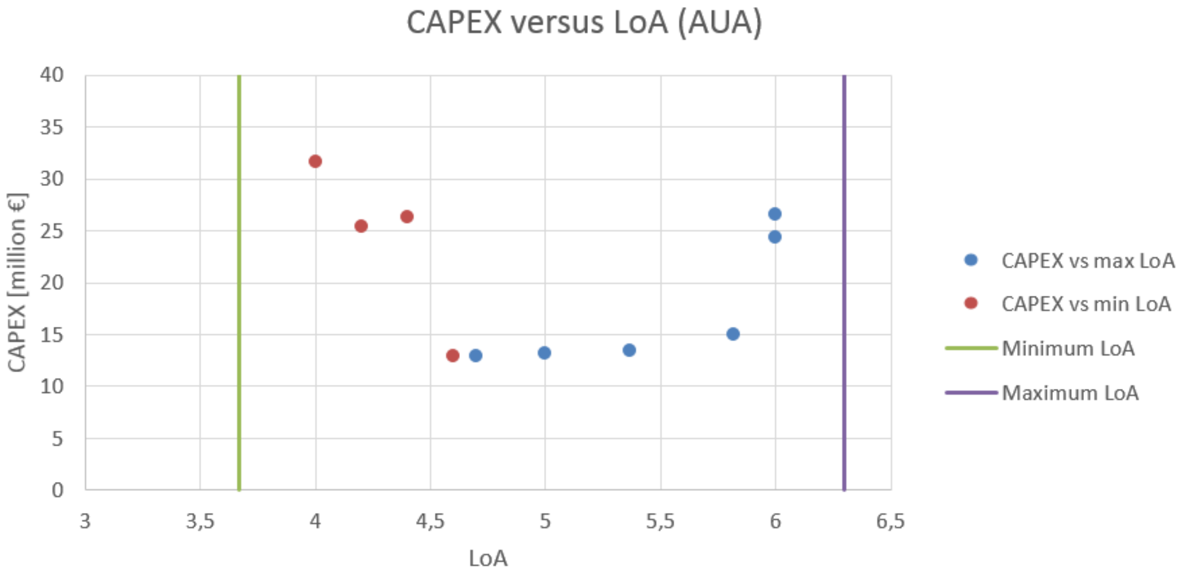


Figure 5.14: The relation between the CAPEX and the LoA for AUA.

scenario 10 (minimizing CAPEX 0.1 and maximizing LoA 0.9) the CAPEX doubles while the LoA only increases with 3.5%. When minimizing the LoA, as of scenario 5 (minimizing CAPEX 0.6 and minimizing LoA 0.4) the CAPEX doubles while the LoA only decreases with 4.5%.

5.3 Model improvement

The SA showed that the energy optimization parameter does not provide the desired result. The cause of this is that the ground equipment optimization and the transport optimization are executed after each other, and not together. First the ground equipment is chosen, and only after the placement model is executed, the transportation equipment is chosen. Almost 90% of the energy consumption of a BHS comes from the transportation equipment. However, the choice of transportation equipment is restricted by the choice of make-up loading equipment in the first optimization. The make-up equipment that uses the least amount of energy, requires more transportation equipment, which uses more energy. Thus, the better choice of make-up equipment is the one that requires less transportation equipment.

An attempt is made to solve this issue. There are four types of make-up loading equipment: chutes, laterals, carousels, and robots. For every equipment an estimation is made of how much energy the equipment *and* transportation equipment will consume. On average, for every meter of make-up sorting equipment the sorting equipment consumes 2 kilowatt hour of energy. For every meter of make-up sorting equipment, this value is added to include in the first optimization.

Another SA is executed to test if the energy optimization parameter is more reliable now. Again 11 runs ranging the energy optimization parameter with the CAPEX are carried out. Figure 5.15 shows how each scenario scores on the different decision variables. The diagram clearly shows that the scenarios that score high on the CAPEX, score low on the energy consumption, and visa versa, which is desired. Additionally, a scatter plot of the CAPEX versus the energy consumption even shows a negative linear relationship (see Figure 5.16). Though, one data point, scenario 7 (the red point in the diagram), does not fit in that trend. This is due to a change in equipment of screening level 1 from medium speed EDS to high speed EDS. Even though the high speed equipment uses less energy, the amount of conveyor belt needed with this equipment nullifies and even increases the CAPEX and energy consumption.

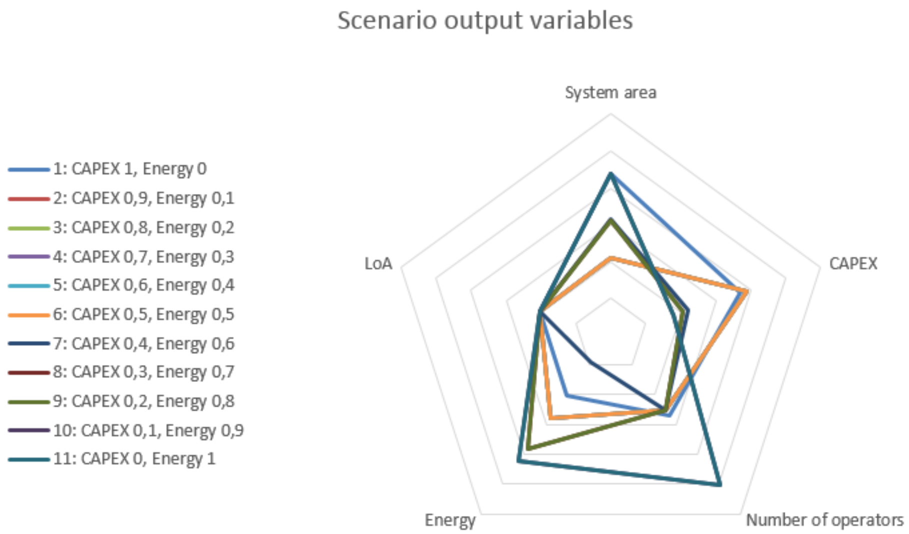


Figure 5.15: Radar chart of the CAPEX and energy consumption, based on the new make-up energy parameters for AUA (more outward is better).

Concluded from this last SA can be that the change of parameter values, improves the reliability of the energy consumption optimization parameter. However, as the transportation not solely depends on the make-up equipment, there are still exceptions. More research should be conduction to further develop the model optimization of the energy parameters.

5.4 Chapter summary

This chapter answers the second sub-question: *How can the variation in the output of the model of the conceptual design of the baggage handling system be apportioned to different input parameters?* A Sensitivity Analysis (SA) is executed to assess uncertainties in the parameters and demonstrate that the model output is reliable. A local SA is used because there is not enough computational power and time to perform a global SA. A disadvantage of this method is that it is only possible to analyze the relationship around the input variables, but not the interaction effects between the inputs.

Three input categories are analyzed: (1) the demand parameters, (2) the airport specific input parameters, and (3) the optimization parameters. The following conclusions were reached from the SA. First, the type of equipment that is chosen is the critical factor for the capacity of a

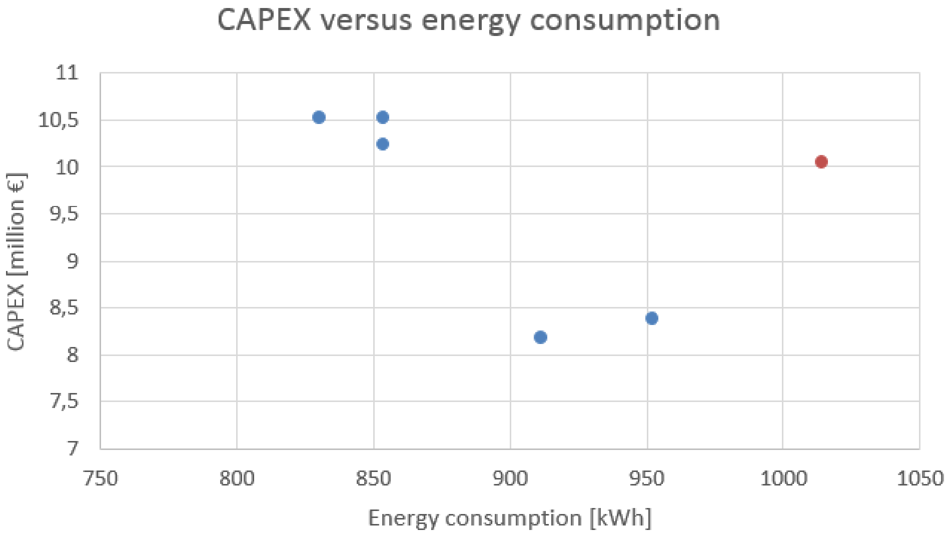


Figure 5.16: The relation between the CAPEX and energy consumption, based on the new make-up energy parameters for AUA.

subsystem. It is also the critical factor for how good the decision variables score. The type of equipment can be changed at 'break points' to respond to changes in demand. As every piece of equipment has a maximum capacity, as long as the demand is within the range of that capacity, the model outcome does not change. But, if the demand exceeds the maximum range, then other equipment is necessary. These are the 'break points' due to changes in demand.

Second, because the optimization is split into two phases, ground equipment and transportation, the model does not deliver the desired results. When choosing the ground equipment, the model behaves as expected. If the model is optimized on the CAPEX, the ground equipment with the lowest CAPEX, that fits inside the BHS terminal, is selected. But, when used *in combination with* the transportation optimization, it does not give the desired results. This is because the transportation choice is dependent on the type of ground equipment selected. So, the best alternative for ground equipment could be different depending on the choice of transportation. For example, if the objective is to determine the minimum *total* CAPEX, this can create a combination of the two optimizations that is a non-optimal solution.

Additionally, the SA has demonstrated that the model is not reliable for the optimization of energy consumption. This is because the transportation system is responsible for most of the energy use. But when optimizing on energy consumption, the ground equipment with minimal energy consumption often requires transportation equipment with very high energy consumption. In this case, the model does not provide reliable results when optimizing for energy consumption. An attempt has been made to improve the reliability of the energy consumption optimization parameter, by using the expected energy consumption of the transport equipment during ground equipment optimization. There is a negative linear relationship between the CAPEX and energy consumption. Even though this is an improvement, changing equipment type can alter this relationship and delivers alternative results.

Lastly, there is a non-linear relationship when optimizing the model on the CAPEX versus the number of operators, or the CAPEX versus the LoA. When the number of operators and LoA are minimized, the relationship is negative. Thus, when increasing the optimization parameters of the minimum LoA or number of operators, the CAPEX rises. When the operators and LoA are maximized, the relationship is positive. Thus, as the optimization parameters are increased, more the CAPEX is required. So, decreasing the focus of optimizing the CAPEX, and increasing the focus of optimizing the number of operators or LoA, causes an increase in CAPEX. In addition, the SA demonstrates that there are certain 'break points' where the type of equipment changes, which affects the other results. At these break points, a minor change in the optimization parameters, causes the type of equipment to change.

To answer the sub-question, the variation in the output of the model is mainly due to changes in the choice of the type of equipment. Several factors affect the choice of the type of equipment, namely the BHS demand, choice of optimization, the required redundancy, loop sorting, and what the level of the HBS rejection rates are. These factors affect the model outcome as desired. The conclusion is that the type of equipment has the most effect on the decision variables. There are certain 'break points' which cause the type of equipment to switch. This can cause unreliable results as changing equipment can have significant effect. Further research should be conducted into these break points.

Chapter 6

Customizing designs

While talking to airport design specialists it became clear that every airport is unique. As a specialist from NACO stated, "if you have seen one train station, you have seen all train stations. If you have seen one airport, you have seen just *one* airport." Every airport design differs due to the numerous different criteria. As the goal of the model developed for this thesis is to design a generic design for BHS's for many different airports, it is important to research the criteria so that they can be incorporated into the model.

This chapter addresses the fifth sub-question: *Which criteria impact the design of baggage handling systems and how can these criteria be taken into account when modeling the conceptual design?* The chapter is structured as follows. The first section explains the method used to gather information necessary for the first sub-question. The next section analyzes various design rules that are used to form the scenarios. Section 6.3 discusses the implementation of the design rules in the model and the last section evaluates the implementation of the rules.

6.1 Interviews

As the users of the model are the BHS designers from NACO, the criteria is researched by interviewing experts from NACO. Interviews can be useful for collecting detailed information. The researcher has direct control over the subjects and has the opportunity to go further into detail and ask follow up questions. Moreover, interviews are generally easier for the respondent, especially if the answer concerns opinions. However, interviews can be time consuming. Furthermore, it can be hard to compare interviews and to use the data for research.

There are three different formats of interviews: structured, semi-structured, and unstructured. Structured interviews are held by asking interviewees a series of pre-determined questions in the same order, leaving no room for extra questions or comments. If no questions are prepared prior to an interview, this is considered an unstructured interview. This can be associated with a high level of bias and can be difficult to compare. Semi-structured interviews have characteristics of both forms, where the interviewer prepares a set of questions, but during the interview there is room to clarify and/or expand certain issues.

The interviews for the design choices in this thesis are semi-structured. Several subjects are prepared, but there is room to expand on certain aspects of the subjects. This interview technique fits the research since every BHS designer uses his own experience/habits/opinions in the design, and the model needs to contain the elements that the designers agree on. By doing a semi-structured interview, the BHS designers can explain their thoughts and opinions about certain subjects. The users of the model are the BHS designers at NACO. Half of all designers are interviewed to gather the data. The interviews are checked by the interviewees to ensure the validity of the answers.

There is a pitfall from incorporating per airport specific information into a generative design model. The model is supposed to design optimal, but also original BHS designs. By incorporating airport specific criteria, the model should not provide the same design for every airport due to the criteria restrictions. Thus a balance needs to be found between incorporating the important specific airport constraints to create a realistic scenario and creating a tunnel vision scenario which is (almost) the same for every airport. This balance is found by only incorporating the most important design rules that the experts could reach a consensus on. A summary of the interviews is provided in Appendix D.

6.2 Airport design decisions

The expert interviews resulted in design rules which can be used to create generative BHS designs. These design rules are grouped in a couple of design categories. Each category is discussed in the following sections. Figure 6.1 shows the legend for the figures in the following sections.

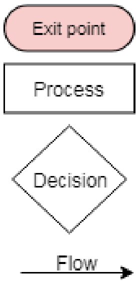


Figure 6.1: Legend for the design decision flow diagrams.

6.2.1 Order of placement

The order in which the subsystems are placed can have a big impact on the BHS design. For instance, if an EBS (which is often a very large system) is placed first in the middle of the terminal, in such a way that make-up can only be placed in a far corner. This can cause longer transportation times, higher IST and higher costs. If a low OPEX is required, the location of make-up is more important than the location of EBS. However, placing make-up (or another system) first, can change the entire BHS concept design. It is thus very important to choose an order of placement that helps reach the goals of that airport. Through expert interviews the following design rules are made:

I. It is important that make-up is placed as close a possible to the aircraft. Not only because make-up is time critical, but also because you don't want the CO2 emissions from the vehicles inside the terminal. Thus make-up needs to be placed as one of the first subsystems.

II. The placement of screening is also important. First of all often because of legal requirements, but also because the screening equipment is very big. Furthermore, all three levels of screening should be placed close to each other. They could even be placed as one system. So, screening level 1 does not have first priority in placement order, but it is preferred if it is placed sooner rather than later.

III. At what time the EBS is placed depends on the wishes and experience of designers. One designer states that if the demand for EBS is high, the EBS is often placed in a different part and can thus be placed last. On the other hand, another designer states that the bigger the airport is, the higher the desired to place the EBS sooner rather than later, as the demand for EBS will be higher. Another designer states that the time that EBS is placed, and even if an EBS is desired, depends on the number of transfer passengers. The higher the amount, the higher the need for a EBS. Where the EBS needs to be located then, depends on the number of transfer passengers with a long layover. Concluded from this is that the placement of EBS depends on the wishes of the BHS designer.

IV. The placement of sorting is the most flexible and thus can be placed last.

V. The capacity of a subsystem could be a determining factor in the order of placement. As a system cannot exceed the IST, which is linked to capacity.

VI. The required space hangs together with the capacity, as usually a system with a higher capacity requires more space. However, also this could be used to determine the order of placement, especially in tight terminals.

Figure 6.2 shows these placement rules in a flow diagram which can be used to determine the order of placement. The diagram goes as follows. If the client has a specific preference in order, follow the order of the preference. This needs to be modelled by hand. If not, first make-up (MU) is placed which is followed by the first level of screening (HBS1). The next decision is to choose a placement order system, either capacity or space requirements. To determine the placement order, another decision needs to be made about the placement of the EBS. These two decisions lead to one of the four placement orders.

6.2.2 Centralized versus decentralized subsystems

The model from Vijlbrief (2019) is only able to design centralized BHS designs. A centralized BHS is a system where all subsystems of the BHS for an airport are placed once, in a central point of the terminal. In a centralized system all baggage needs to go through these systems at the central place, even though it might be a detour and take more time. In a decentralized system one or more subsystems are divided over the area of the airport. For instance, if there are two terminals at an airport, make-up could be divided into two systems, each one placed in a terminal covering the baggage of that terminal. A decentralized system could reduce the IST of baggage, but at the same time could increase capital expenditure because more equipment is needed. Furthermore, it can reduce the maximum capacity usage of an airport when peak hours

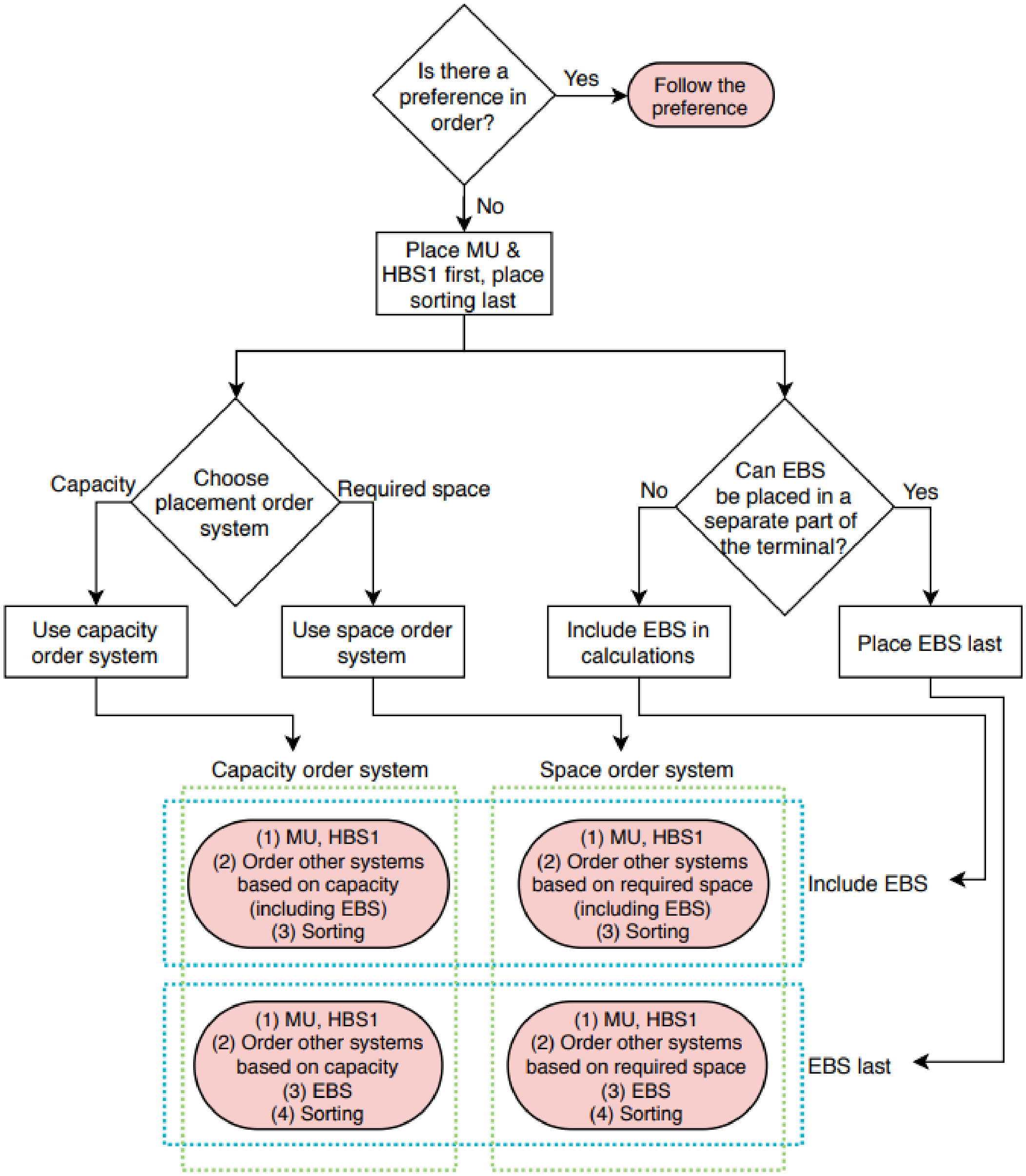


Figure 6.2: Design decision flow diagram of the placement order.

are not evenly divided between terminals. The expert interviews have led to the following design rules:

I. Preferably all systems are placed as a centralized system because BHS equipment is expensive. However, if a centralized system creates a gigantic spaghetti of transportation lines, a decentralized system can be more efficient. But, if it is possible it is preferred that BHS follows a centralized system.

II. The more transfer bags inside a terminal, the higher the demand for a decentralized system.

III. The trade-off between a centralized and decentralized system is: how big the distance is between transfer offloading and make-up.

IV. If there are a lot of transfer passengers inside a terminal, screening level 1 should be decentralized.

V. If make-up is decentralized, screening level 1 should be decentralized.

VI. If all baggage in the BHS system needs to be 'customs cleared', meaning that all baggage has passed the screening tests, an extra screening level 1 system is needed for the transfer baggage. Thus, decentralizing screening. If uncleared baggage is allowed inside the BHS, the baggage goes into the sorting system and from the sorting machine to the screening. This option is cheaper qua equipment, since less equipment is needed.

VII. If a baggage handling system should be centralized or decentralized, depends on three things:

    i. The terminal shape: if there are several terminals far apart from each other, a decentralized system is more useful than a centralized.
    ii. The gate layout: the further the gates are apart from each other, the efficiency of a centralized system goes down.
    iii. The number of handling operators: if there are two or more handling operators at one airport, which is often the case when there are several alliances at an airport, make-up is often decentralized.

Figure 6.3 shows the flow diagram which can be used determine when a decentralized system is preferred versus a centralized system. When the client has a preference for a decentralized system, follow the preference of the client. If not and there are no transfer passengers, keep the entire system centralized. When there are transfer passengers, the next question is how long the handling distance is. If the distance from transfer offload through screening and back to make-up is big, it is useful to decentralized make-up, transfer offload and screening level 1. If the distance is small the follow up question is if the baggage needs to be customs cleared before it enters the BHS. This is an airport specific requirement. If baggage needs to be clean, screening level 1 should be decentralized, otherwise the entire system can be centralized.

6.2.3 Optimal floor level

As already mentioned, each airport is different. This leads to different subsystem layouts for every airport. However, there are a lot of similarities between airports on which level each subsystem is placed. This can be explained by the fact that the baggage follows a flow from subsystem to subsystem and that ideally subsystems are placed near the entry and exit points in the system. Figure 6.4 shows some typical airport terminal layouts. The dotted lines indicate the baggage flow.

However, no information can be found on what the optimal floor level is for each subsystem. The interviews with NACO experts have shed more light on this subject and have led to the following design rules:

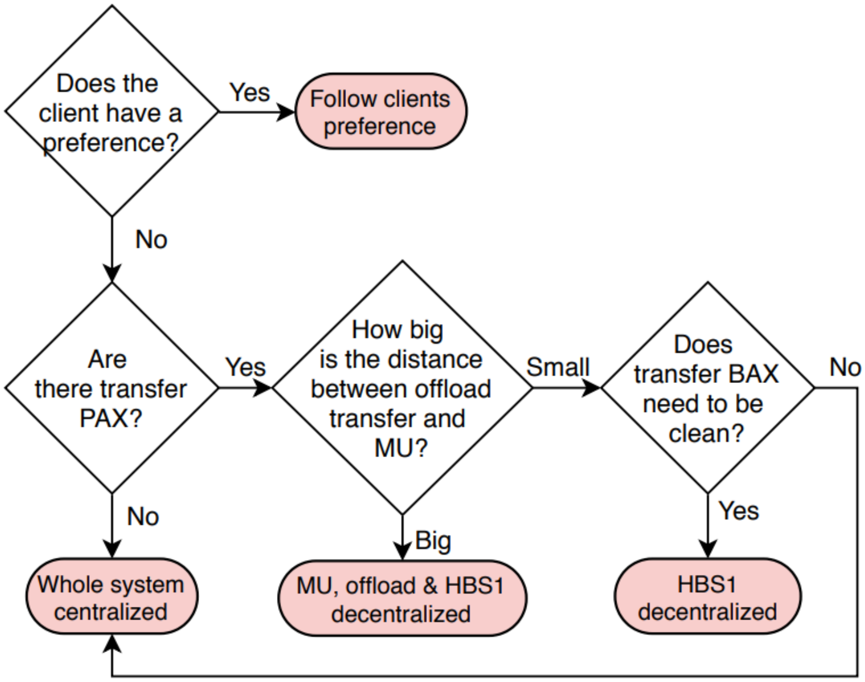


Figure 6.3: Design decision flow diagram of centralized versus decentralized systems.

I. All operations including driving vehicles, thus make-up and offloading, are preferably placed on the same level.

II. Make-up and offloading are preferably placed on the same level as the aircraft outside (from now on called 'aircraft level'). If there is not enough space for both subsystems, it is more important that make-up is placed on aircraft level due to two reasons:

  i. Make-up is time critical, and therefore more important to have the shortest possible route from make-up to the aircraft.

  ii. The vehicles driving from and to the aircraft have a different load. The vehicles driving from make-up to the aircraft are full on the way over and empty on the way back. For offload this is the other way around, the vehicles from offload to the aircraft are empty on the way over and full on the way back. As it is more difficult for full vehicles to drive uphill, it is more important that make-up is on aircraft level.

III. Is the client willing to let the vehicles drive on a ramp from make-up to the aircraft and from the aircraft to offloading? If yes, make-up and offloading can be a level beneath the aircraft level. If not, make-up and offloading must be at the same level as the aircraft level.

IV. Sorting is preferred above make-up rather than below make-up because:

  i. The airport can use the space above make-up, which is otherwise often not used.

  ii. One supplier can be in one room instead of having to move between floors.

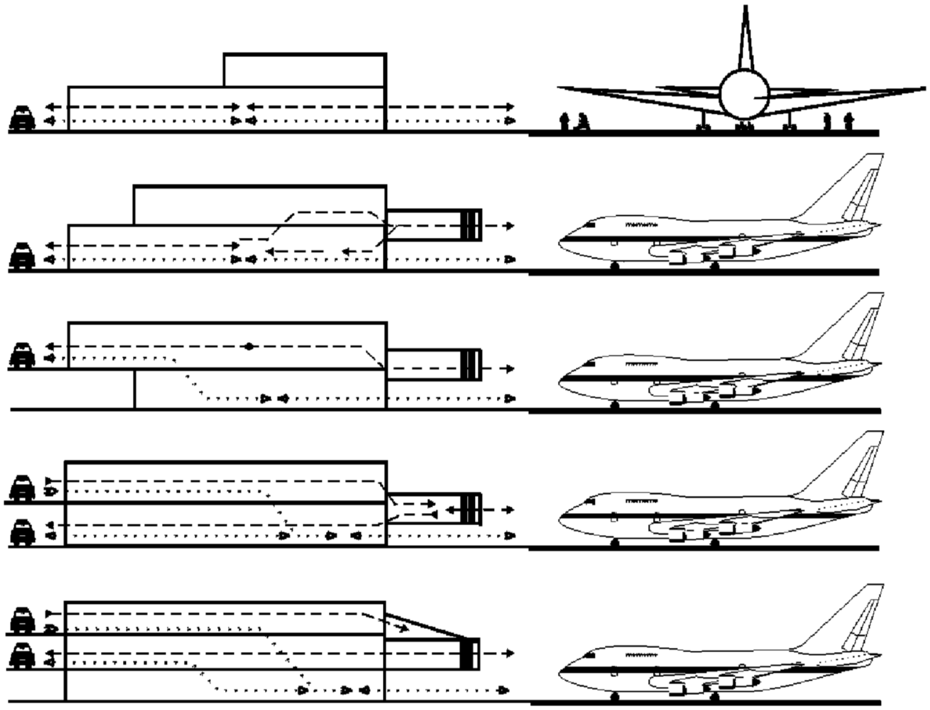


Figure 6.4: Typical airport terminal layout for a different number of levels, retrieved from Kazda and Caves (2015, p. 247).

   iii. The tender for baggage is often before the tender for the building. Because of this it is very difficult to reserve room for sorting in a basement, because often just a part of the basement is then used (based on the efficiency of the tender). While if sorting is above make-up, the left over room can be used for something else.

V. If there are multiple floors, reclaim should be a level below check-in. Actually two levels, because usually big spaces such as reclaim need a double ceiling for the space to feel open.

VI. Check in and reclaim are preferably not on the same level as the subsequent (or previous for reclaim) subsystem. This is because otherwise the baggage needs to go to another floor to transport, and then back to the same floor.

VII. Screening is preferably placed on the ground floor due to two reasons:

   i. Screening machines are very heavy.
   ii. If the bag contains an explosive, it needs to be brought outside as fast as possible.

VIII. It does not matter much on which floor EBS is placed. If there is room on the ground floor, start searching there.

Figure 6.5 shows the flow diagram which can be used to determine on which floor level the model is going to try and find a location. The diagram can be read as follows. If the client has a preference in floor level, that preference should be followed. If not, the number of levels the terminal has available for baggage handling systems is the changing factor. Which floor level is optimal for each subsystem can be found in Figure 6.5. Furthermore, each floor level is ordered based on importance. For instance, in a two level terminal on the ground floor (level aircraft) the most important system that should be placed on that floor is make-up, followed by transfer offload, screening and EBS.

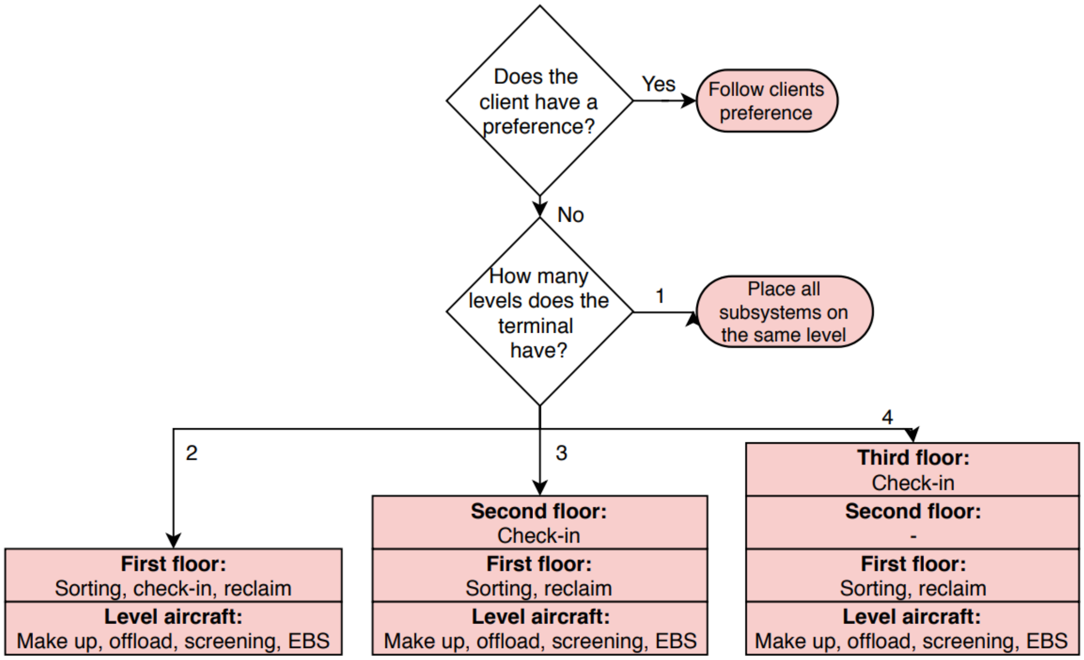
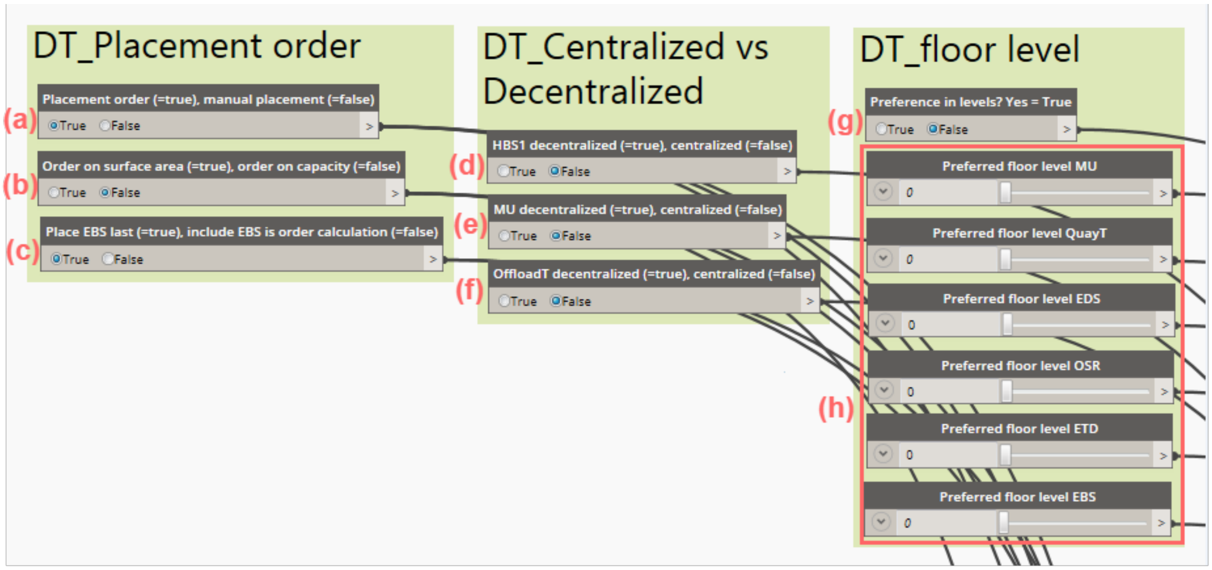


Figure 6.5: Design decision flow diagram of the desired floor level for subsystems.

6.3 Model improvement

For the placement order several switches are added in the model. These switches are used to constrain the model based on the airport specific design rules. The switches are grouped per design flow diagram that are discussed in the previous sections. The switches are shown in Figure 6.6. The settings of these switches are used as the standard implementation.

The first switch (a), which belongs to the order of placement design decision, is the option to choose manual placement order. This is when the client has a preference in placement order (switch is True) or to use a placement order system (switch is False). If a placement order system is chosen, the next switch (b) represents which system is chosen: capacity or required space. If the capacity system is chosen, the subsystems are ordered from highest capacity to lowest capacity. If the required space order system is chosen the subsystems are ordered from most square meters required to the least. However, as Figure 6.2 showed, make-up and screening level 1 are always placed first. So, the placement order systems are only used to determine the remaining subsystems. The last switch (c) is used to either include the EBS in the placement



Placement order (=true), manual placement (=false): ● True ○ False

Order on surface area (=true), order on capacity (=false): ○ True ● False

Place EBS last (=true), include EBS is order calculation (=false): ● True ○ False

HBS1 decentralized (=true), centralized (=false): ○ True ● False

MU decentralized (=true), centralized (=false): ○ True ● False

OffloadT decentralized (=true), centralized (=false): ○ True ● False

Preference in levels? Yes = True: ○ True ● False

Preferred floor level MU: 0

Preferred floor level QuayT: 0

Preferred floor level EDS: 0

Preferred floor level OSR: 0

Preferred floor level ETD: 0

Preferred floor level EBS: 0

Figure 6.6: Switches to customize BHS designs implemented in Dynamo.

order system or to place EBS last. These three switches enable all options that are shown in the flow diagram in Figure 6.2.

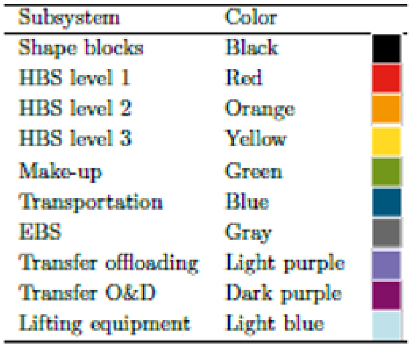
The second set of switches (the middle switches in Figure 6.6) represent the flow diagram from a centralized versus a decentralized system (shown in Figure 6.3). In this set there are three switches: screening level 1 (EDS) decentralized (d), make-up decentralized (e) and transfer offload decentralized (f). Each subsystem can be chosen to be decentralized and the subsystem is then placed accordingly. If the EDS machines are decentralized, the machines are split up between check-in and the aircraft point(s). Aircraft points are the places in the BHS terminal where the baggage from the aircraft comes into the BHS hall and leaves the BHS hall to go to the aircraft. Thus, the places where routing is possible between the BHS hall and the aircraft. If there are several aircraft points, the EDS machines are split up again between these points. If make-up is decentralized, the make-up equipment is divided over the aircraft points. If transfer offload is decentralized, the equipment is also split up between the aircraft points.

The last switch (g) is to choose between manual floor level or standardized floor level. The standardized floor level is based on expert knowledge from the interviews and is shown in Figure 6.5. It is important to mention that in the model sorting is automatically placed on top of make-up. Furthermore, check-in and reclaim are already predefined on both the location and floor level. These three subsystems are thus already implemented in the model and cannot be changed. If the client has a preference of floor level, these can be changed using the sliders (h).

6.4 Evaluation

To evaluate the new model with switches, the model is tested for Aruba International Airport (AUA) to see if it acts as expected. The full results are discussed in Appendix F.2. The most important results will be reviewed here.

First, the order system that is used affects the design. The higher labeled subsystems are placed earlier, and the results show that they have a more desirable location than the lower labeled subsystems (see Figure 6.8 (a) and (b)). The legend in Figure 6.7 shows which color is which subsystem. At what time the EBS is placed does not seem to effect the spacial planning of AUA. Though, this can be explained by the fact that the EBS is placed in a spot that is not optimal for the other subsystems. This, that the design does not change, can demonstrate the opposite of what the designers have stated in their interviews, but could also only be valid for AUA and not all other airports. Even if it demonstrates that at what time the EBS is placed is not as important as the designers have stated, this could also be due to the fact that a model builds a design based on rules and requirements, while designers base their design a lot on experience. Either way, this still needs to be researched in more detail. Furthermore, the subsystems that are placed decentralized are divided equally over the aircraft outlet points (top-left and top-right corner, 1st floor), just as expected (see Figure **??** (c)). Last, if a specific floor level is requested for a subsystem, the system is also placed on that floor.



Subsystem	Color	
Shape blocks	Black	⬛
HBS level 1	Red	🟥
HBS level 2	Orange	🟧
HBS level 3	Yellow	🟨
Make-up	Green	🟩
Transportation	Blue	🟦
EBS	Gray	⬛
Transfer offloading	Light purple	🟪
Transfer O&D	Dark purple	🟪
Lifting equipment	Light blue	🟦

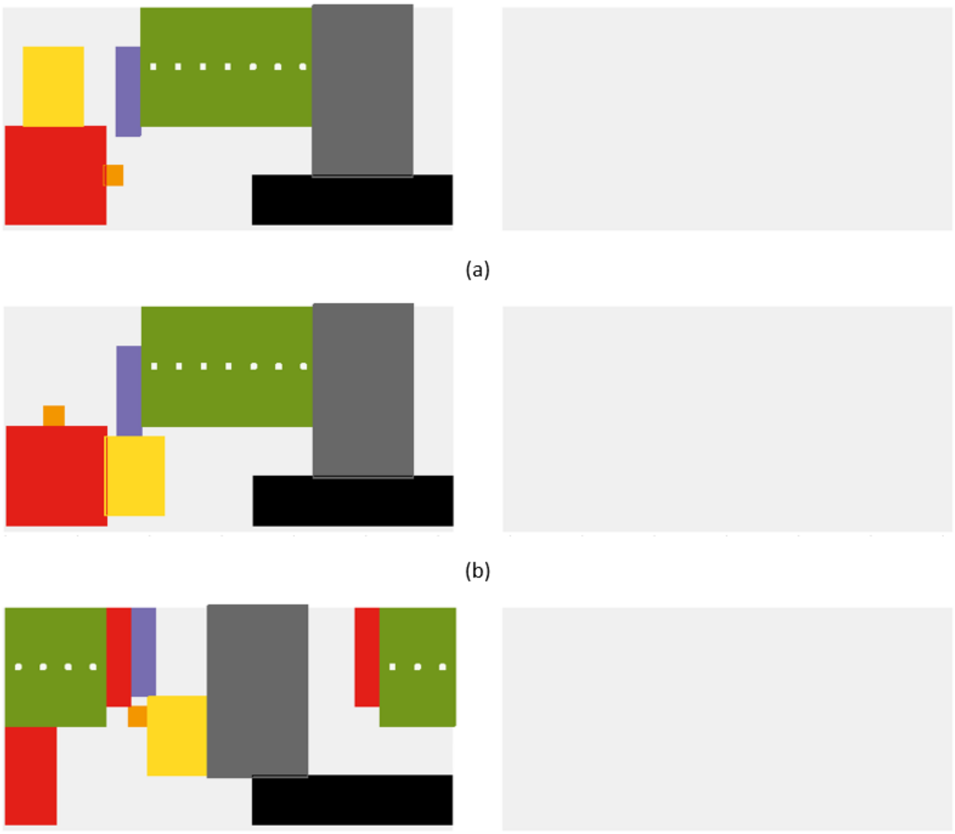
Figure 6.7: Legend for the 3D drawing of a BHS.

6.5 Chapter summary

This chapter answers the question: *Which criteria impact the design of baggage handling systems and how can these criteria be taken into account when modeling the conceptual design?* The raw data for the criteria was gathered through semi-structured interviews with approximately 50% of the users of the model, the BHS designers at NACO. The BHS designers often make design decisions based on their personal experience and opinions. As the model is a generic model for all the designers, and the design needs to be optimal but also generic, only the design rules mentioned by multiple interviewees are included.

Three important design rule categories emerged from the interviews, (1) the order of placement, (2) centralized versus decentralized subsystems, and (3) the optimal floor level.

- The order of placement can change the entire BHS design and impacts the efficiency and cost. Selecting the right placement order to achieve the goals of the specific airport, is therefore extremely important. The following rules apply for all airports. Make-up and


(a)

(b)

(c)

Figure 6.8: Subsystem placement capacity optimized, where (a) is based on the size of the capacity, (b) on the size of the required area, and (c) where with make-up, screening level 1 and offloading are decentralized.

screening level 1 are always placed first. Sorting is always placed last. The order of the other subsystems can be based on one of the placement order systems, capacity, required space, and the designers experience and opinion on the EBS.

- A choice needs to be made to either centralize or decentralize the subsystems. A decentralized subsystem could reduce the IST, but could increase capital expenditure because more equipment is needed. Furthermore, it can reduce the maximum capacity usage when peak hours are not evenly distributed between terminals. The critical factor selecting a centralized or decentralized system is the number of transfer passengers. In addition, a large distance between transfer offload and make-up can cause designers to choose a decentralized system. Finally, some airports require decentralized screening when transfer baggage needs to be cleared by customs.

- The optimal floor level is selected for each subsystem. The interviews illustrated that designers prefer that all subsystems are placed on the ground floor. However, the most ideal terminal has four levels, where make-up, offload, screening and EBS are placed on the ground floor, sorting and reclaim on the first floor, and check-in on the third floor.

The model is improved to include these rules as design options. A flow diagram for each category can be used to determine which settings to use for each scenario. Evaluation of the model showed that these settings can achieve the desired result. To summarize, there are several criteria that impact the BHS design. These criteria are the order of placement, centralized versus decentralized subsystems, and the optimal floor level. Each criteria can be specified in the model settings.

Chapter 7

Model extension for brownfield airports

There are two types of BHS design projects, greenfield and brownfield. A greenfield project is when the BHS design starts from scratch. All subsystems are placed in an empty, or nearly empty, terminal. A brownfield project is when a BHS already exists but needs to be expanded or renewed. So, some or all of the subsystems are already available, but need to be redesigned for a higher capacity, shorter IST, a newer system or other reasons.

Many airports face the simultaneous demands of expansion, renewal and replacement of systems while they are still operational. These projects are brownfield projects. Up until now the model could only be used to design a greenfield BHS. To increase the usefulness of the model, it needs to be developed to work for brownfield airports. When designing a brownfield BHS, there is an extra set of requirements. This chapter addresses the following sub-question: *How can the model be adapted to be able to include brownfield baggage handling systems?* The chapter is structured as follows. Section 7.1 provides background information on designing brownfield airports. Section 7.2 elaborates on improvements to the model to include the designs of brownfield airports. Section 7.4 shows the implementation of the new model for Schiphol Area A BHS and evaluates the model. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

7.1 Designing brownfield airports

In the past years the work of the BHS designers at NACO mainly consisted of redesigning brownfield projects. Ten of the twelve recent projects were brownfield designs. For brownfield designs it can be a challenge to fit the system in, an often small and restricted, terminal. For instance, the redesign of the BHS of Aberdeen airport in North East Scotland in 2013, had to accommodate the baggage from additional check-in desks in a small and restricted baggage hall. The current BHS could process 10 bags per minute, while the new BHS had to meet 15 bags per minute. In order to meet this increased demand of 50%, the BHS had to be designed to increase the capacity, while minimizing the surface area. At another brownfield project, Amsterdam Airport Schiphol (AAS) which is a lot bigger than Aberdeen airport, NACO has been involved in the design and redesign of the BHS in every part of the airport. During every redesign the airport continued to be operational, while increasing the capacity and improving the systems. As most of the BHS designs are brownfield designs, it is important to take this into account in the model.

For airports, there are two financial advantages of brownfield projects over greenfield projects. First, as the projects are executed in phases, the brownfield airports have the possibility to remain operational. This ensures revenues during the project. Second, as some of the BHS structure already exists, the CAPEX is usually lower. However, this is only the case if the added transportation between the system is not more expensive then the installation cost of all the equipment.

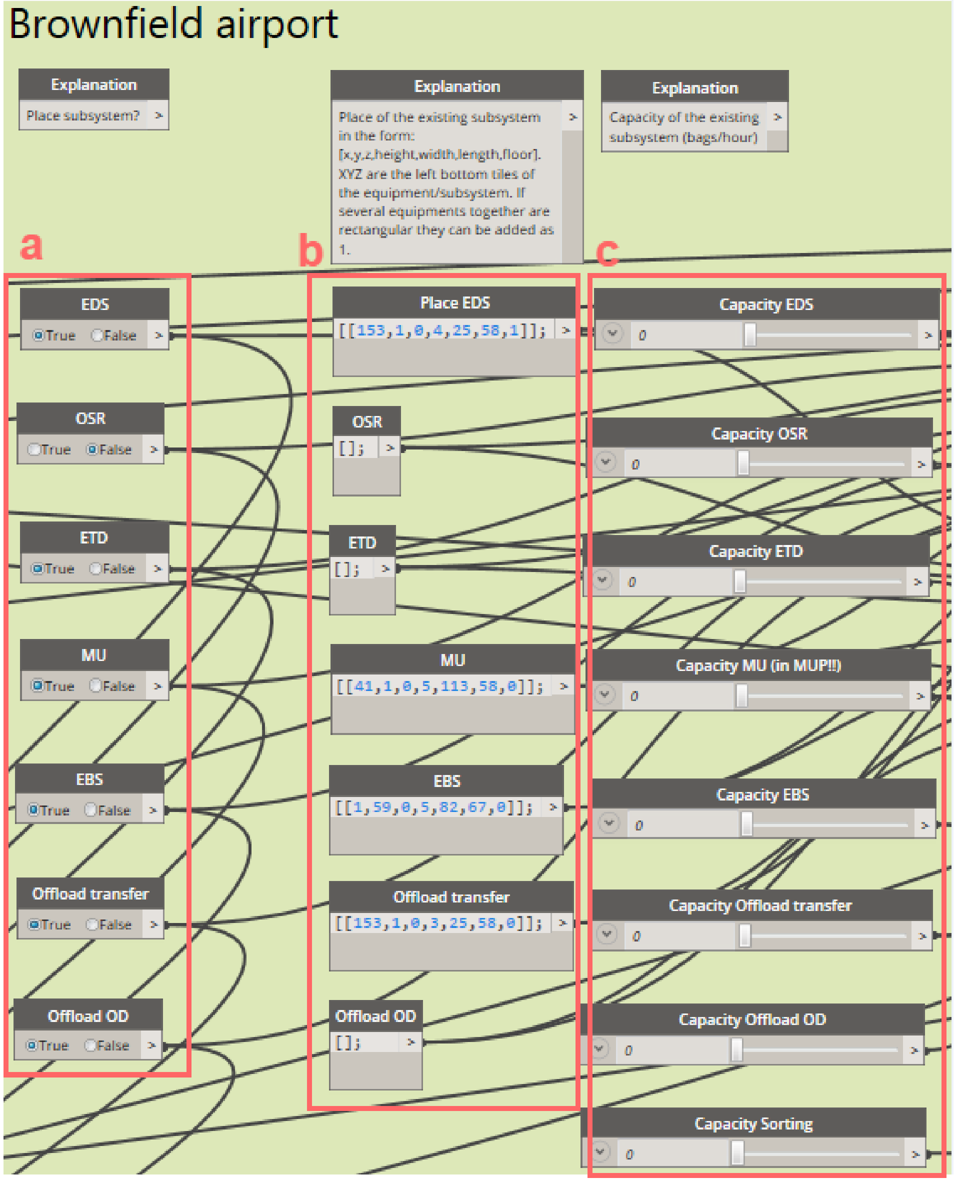
However, designing a brownfield BHS can cause difficulties. In brownfield projects the structure and (some) BHS subsystems already exist. When expanding an existing design, this influences the new design. For instance, if make-up requires a higher capacity but there is no space available next to the existing make-up system, a new system needs to be built. If this is the case, baggage needs to be able to be transported between the two systems. The two systems need to be able to work together. On the other side, if there is space available to extend make-up inside the existing structure, it needs to be possible to build inside the structure without disturbing the current BHS operations. Next, if the previous design did not take expansion of the BHS into account, the system could become inefficient when expanding. Third, the current BHS needs to stay operational. Especially for airports that are already operational, systems are difficult to change and interruptions can be very costly (Rengelink & Saanen, 2002). This can make the building process more difficult. Last, for every subsystem there are different types of transport equipment possible. The equipment can use a belt conveyor, DCT or DCV (see Appendix B) to transport baggage in and between subsystems. The transportation between subsystems needs to use the same transportation type or have a hand over point in between, for the subsystems to be able to work together.

There are also modeling difficulties. It has to be possible to fixate subsystems to a certain location. Furthermore, these fixed subsystems should be the leading factor in determining the location of the extended subsystems. The subsystem should be placed as close as possible to the existing subsystem. Moreover, the different systems have to be operational together. Though, as interruptions in the operational process are very costly, it is important to evaluate the BHS designs. Using the model to build brownfield conceptual designs and being able to compare these different scenarios, is therefore of importance for the development and maturation of these airports.

7.2 Model improvement

Several improvements to the model are made in order to apply it to design brownfield projects. Figure 7.1 shows the added model parts. First, the location of existing subsystems needs be fixed to a point in the terminal. This is done by inserting the coordinates, width, length, and height of the subsystem at number (2) in Figure 7.1.

Second, the required capacity needs to be calculated. Just as greenfield projects, a flight schedule can be used to calculate the required capacity of the entire terminal. However, for brownfield airports the existing subsystems can already handle a certain capacity. This capacity needs to be subtracted from the total capacity to calculate the capacity requirements of the new



Explanation: Place subsystem?

Explanation: Place of the existing subsystem in the form: [x,y,z,height,width,length,floor]. XYZ are the left bottom tiles of the equipment/subsystem. If several equipments together are rectangular they can be added as 1.

Explanation: Capacity of the existing subsystem (bags/hour)

EDS: ● True ○ False
OSR: ○ True ● False
ETD: ● True ○ False
MU: ● True ○ False
EBS: ● True ○ False
Offload transfer: ● True ○ False
Offload OD: ● True ○ False

Place EDS: `[[153,1,0,4,25,58,1]];`
OSR: `[];`
ETD: `[];`
MU: `[[41,1,0,5,113,58,0]];`
EBS: `[[1,59,0,5,82,67,0]];`
Offload transfer: `[[153,1,0,3,25,58,0]];`
Offload OD: `[];`

Capacity EDS: 0
Capacity OSR: 0
Capacity ETD: 0
Capacity MU (in MUP!!): 0
Capacity EBS: 0
Capacity Offload transfer: 0
Capacity Offload OD: 0
Capacity Sorting: 0

Figure 7.1: Added switches in Dynamo to accommodate brownfield airports.

system. The existing capacity for every subsystem needs to be inserted at (3) in Figure 7.1.

Next, at a brownfield airport, not all subsystems have to be placed. For instance, OSR is a room with computer screens which are used to visualize the screened baggage that is flagged at the EDS machines. If OSR already exists somewhere else in the airport, it does not need to be placed again. In the model the option is added to leave out certain subsystems (see (1) in Figure 7.1).

Last, to adjust the model for brownfield airports, some placement rules change. When a subsystem already exists somewhere else in the terminal and more equipment is added to that subsystem, the equipment is placed as close as possible to that subsystem. To accommodate this rule, the optimal starting point for new equipment is changed to be placed near the existing equipment. If there is no existing equipment for a subsystem, the greenfield rules apply.

The brownfield model does have a constraint. As both the brownfield placement model and the greenfield decentralized placement model depend on a different optimal starting point that differs from each other, the two models cannot be combined. If an airport is a brownfield project, and also subsystems are preferred to be decentralized, the decentralized part should be modelled as a greenfield project.

7.3 Cost cone of uncertainty

To analyze how well the brownfield model performs, the definition of a valid solution needs to be defined. It is impossible to fully validate the model. Yet, if the model outcome is close to the actual design, it has high value for the BHS designers. The most important evaluation of a BHS is the CAPEX. Defining the accuracy of the model for the CAPEX is therefore necessary.

However, comparing the estimated cost of a conceptual design with the actual full design is not realistic. The cost cone of uncertainty by Boehm (1984), shown in Figure 7.2, can be used to compare the two designs. The horizontal axis shows the different phases of design and the vertical axis the degree of error that is accepted during each phase. The output of the conceptual design is very early in the process and therefore falls in the ’concept of operation’ phase. This means that the model outcome can be inaccurate by a factor 2.

The exact CAPEX values of a BHS of an airport are usually confidential information. Therefore it is not possible to show the CAPEX and design of the actual design. Though, some information on the actual design is provided in the confidential appendix A.

7.4 Evaluation: Schiphol Area A

The model is evaluated through a case study of one of the piers at Amsterdam Airport Schiphol (AAS). AAS is one of the largest hub airports in Europe. In 2018, AAS had 327 direct destinations, transported 71.1 million passengers of which 36.6% were transfer passengers, and almost 500 thousand air traffic movements (Schiphol, 2018). The BHS at AAS handles around 70 million baggage items annually, which is about 200 thousand bags every day, and it can even be as high as 300 thousand bags on the busiest day of the year. The BHS of AAS is located at different parts of the airport (Figure 7.3). The BHS consist of the following areas: (1) BHS South, (2) BHS Central, (3) BHS West, (4) the new Area A BHS, (5) BHS Pier D which includes transfer screening, (6) BHS Pier E which includes offloading, and (6) the backbone of AAS which connects the different baggage handling systems.

The project for NACO is to design the Area A BHS. Area A BHS needs to be combined with the Handling Area South to create an integrated homogeneous operation. The terminal layout for this project is shown in Figure 7.4. Figure 7.5 shows the location of the subsystems in the South BHS terminal.

Several scenarios are run to evaluate the conceptual design of the BHS. For AAS it is important

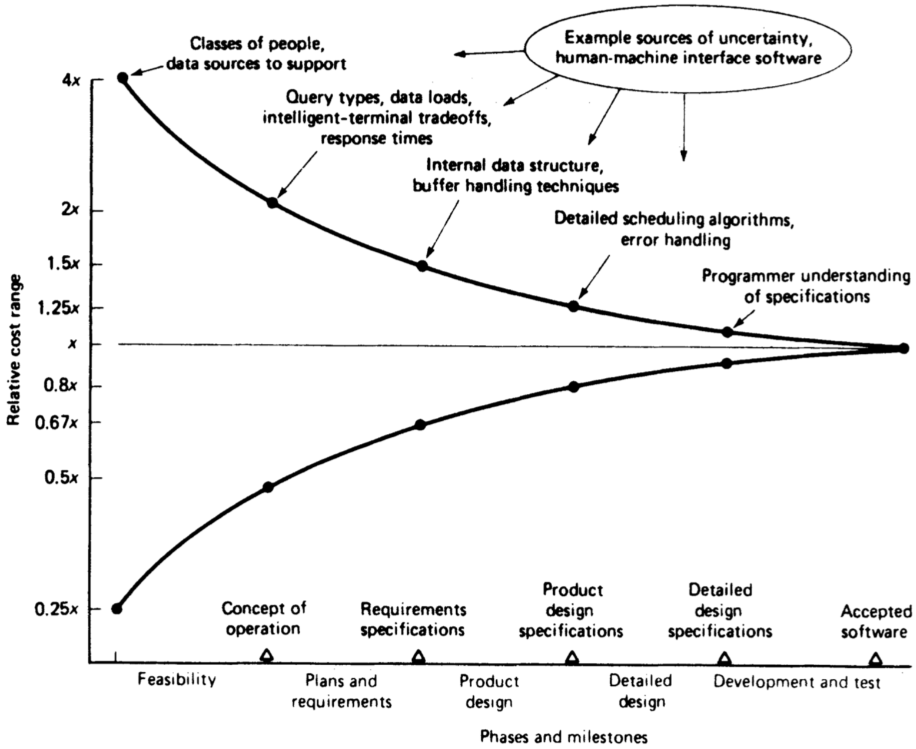


Figure 7.2: The cost cone of uncertainty by Boehm (1984, p. 8).

that the CAPEX is as low as possible. Though, there is another objective that is important for the design. The main carrier at the airport, Koninklijke Luchtvaart Maatschappij (KLM), wants the design to be as automated as possible with a minimum number of operators. Furthermore, AAS has been developing and innovating over the past decades and wants a BHS design that can accommodate this. Additionally, AAS prefers designs without laterals.

7.4.1 Model outcome

The following scenarios are run: (1) 100% CAPEX, (2) 100% CAPEX, no laterals, (3) 60% CAPEX, 40% max LoA, (4) 60% CAPEX, 40% min operators, (5) 40% CAPEX, 30% max LoA, 30% min operators, and (6) 10% growth (60% CAPEX, 40% max LoA). In the first scenario, laterals are chosen for make-up equipment. As Schiphol prefers designs without laterals, this equipment is removed from the equipment list for the other scenarios. The scenarios are run with the standard settings (namely, order based on capacity, EBS placed last, no subsystems decentralized). Figures 7.6-7.7 show the outcome of the six scenarios based on the decision variables and capacity of subsystems.

All scenarios have the same check-in, screening, EBS and offloading equipment. Scenario 2 (100% CAPEX, no laterals) and 4 (60% CAPEX, 40% min operators) are exactly the same. Thus without optimizing on the minimum number of operators, a low number of operators is already chosen. These two scenarios, score similar to scenario 1 (100% CAPEX) except that it has a bigger system area. Scenario 3 (60% CAPEX, 40% max LoA) scores worse than scenario 2 (100%

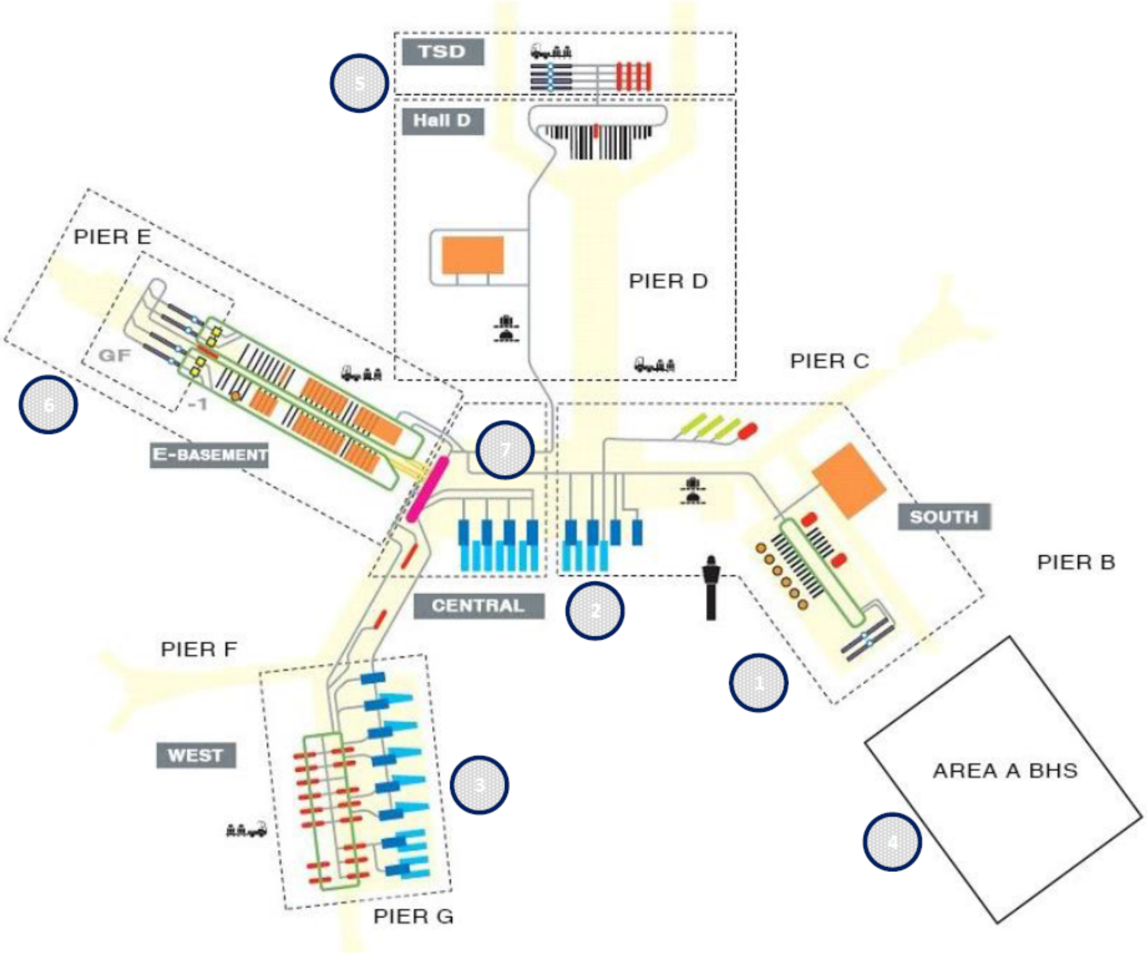


Figure 7.3: BHS at AAS.

CAPEX, no laterals) on every decision variable. In scenario 5 (40% CAPEX, 30% max LoA, 30% min operators), a different transportation system is chosen. As this system costs €4 million more. this scenario has a higher CAPEX. However, the LoA is the highest and the number of operators the lowest. Scenario 6 (15% growth) scores the lowest on all decision variables, which is as expected as it requires 15% extra capacity. Figure 7.7 shows in which subsystems capacity is added to accommodate this growth.

Even though all scenarios have different outcomes, the placement in the terminal is similar (see Figure 7.8 and the legend in Figure 7.9). Make-up is placed on the bottom left in Area A and transfer offloading is placed right beside it. O&D offloading is next to transfer offloading, and EBS on the right on the the ground floor. On the first floor the EDS machines are placed on the side of the existing EDS and ETD right beside it.

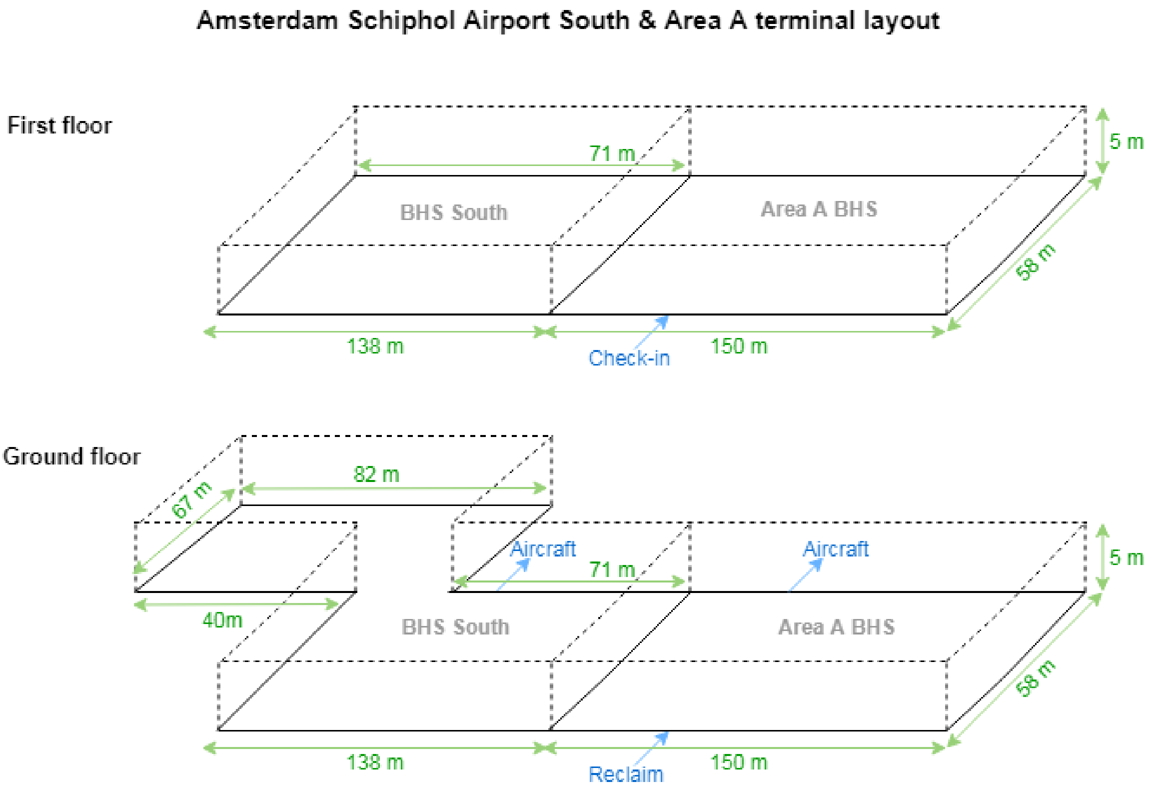


Figure 7.4: Terminal layout the South terminal and Area A at AAS.

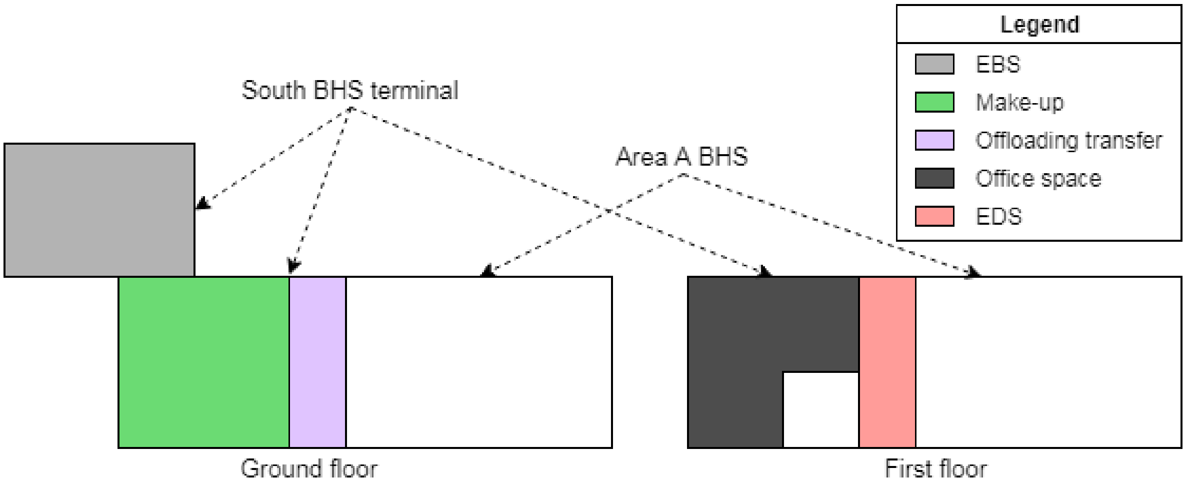


Figure 7.5: Location of the existing subsystems in the South terminal at AAS.

7.4.2 Comparing the actual design

Just as for many airports, the actual designs and costs of the BHS design for Schiphol Area A BHS are confidential. The layout of the actual designs of Schiphol Area A are presented in the

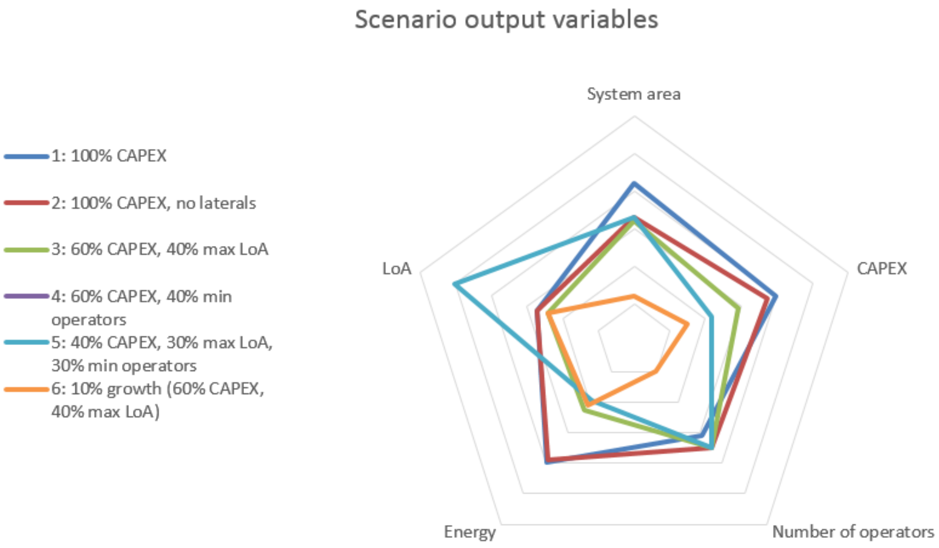


Figure 7.6: Spider chart of the decision variables of the scenarios of Area A BHS at AAS (more outward is better).

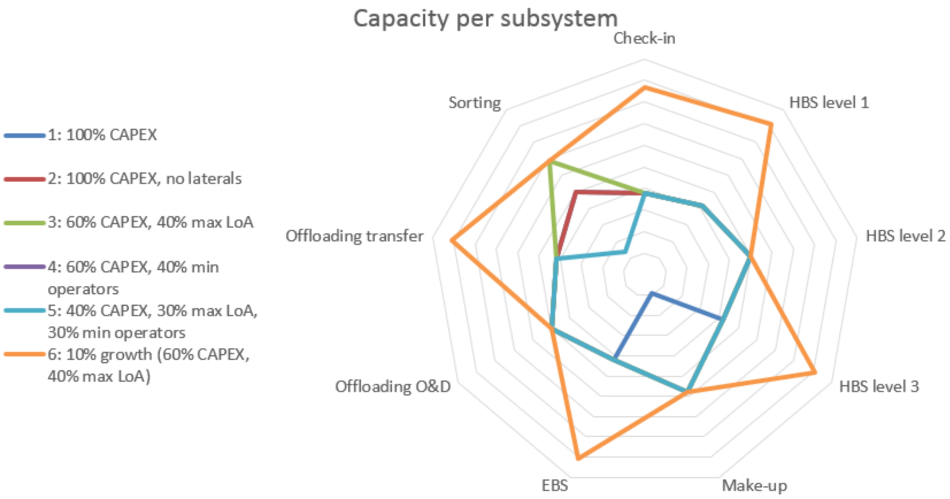


Figure 7.7: Spider chart of the capacity of the subsystems of the scenarios of Area A BHS at AAS (more outward is better).

confidential appendix (see Appendix A). In this chapter only the conclusion of the actual design versus the model outcome is discussed.

The CAPEX in the model differs between 15% and 33% from the CAPEX of the actual design. As the cost cone of uncertainty states, the CAPEX can vary with a factor of 2. Thus according to the cost cone of uncertainty these scenarios can be valid solutions. Also the number and type of equipment are similar to the actual design.

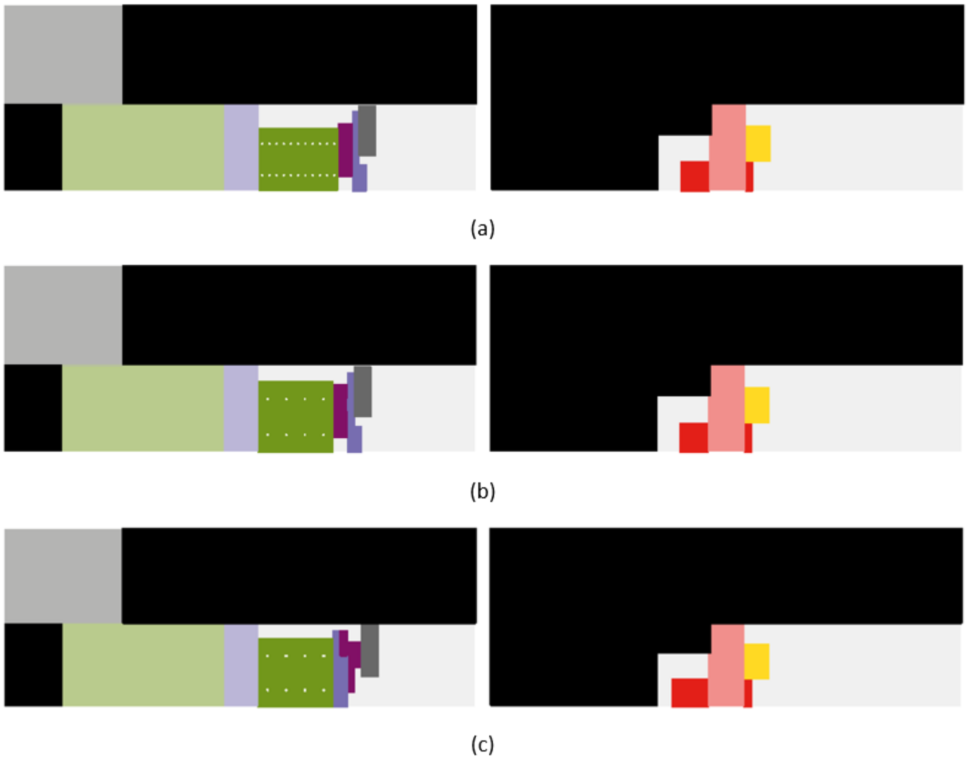


Figure 7.8: Placement of the scenarios of Area A BHS at AAS. (a) scenario 1, (b) scenario 2-5, (c) scenario 6.

Figure 7.9: Legend.

The placement of the two designs show similarities, but also differences. Even though the placement designs are somewhat different, they do not differ a lot. The biggest difference is the area of the terminal that is used for the conceptual design. In the actual design, the full floor space is used while in the model design this is not the case. One cause for this is that the cubic floor space for AAS is very expensive. In the model, when optimizing on the CAPEX, this results in a minimum system area. Moreover, the model does not take everything into account. For instance, not all transportation lines, odd sized baggage, other space requirements, special handling, etc. Additionally, the CAPEX of the concept design falls inside of the range of uncertainty.

Furthermore, the model does not take into account when it is better to move and rebuild a subsystem to a new place. For instance, the EDS machines are moved to a new space. In the model the existing subsystem are fixed to a certain space, which is also the leading factor in the location of the added equipment of that subsystem. An improvement to the model could be to let the model search for the optimal location for the full system, while taking the moving costs into account. However, a new trade-off then needs to be made with the longer model run time, as the scenario space enlarges.

7.5 Chapter summary

Many airports face the simultaneous demands of expansion, renewal and replacement of an existing BHS. To increase the usefulness of the model, the model needed to be adapted to include these brownfield BHS designs. This Chapter answers the third sub-question: *How can the model be adapted to be able to include brownfield baggage handling systems?*

To accommodate this, an extra set of requirements is added to the model. The location of existing subsystems can be inserted. Furthermore, by adding the capacity of the existing subsystems, the remaining required capacity is calculated. But, at brownfield airports often not all subsystems need to be included. The new model has the option to choose which subsystems are placed, and which are not. When a subsystem already exists, the new subsystem is placed as close as possible to the location of the existing subsystem.

The model is tested using a case study of a large brownfield project. Using the cost cone of uncertainty by Boehm (1984), the model is valid if the calculated CAPEX does not vary by more than a factor of 2 above or a factor of 0.5 below the actual CAPEX. The outcome from the model is between 0.75 and 0.87 of the actual CAPEX, leading to the conclusion that the model is valid. The actual design does differ somewhat from the model design. However, as there are many good conceptual designs, the fact that the actual design is different from the model design, does not mean that the model design is not good.

Chapter 8

Use of the model

Automation and simulation have led to superior productivity, efficiency and quality control (Noyes et al., 2007). Automation can help in guiding the decision maker to choose the conceptual design and speed up the process. Yet, some researchers have shown that if a decision maker does not trust a model, he will not use it in his decision (Camp, 2003; Inagaki, 2008; Muir, 1987).

The actual use of an automated model can be a thesis by itself. However, there is not enough time to fully analyze the use of automated models. Still, for the BHS model it is important that this issue is addressed. This chapter highlights the most important aspects of how to increase the use of an automated tool, such as the concept design tool of the BHS. This chapter will answer the sub-question: *How can the use of the model of the conceptual design of the baggage handling system be improved, by increasing trust in the model?* First a literature study is conducted on the actual use of automated models. Then, this literary study is applied to the BHS model, to increase trust and increase the likelihood that the model is used by the users from NACO.

8.1 Literature on human-automation interaction

A human uses a machine for two reasons. He either expects that the machine will extend his capability or he expects it will help him achieve a goal in a more efficient way. As Inagaki (2008) states, the machine needs to be an agent that is faithful to the human and is capable to perform the precise task that the human ordered it to do. In other words, the machine needs to be designed in a manner that it is easy for the human to (1) understand what the machine can and cannot do, (2) tell the machine what to do, (3) keep track of what the machine is doing, and (4) intervene the machine if necessary. If the machine works appropriately and the human gives proper directives to the machine, the human can obtain a result from the machine that matches his goal and situation at that time.

However, automation if often problematic (Lee & See, 2004). Automation is often misused, when humans inadvertently violate critical assumptions and rely on automation inappropriately, or disused, when humans reject the capabilities of automation. The misuse and disuse of automation can be because of certain feelings and attitudes towards automation, such as trust. To analyze trust between humans and machines and how this affects the design of decision aids in human-machine relations, the concept trust needs to be defined.

8.1.1 Trust

Humans tend to rely on automation they trust and reject automation they do not (Kunze, Summerskill, Marshall, & Filtness, 2017; Muir, 1987). Only if a human trusts a decision aid, the aiding tool will be used to guide his decision. Even if a tool is intelligent and the decision maker does not trust it, he will not use it and all the benefits from this tool will be lost. On the other hand, if a decision maker trusts a tool too much and uses the tool to perform tasks that are performed better by humans, it could lead to system failures. The challenge is thus, as Muir (1987) states, to design a decision tool that humans trust enough to guide their decisions, but will use discriminatingly and effectively.

Figure 8.1 shows this relationship. The goal is to reach trust that is equal to the tools capabilities, e.g. calibrated trust. Only if calibrated trust is reached, the tool can be used appropriately. If the tool is trusted more than it is actual capable of, it could lead to misuse of the tool. However, the tool can be disused if the human does not trust the tools capabilities. Trust in a tool can rely on a different range of resolution. Resolution is how precisely a judgment of trust differentiates on levels of automation capability. If there is low resolution, big changes in automation capability only reflect small changes in trust.

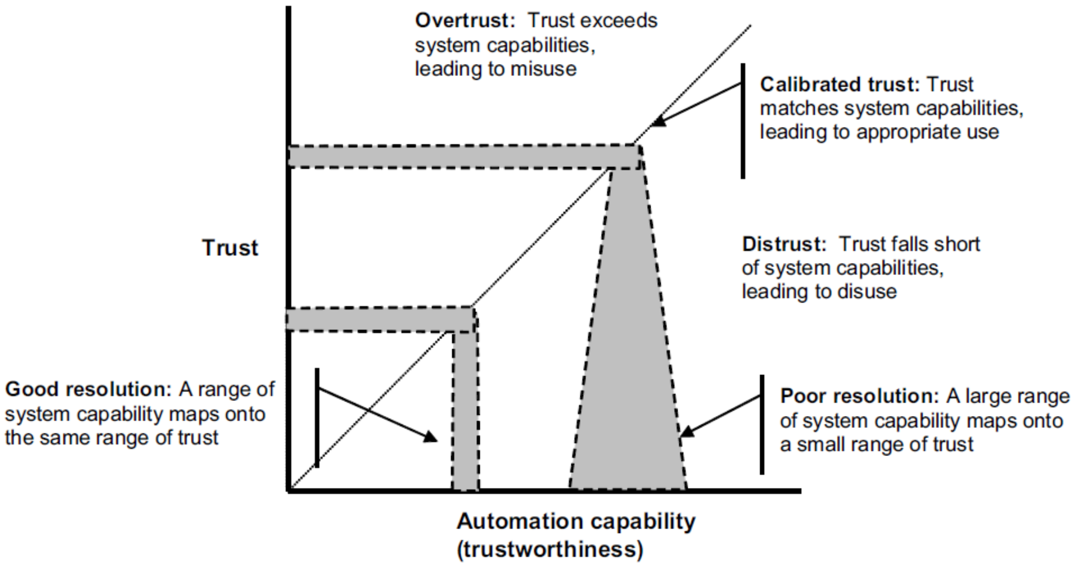


Figure 8.1: The relation between trust in a model and a models automation capabilities, retrieved from Lee & See (2004).

Previous research has shown that trust affects the use of automated tools. Hoff and Bashir (2015) have classified trust into three categories. The first is dispositional trust. This refers to a humans overall tendency to trust automation, independent of context or a specific system. These tendencies arise from biological and environmental influences, such as gender, age, culture and personality. The second category is situational trust, which is associated with external and internal variability. External variability means that a humans trust in automated tools depends on the type of system, its complexity and how difficult the task is it is used for. Internal variability covers the more temporary characteristics that depend on context, such as self-confidence, expertise, affect and attentional capacity. The last category of trust is learned trust. This trust is similar to interpersonal relationships. It is trust created by a humans knowledge from past interactions with automation when assessing the reliability of new systems. This trust is thus based on past experience or the current interaction with a tool. In contrast to dispositional trust, situational and learned trust depend on time-varying factors, such as task difficulty, self-confidence and experience. Consequently, only the last two categories influence real-time human decision making during interactions with automated systems (Hu, Akash, Jain, & Reid, 2016).

8.1.2 Model complexity

The computational power of computers has increased enormously over the past decades. This increase in computational power has enabled people to build huge and complex models. Chwif et al. (2000) provide several reasons for the increasing model complexity. The reasons are split up in two categories: non-technical and technical. Both categories are again split up into several reasons. The first non-technical reason is the 'show off factor', meaning that even if two models can perform the same task, showing a more complex model to your supervisor has more impact than a simple model. Second, modelers have the tendency to include everything that is possible in a model, even if it is not necessary. Last, as already mentioned before, due to the increase in computational power, complexity and size of a model are not a constraint anymore. The first technical factor is that there is lack of understanding of the real system. If the modeler does not understand the system correctly, the model will be a result of the modelers misunderstandings. Second, the lack of ability formulate the conceptual model correctly. Modelers have the tendency to build the model as close as possible to reality, rather than modeling an abstraction of reality (which is the goal of modeling). Third, the inability to translate or code the conceptual model into a simulation model correctly. Last, the simulation objectives are unclear.

Chwif et al. (2000) have found a relationship between complex models and model validity (see Figure 8.2). In the beginning making the model more complex adds to the model confidence, but there is a turning point. When the model gets to complex, the confidence in the model decreases. Furthermore, even though this relationship is quite obvious, Chwif et al. (2011) have proved that the more complex a model is (calculated through the number of variables), the more hours it takes to build that model. However, this relationship is exponential (see Figure 8.3), showing at a certain point a little added complexity can take a lot of hours to build.

8.2 Trust in the BHS model

Research states that in order to increase the use of automated models, the user needs to trust the model. If the BHS designers trust the model can be evaluated through the three trust categories by Hoff and Bashir (2015).

8.2.1 Dispositional trust

Dispositional trust is the overall tendency to trust automation in general. As these tendencies depend on biological and environmental influences, they cannot be influenced to increase trust. Though, the users of the model are the BHS designers at NACO. NACO is an engineering firm,

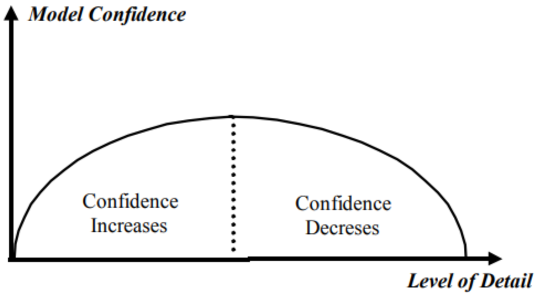


Figure 8.2: The level of detail versus model confidence, retrieved from Chwif et al. (2000).

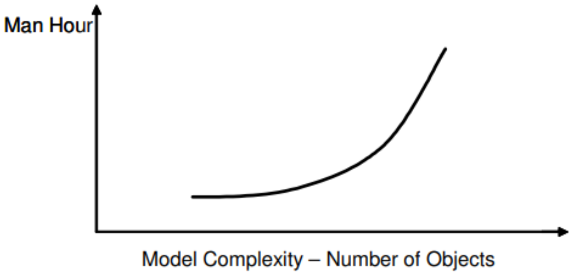


Figure 8.3: Complexity versus hours, retrieved from Chwif et al. (2011).

and is investing in the automation in every department of the company. As NACO has been developing automated models for many processes, it can be assumed that they are open to automation and have at least an average overall tendency to trust automation.

8.2.2 Situational trust

Situational trust depends on two variability's: internal and external. Internal variability entails how self confident the user is, how his mood is, how long he can concentrate, and how much does he know about the matter. The internal variability changes over time depending on the task and environment, and can even change during the task. The characteristics of the developer can effect the internal variability of the user. It is thus important that the developer of the model shows self confidence, is in a good mood, answers any questions, etc. Even though the internal variability of a human can be clear while being in his presence, it is a hard concept to measure. Due to this it is difficult to take internal variability into account when addressing trust in the BHS model.

The external variability depends on the complexity and reliability of the model. As described in Section 8.1.2, in order to trust a model, it needs to have the right amount of complexity. The complexity of the model, or actually the *visible* complexity of the model, depends on several things. As every relation between variables is connected through a line, the model itself seems very complex (see Figure 8.4). As there are many variables, the model looks very complex. Though, the only part that the user of the model needs to understand and adjust is the green blocks. Everything that needs to be inserted for an airport, happens in these green blocks and excel sheets. Nothing needs to be altered in the code anymore. This reduces the complexity of the model. Thus, even though the 'show off factor' of the model is high, the actual complexity is lower. Furthermore, not every aspect of BHS systems should be taken into account when modeling the system, especially when considering that a lot of BHS designs are based on exceptions. Choices are made on which options and possibilities need to be included in the model. This is done by interviewing the BHS designers, the users, of the model (see Chapter 6). A model can get more complex if the modeler does not understand the system correctly. The model is built with the knowledge from the experts of NACO. As three graduate students have worked on the model, each with different perceptions, an overall view of BHS designs is created. All formulas are discussed and evaluated with the experts, leading to the conclusion that the modeler, in combination with the experts, understands the system correctly. Furthermore, even though the model is executed in Dynamo, the results are automatically inserted into an Excel file. This Excel file displays the results through an interactive dashboard, which makes it easy to compare scenarios. As the results in Excel, a widely used program, and not in Dynamo, it reduces the visible complexity for the users of the model to analyze the results.

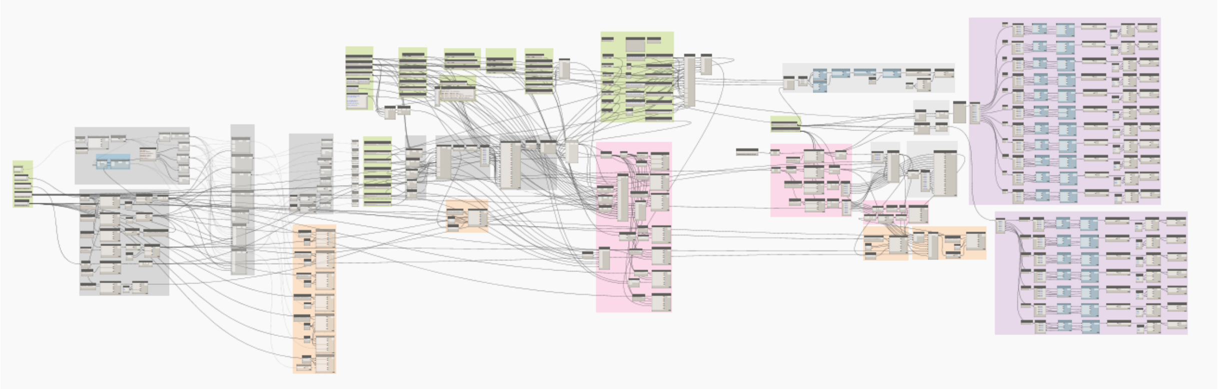


Figure 8.4: BHS conceptual design tool in Dynamo.

The reliability of the model is, even though still complex, simpler to measure. Boehm (1984) researched when a design is accurate enough through the cost cone of uncertainty (see Section 7.3). If the cost of the conceptual design is within a factor two of the actual design, the model is accurate enough. If the model is accurate is further evaluated in the case study chapter 9.

8.2.3 Learned trust

Learned trust is the trust that is created by past interactions with the automated tool when assessing the reliability of the tool. This trust can be created and increased by good interactions with the tool. The developer of the tool can thus put effort into creating good interactions. For instance, the tool is developed where the BHS designers work. Hence, the users have been connecting with the tool and also collaborating with the developer to design the tool. Moreover, the users have shown lot of interest in the tool and been asking questions about the ability of the tool. For instance, the BHS model is run multiple times for current BHS projects at NACO to be able to compare the outcomes. Furthermore, the tool has been used to compute equipment calculations for running projects, and to see the effect of altering the number of equipment on the rest of the BHS system. Even though the full model is not run in this case, is has been used to provide insight in BHS designs. Also, the users have provided input through several interviews (see Chapter 6) on what is desired of the model.

To increase the learned trust of the future users of the model, a workshop is organized to have the users work with the BHS tool. During the workshop the users had to do a simple case study. For a small airport, namely AUA, the users had to insert the right data and run the model. The full case study is described in Appendix E. The case study guides the users from the first things they need to do, to analyzing the actual results. Every step of the model is explained. From which files are needed and converting a flight schedule, to how choices of the design can be made through the flow diagrams. During the workshop the designer of the model was present to answer questions about the model to reduce any doubts that the future users have.

As the users of the model have been, and still are, interacting with the BHS tool in many ways, it can be assumed that they have a good amount of learned trust, which will increase more as the time goes. Moreover, as the users have seen the model perform in the way they wanted, the change of having a bad experience during future interactions is low.

8.3 The expected use of the BHS model

The previous section shed light on how much the future users of the tool trust the model. As previously mentioned, only if calibrated trust is reached, e.g. trust in the tool is equal to the tools capabilities, the tool can be used appropriately.

Over the past year, the users of the model have been in contact with the model multiple times, increasing the amount of learned trust. Furthermore, through a workshop with a case study they got to learn how to use the model. During the workshop, situational trust was at least attempted to create, as the confidence of the developer was high, was in a good mood, and know everything about the model. Furthermore, the visible complexity of the system decreased and the reliability of the model increased, resulting in more situational trust.

It is important to note that the BHS model can be used as a tool to explore scenarios of BHS designs and speed up the project throughput time. But it can never replace the BHS designers, because they and their knowledge are needed to insert the data and analyze and interpret the results. Without the BHS designers the model is useless. The model has a lot of capabilities, but is still only one phase of a full BHS design. The fact that the model can be used to compare different scenarios and designs, adds value to the model. When the BHS designers develop a conceptual design for an airport, they do not have time to make several and compare them. That the model can be used to analyze different conceptual designs, can lead to a lot of insight on BHS designs.

Even though trust is difficult to measure and it is even difficult to analyze the capabilities of the model, the two concepts seem to lie close together. The amount of trust matches with the system capabilities, e.g. calibrated trust, leading to the appropriate use of the model. It is thus expected that the model will be used to help develop conceptual designs and shorten the project throughput time.

8.4 Chapter summary

The use of automated models can be increased if the users trust the model. If the user does not trust a model, he will not use it or is unlikely to apply the results. This chapter answers the last sub-question: *How can the use of the model of the conceptual design of the baggage handling system be improved, by increasing trust in the model?*

Trust in a model can be evaluated using three categories: dispositional, situational and learned trust. According to Lee & See 2004, if the amount of trust in a model is equal to the capability of the model, the model will be used, and even more, will be used appropriately. The users of the model, the BHS designers at NACO, have been involved with the model many times, and their trust is increasing. The model has a lot of capability, but the BHS designers need to be able to analyze and evaluate the model outcome to increase trust. The trust in the model seems to match the model's capabilities, leading to the conclusion that the model will be used during projects at NACO.

Chapter 9

Case study

With the model improved, it can be applied and validated on case studies. So, the last subquestion can be addressed: *How does the outcome of the model compare to the manually developed conceptual BHS designs for different airports?* During the development of the model, the model is already run for small airports to test the new developments. In this chapter the model is run for three bigger case studies. As already mentioned in Section 7.3, a model for the conceptual design of baggage handling systems is valid when the CAPEX does not vary by more than a factor of 2 above or a factor of 0.5 below the actual CAPEX.

9.1 Taiwan Taoyuan International Airport

Taiwan Taoyuan International Airport, also known as TPE, is an international airport in the North of Taiwan positioned near the capitol Taipei. It is the busiest and largest airport in the country. In 2016, it has been ranked as the number 1 airport worldwide for the best airport in the category airports with 25-40 million annual passengers (Lee, 2017). Currently the airport handles 25 million passengers annually and it is preparing to grow to 60 million passengers in 2030 (NACO, 2018). The expansion of the airport will allow the airport to regain a position as a major aviation hub and become an even stronger driver for the national economy.

NACO is involved with the development and planning of the new Terminal 3 facility. Figure 9.1 shows the layout of the airport. Terminal 1 (T1) and Terminal 2 (T2) already exist, the assignment is to develop Terminal 3 (T3). The expansion of Terminal 3 includes a newly designed BHS. It is thus a greenfield project.

The layout of the BHS area is shown in Figure 9.2. The area consists of 5 floor levels on top of each other. Check in and reclaim are located on the right of the BHS terminal, and the baggage from make-up exits the terminal at the front and back of the left side. The airport has a preference for each subsystem to be placed on a certain floor level. There is no flight schedule available, but the expected demand of each subsystem is known. The objectives of the BHS are to have a CAPEX as low as possible, but also the energy consumption needs to be within bounds. Furthermore, the subsystems need to be placed centralized. Three scenarios are run. The first scenario is optimized solely on minimizing the CAPEX, the second 50% CAPEX and 50% energy

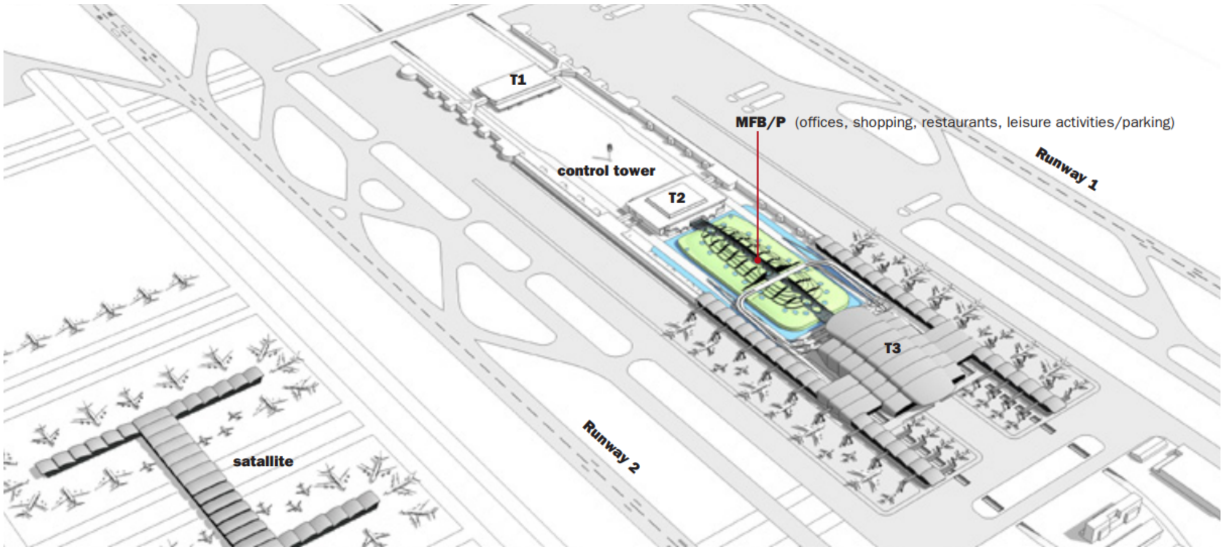


Figure 9.1: Layout of TPE.

consumption, and the third entirely on the energy consumption. All other parameters are kept the same.

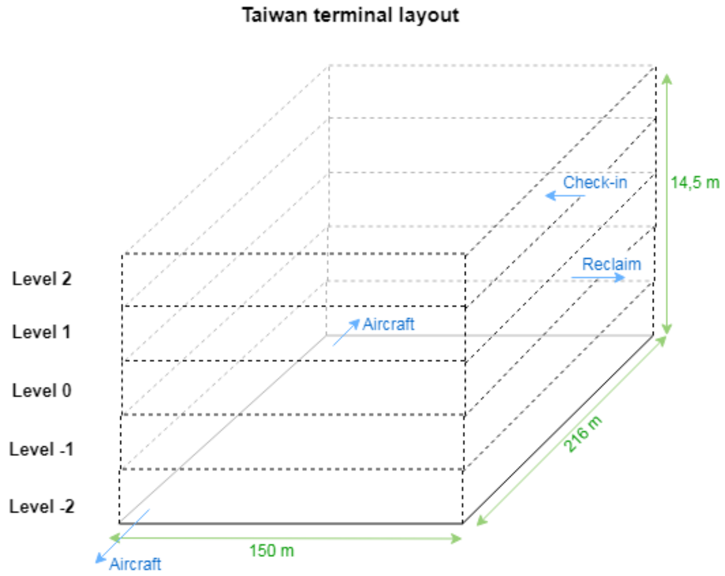


Figure 9.2: BHS terminal layout of TPE.

Scenario 1 (CAPEX optimized) and scenario 2 (50% CAPEX, 50% energy) have the same type and number of equipment. Thus, only if the focus of the optimization exceeds 50% energy, the outcome changes. As the two outcomes are the same, from now on both scenarios will be referred to as scenario 1. Scenario 3 (energy optimized) does differ from the others. For screening level 1 high speed EDS is chosen rather than medium speed, for make-up a carousel and transfer vehicle ALT is chosen rather than a carousel and train, and for EBS a crane rack is chosen rather than a shuttle rack.

Figure 9.3 shows how high the scenarios score on each decision variable. Scenario 3 (energy optimized) scores the same or higher on all decisions variable except for the CAPEX. The CAPEX of scenario 3 is 11.5% higher than the CAPEX of scenario 1 (CAPEX optimized). Moreover, the capacity of each subsystem is the same or higher in scenario 3 than scenario 1 (see Figure 9.4. If this difference in CAPEX is not a deal breaker, scenario 3 seems to be the better solution for TPE.

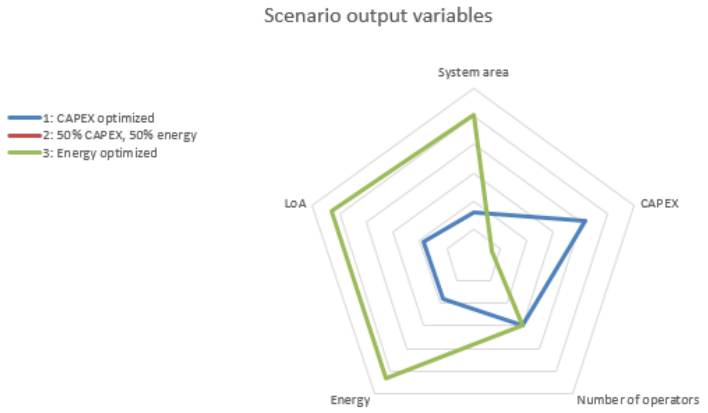


Figure 9.3: The scenarios rated based on the decision variables of TPE (more outward is better).

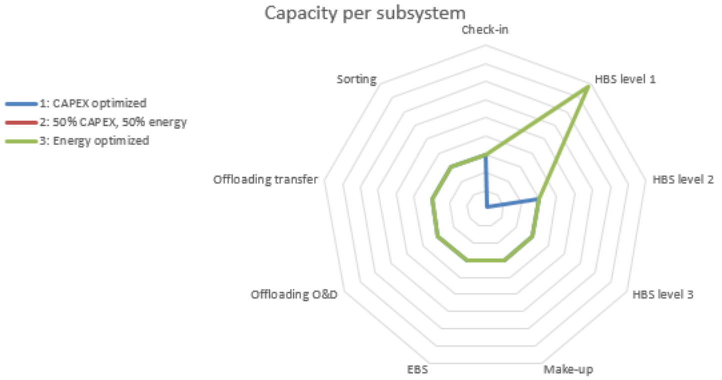


Figure 9.4: The capacity of the subsystems of TPE of the scenarios (more outward is better).

Figure 9.5 shows the placement of the subsystems in the BHS terminal. Each subsystem is placed on a preferred level. Make-up and offloading in the basement on floor level -2, the EBS on floor level 0, screening level 2 and 3 on floor level 1, and screening level 1 on floor level 2. The only difference in the placement is screening level 1 on the top floor. This is due to a different equipment choice.

As there is a lot of free space available in the BHS terminal, the model is also run to place all subsystems on one floor level (see Figure 9.6). During this run also the transportation is placed.

Figure 9.5: Placement of subsystems of TPE with floor preference for scenario 1 (a) and scenario 3 (b).

Transportation is requested between several subsystems. Routing between screening level 1 and 3 is not necessary, since they are directly connected. Routing between screening level 1 and sorting is placed on the bottom of the two subsystems. As the routing algorithm searches for the tiles in a rectangular circumference around the subsystems, the routing does not touch screening level 1. This is an issue that needs to be resolved through further improvement. However, as this is a conceptual design, this provides a good indication of how the routing would be. Furthermore, routing is placed between the EBS and make-up systems, which is located above offloading. The routing between transfer offloading and screening level 1 is placed next to the routing between screening level 1 and make-up. An advantage of placing the subsystems on different floor levels can be that there is more room for expansion later on. As TPE is growing, this can be taken into consideration.

Figure 9.7 shows the actual conceptual design of TPE. There are several differences. First, the space of the subsystems in the model outcome is about half the size of the actual design. This is due to the fact that the placement at TPE is enlarged due to the column structure. This causes the make-up carousels to be bigger, the offloading area to have more room in between pieces of equipment, and so on. Furthermore, screening level 1 is spread out over all check-in points, which are located on the whole left side of the top level. Furthermore, TPE wants more EDS machines to ensure that screening level 1 will not be a bottle neck. Also extra OSR machines

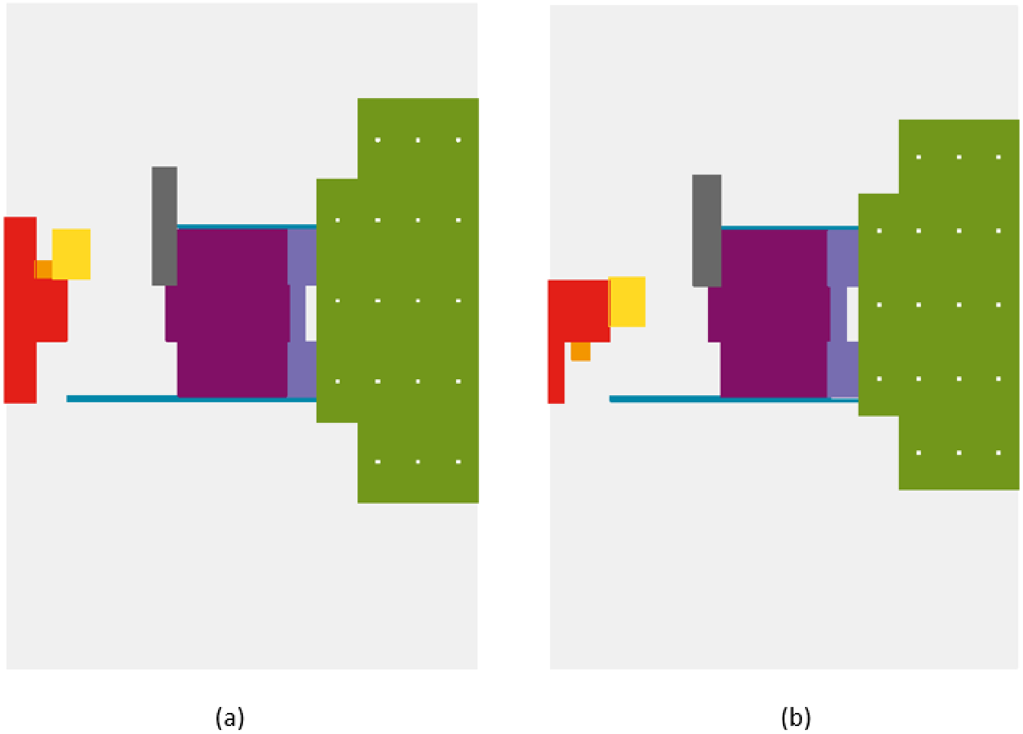


Figure 9.6: Placement of subsystems of TPE on one floor level for scenario 1 (a) and scenario 3 (b).

are added for when there is simultaneous demand. Furthermore, also the pieces of equipment for each subsystem are less than in the actual design. As both the amount of space used as the pieces of equipment is too low, this can indicate that the demand used as input in the model is too low. Also the CAPEX differs a factor of 0,31 to 0,34 of the actual CAPEX, which indicates that the model is not valid (through the cost cone of uncertainty). However, as every value is a lot lower than the actual design, the CAPEX should also be lower than expected. Thus, even though the CAPEX does not fit inside the range of 0,5 to 2, with these model outcomes compared to the actual design, the CAPEX is not supposed to fit inside this range. Everything indicates that the demand used to determine the conceptual design, is too low.

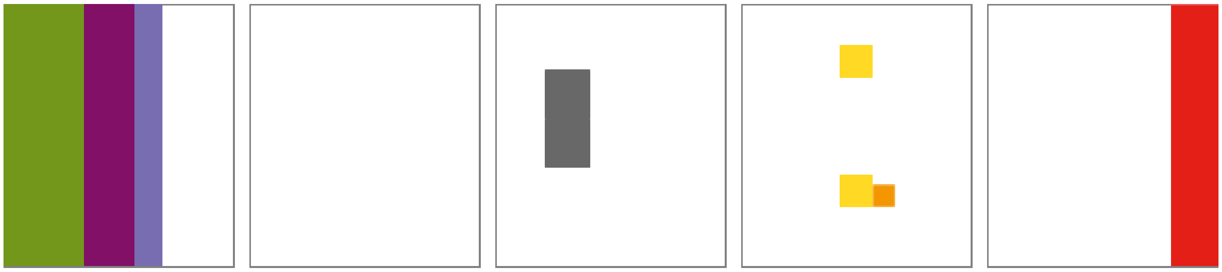


Figure 9.7: Placement of subsystems of actual TPE design.

9.2 Carter International Airport

The second airport for which a case study is conducted is still completely confidential and cannot be named, so let's call it Carter International Airport (CIA). The airport currently handles about 60 million passengers annually and has been growing 10% per year for the last three years. The scope of this project is quite different from the others as the design is still in a very early stage, even before the conceptual design. CIA is an airport which currently consists of two buildings, Terminal A and Terminal B, but is building a third, namely Terminal C (see Figure 9.8). Terminal B and C are satellites, which are connected to Terminal A through a tunnel. In Terminal A there is a full BHS with all subsystems. In Terminal B, the only subsystem present is offloading. All other handling of baggage happens in Terminal A. The two baggage handling systems are connected through the tunnel.

Now that a new terminal is planned, CIA wants to know if the best strategy for the BHS of Terminal C is the same as for Terminal B, or that it is better for Terminal C to have several subsystems present at the terminal. While the objective of the project is to figure out a strategy for Terminal C, the BHS strategy of Terminal A and B may also be revised. While designing the strategy another objective of CIA needs to be kept in mind. The CAPEX of the system cannot be too high, but it is not the main consideration. Furthermore, it is important that the system has a high LoA.

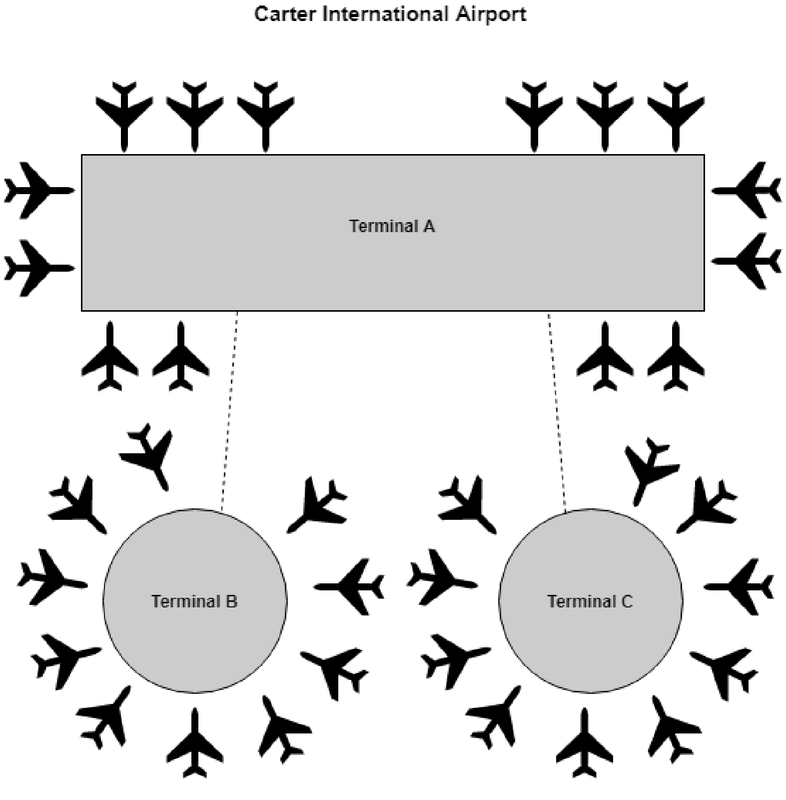


Figure 9.8: The layout of CIA.

Three scenarios are run to analyze these strategies. All three scenarios are optimized with a focus of 30% minimizing the CAPEX and 70% maximizing the LoA. In the first scenario all BHS subsystems are evenly divided over the three terminals, so 33% at every terminal. In reality Terminal A will handle more passengers than the two satellites. The second scenario takes this into account by dividing the subsystems so that Terminal A handles 50% and the satellites both 25%. In the last scenario the current strategy for Terminal B is analyzed, meaning that only transfer offloading is handled in the satellites and all other subsystems in the Terminal A. The exact shape of the BHS area is not defined yet.

The choice of equipment is the same for all scenarios. There is one aspect that should be noted. Due to redundancy extra transfer offloading equipment needs to be placed, even though the machines are not needed to match the demand. However, if one machine in a decentralized space fails, another machine at that location needs to take over. So, 6 transfer offloading machines are placed at CIA in scenario 1, and 8 in scenario 2 and 3, while only 4 machines are required.

However, the scope of this project is to figure out which strategy is best. This can be evaluated through the placement of the subsystems (see Figure 9.9). Scenario 1 (equally divided) and 2 (50% in Terminal A) are restricted to three spots indicating the three terminals. As almost all subsystems in scenario 3 (only offloading decentralized) are placed in Terminal A and it was unknown how much space was required, this scenario is not restricted into three areas.

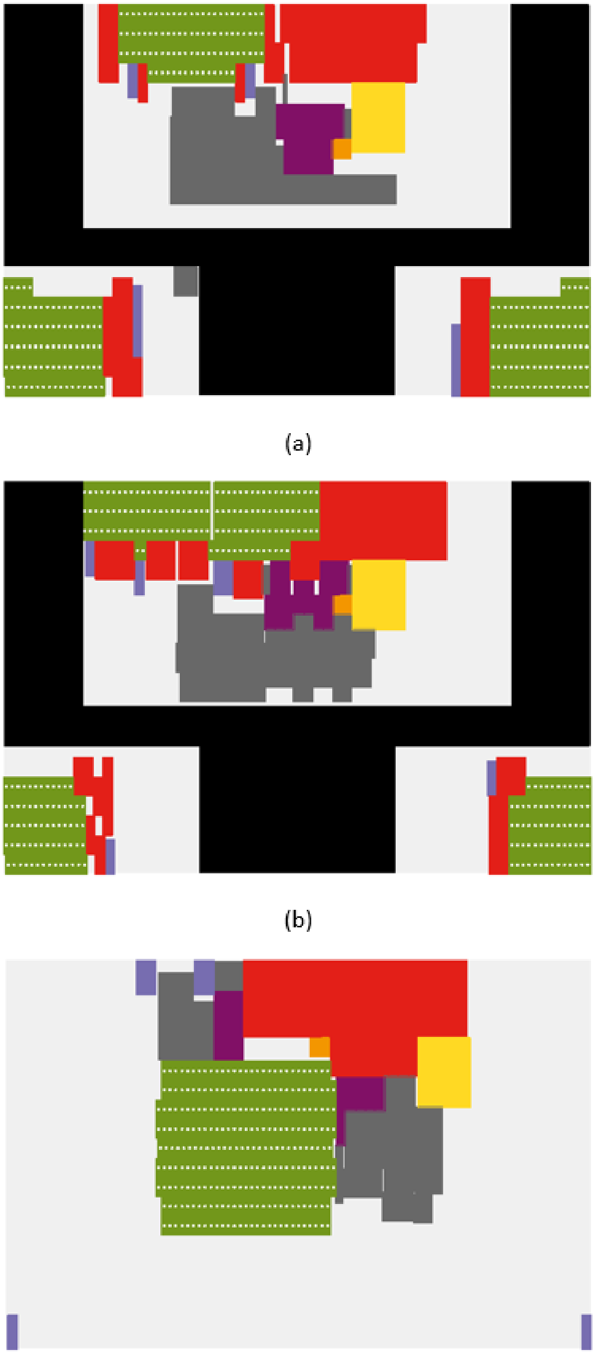
The placement of the subsystems is very messy. This is due to the fact that no explicit placement rules are used. The only expectation of the model is to see which subsystems are placed in which terminal. Table 9.1 shows the required space in square meters that is needed in each terminal for the three scenarios. In scenario 2 and 3, 180 square meters more is needed. This is because of the extra transfer offloading machines needed due to redundancy requirements. Furthermore, in scenario 3 almost all the space is needed in Terminal A. If this does not fit inside the terminal, there is the option to attach another building on the side of this terminal.

Table 9.1: The required space in squared meters per terminal for the scenarios of CIA.

	Terminal A	**Terminal B**	**Terminal C**	***Total***
Scenario 1	11382	4590	4590	*20562*
Scenario 2	13632	3620	3490	*20742*
Scenario 3	20382	180	180	*20742*

9.3 New Mexico City International Airport

The last airport that is used as a case study is New Mexico City International Airport, also known as NAICM. In 2018, NAICM was planned to be the new airport serving Mexico's capital city and replace the current airport Benito Juárez International Airport. Unfortunately, Mexico's President Select cancelled the construction of the new airport in December of 2018. However, as this model is run with the previous model (the existing model before this thesis), it is still a good case study to compare the two models.


(a)

(b)

(c)

Figure 9.9: Placement of subsystems of CIA for scenario 1 (a), scenario 2 (b) and scenario 3 (c).

The plan for NAICM was to have a capacity of 70 million passengers annually in 2020. The airport has space reserved to eventually handle a capacity of 125 million passengers per year.

This would make it the worlds third largest airport. Figure 9.10 shows the terminal shape of NAICM. The area is 500 by 800 meters and is shaped like a chromosome. Running this model is interesting for several reasons. First and already mentioned, the existing model is also run for NAICM. Second, the terminal has a shape that is not often seen. Third, as this airport is extremely big, the speed of the model for big airports can be evaluated.

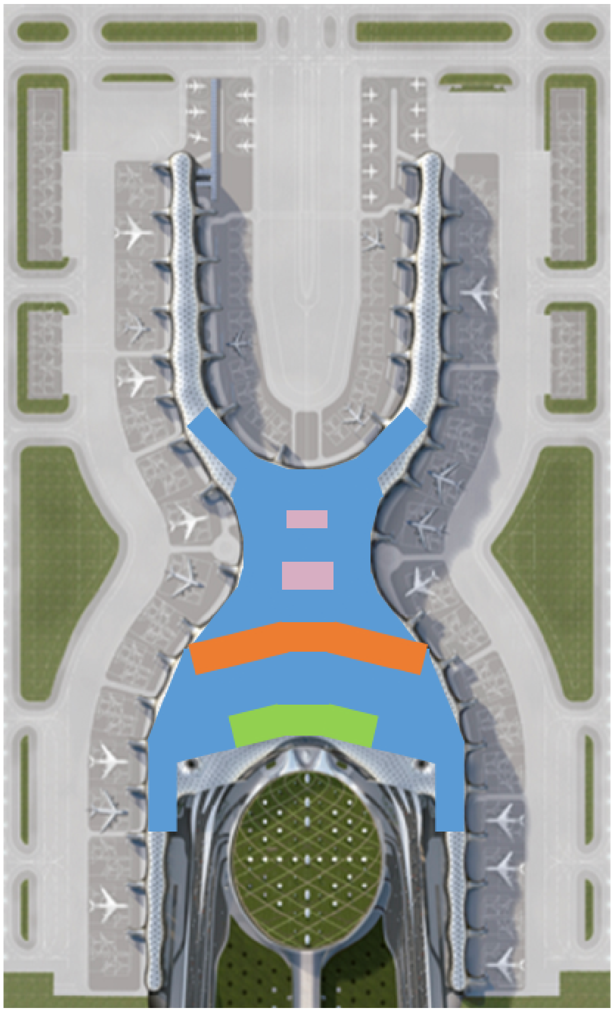


Figure 9.10: Terminal shape of NAICM. The blue area is the available space, green is the check-in area, orange is reclaim, and pink the transfer areas.

Due to time limitations, only the top part of the terminal is run. The part handles 60% of the entire system. The terminal used in the model is 480 by 220 meters. All subsystems need to be placed on the ground level. The area available for the BHS in this part of the terminals is almost 51 thousand square meters. As the terminal is very big, the airport wants decentralized subsystems as much as possible. Another objective of NAICM is to mainly focus on minimizing the cost, but also consider minimizing the LoA.

To analyze the conceptual design for the BHS of NAICM two scenarios are run. In both scenarios baggage screening level 1, make-up and transfer offloading are decentralized. The first scenario is optimized solely based on the CAPEX, the second scenario 30% on the CAPEX and 70% on minimizing the LoA.

There are several differences in which equipment is chosen for each scenario. For instance, in scenario 1 (CAPEX optimized) 5 medium speed EDS machines are required, while in scenario 2 (70% min LoA, 30% CAPEX) 17 stand alone EDS machines are needed. Also check-in and make-up equipment differs.

Figure 9.11 shows how the two scenarios score on the decision variables. Scenario 1 scores higher on all decision variables except for the LoA. It needs to be noted though that scenario 2 scores higher on the decision variable LoA as a minimum LoA is a objective for NAICM. Thus, a BHS with a higher LoA, also has a lower CAPEX, smaller system area, lower number of operators, and a lower energy consumption. Furthermore, also the capacity of all subsystems is equal or higher in scenario 1 versus scenario 2 (see Figure 9.12). Thus, based on these two scenarios it can be concluded that scenario 1 is better in all aspects.

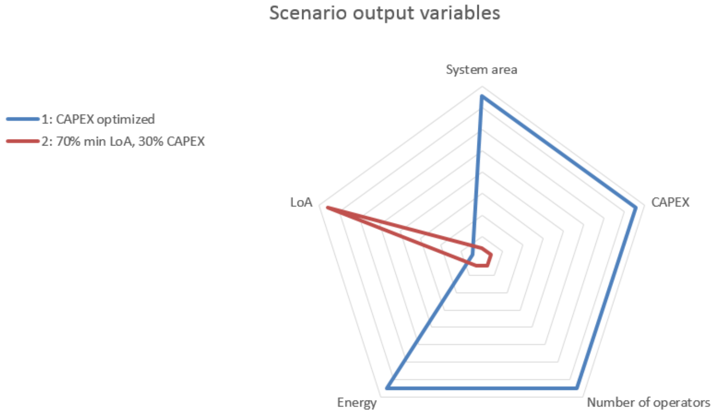


Figure 9.11: The scenarios rated based on the decision variables of NAICM (more outward is better).

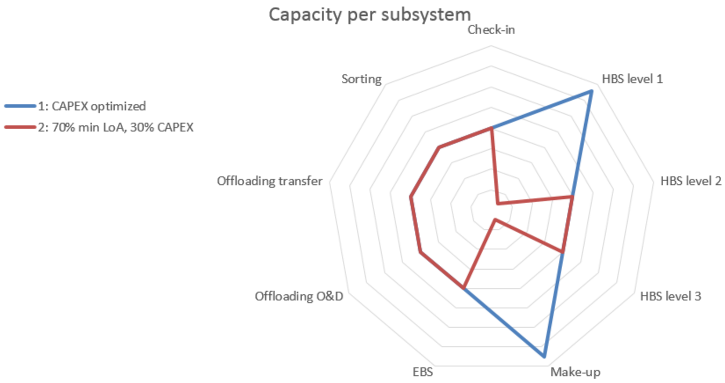
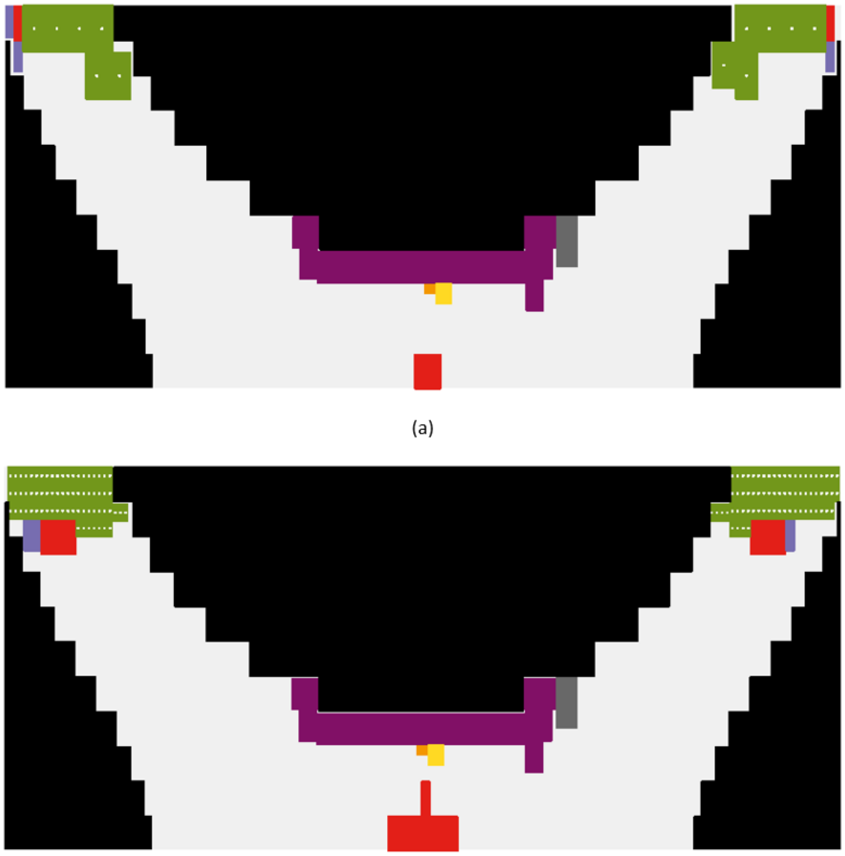


Figure 9.12: The capacity of the subsystems of NAICM of the scenarios (more outward is better).

Figure 9.13 shows the placement of the subsystems. The structure of both placements is the same. This is as it is supposed to, as no placement rules changed. In the actual design, the make-up systems are divided over the span of the top circle, and in both ends an EBS and transfer offloading is placed.


(a)

(b)

Figure 9.13: Placement of subsystems of NAICM for scenario 1 (a) and scenario 2 (b).

Figure 9.14 shows the placement of the previous model, e.g. the model before the improvements for this thesis. As that model was not able to compute for neither the full, nor half of the airport, the model is executed for a quarter. The run time for the previous model for 1 scenario was about 17 hours. The run time of improved model is just over 9 hours, for double the size of the terminal. It can thus be concluded that the improved model has a shorter run time for big airports as well.

The model can be validated through the cost cone of uncertainty (see Section 7.3). The model CAPEX can differ between a factor of 0.5 and 2 of the actual CAPEX. Scenario 1 differs a factor of 1.19 and scenario 2 a factor of 1.36 from the actual CAPEX. As the CAPEX values are within the range, it can be concluded that the model is valid. However, the calculated CAPEX costs are higher than the actual CAPEX. An explanation for this can be that the transport costs of the model outcome are higher because transportation is needed between the two make-up systems,

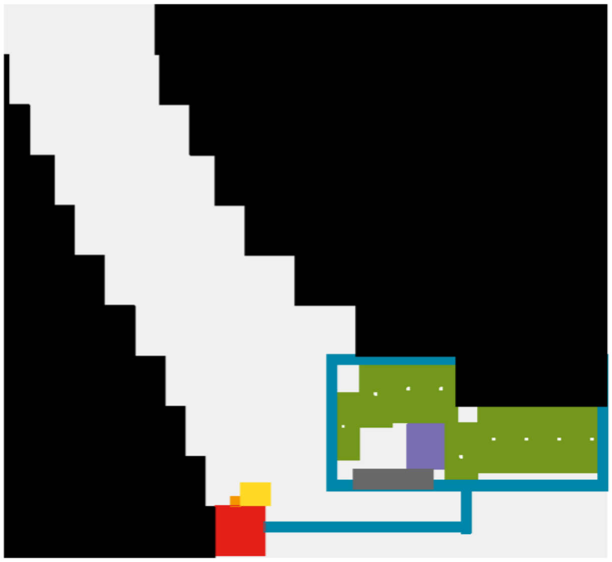


Figure 9.14: Placement of subsystems of NAICM from the previous model.

while in the actual design make-up is connected.

Chapter 10

Model evaluation

The objective of this research is to improve and further develop the existing model of the conceptual design. In order to conclude on how the model is improved, both models need to be evaluated. The models can be evaluated by assessing the usability and usefulness of the model. The usability and usefulness of a model are related properties of model interaction (Tsakonas & Papatheodorou, 2006). These properties together determine the model satisfaction and usage (Buchanan & Salako, 2009). In order to evaluate the models based on these two concepts, first a literary study is conducted on the usability of a model in Section 10.1 and the usefulness of a model in Section 10.2. How the two concepts can be evaluated is explained in Section 10.3.

In the next two sections the initial model and proposed model are evaluated. In Section 10.6 the evaluation of these two models are compared. Last, the model is reflected in Section 10.7 and assessed for other applications in Section 10.8.

10.1 Usability

A term that is often used to evaluate the convenience of a model is 'user friendly'. Though, as Nielsen (1993) states, this term in not appropriate for two reasons. First, it is unnecessarily anthropomorphic. Users don't need models to be friendly to them, but they need the model to perform the task that they requested. Second, different users have different needs, indicating that the convenience of a model cannot be described through one dimension. Nielsen (1993) thus proposed a new word to describe the convenience, namely usability. According to Tsakonas and Papatheodorou (2006) the usability is the interaction between the user and the system features. In other words, the usability covers all aspects of a system with which a human might interact. Nielsen (1993) categorized the usability of a model into five dimensions: learnability, efficiency, memorability, errors, and satisfaction. In the next section each dimension will be discussed.

Learnability
Seffah, Donyaee, Kline, and Padda (2006) refer to the learnability of a model as the capability of the model to enable users to feel that the can productively use the model right away, and quickly learn the new functions. In other words, how easy it is for the users to learn how to use a model in the appropriate way. It evaluates how easily and effectively the user learns how to accomplish tasks. Since learning how a model works is the first user experience, this dimension

is often considered the most fundamental aspect of usability (Nielsen, 1993). When assessing the learnability of a model, one should keep in mind that the users tend to jump right in and use the model, without taking the time to learn how the model works. In order to determine the learnability of the model two factors need to be considered, (1) the time it takes to achieve complete familiarity with the model, and (2) the time it takes to achieve a sufficient level of proficiency to use the model.

Efficiency
The efficiency of a model can only be evaluated after the user has learned how to use the model. Stanley Dicks (2002) defined the efficiency as the task completion in relation to user productivity, in particular the time spent. In other words, once the user has learned how to use the model, the model needs to have a high level of productivity. If the time to use the model takes longer than the task itself without the model, the model has a low level of productivity.

Memorability
Memorability refers to how easy it is to remember how a model works, after some time without using the model (Nielsen, 1993). This concept is important when the model is used by casual users, e.g. humans that are using a system occasionally but have already learned how the model works. The memorability of the model can be measured by assessing how long it takes a casual user to re-obtain full understanding of the model.

Errors
The users of the model should make few errors during the use of the model, and if the users do make errors they can easily recover from it. Nielsen (1993) defines an error as any action that does not accomplish the attempted goal. The usability in errors can be measured through the error rate, which is the number of errors a user makes while performing a task. If the error rate of the model is low, the usability is high. One type of error cannot occur, namely catastrophic errors. Catastrophic errors are errors that are not discovered by the user, which leads to faulty results.

Satisfaction
The last dimension of usability according to Nielsen (1993) is the satisfaction of a model. This refers to how pleasant it is to use the model. As Seffah et al. (2006) state, it is the subjective response from users about their feelings when using the model. In other words, the users needs to like the model. The subjective satisfaction can be measured by simply asking the users for their opinion about the model.

10.2 Usefulness

The usefulness of the model refers to the interaction between the user and the content of the model (Tsakonas & Papatheodorou, 2006). Davis (1989) defines it as the degree to which a human believes that using a particular model would enhance his performance. In other words, it is the degree to which a model will provide the required results to the user. Tsakonas and Papatheodorou (2006) have defined five dimensions of usefulness: relevance, format, reliability, level, and timeliness. Each dimension will be explained in the following paragraphs.

Relevance
Relevance is considered as one of the most fundamental aspects of the useful (Tombros, Ruthven, & Jose, 2005). The model is relevant when it helps you to answer your problem (Tsakonas & Papatheodorou, 2006). Thus, the model should be such that the users need the information it provides, and the model is expected to affect their decisions. The relevance of a model is associated with how well the models enables the accomplishments of the user tasks (Buchanan & Salako, 2009).

Format
Buchanan and Salako (2009) refers to format as a resource attribute that connects with the user's work practice and the available technological infrastructure. If the format the information in is provided is not compatible to the users wishes or it is not possible for the user to access it, the model is not useful.

Reliability
The reliability of a model refers to how sure you are that a the outcome is correct. It refers to the accuracy, dependability and consistency of the information (Z. Yang, Cai, Zhou, & Zhou, 2005). When assessing the reliability of a model, the question asked is if the information retrieved was from a credible source (Buchanan & Salako, 2009).

Level
The level refers to how many representations of information are provided (Tsakonas & Papatheodorou, 2006). It analyzes if it possible to interchange between information that is detailed and abstract.

Timeliness
The timeliness of a model is how current the information resource is. Pipino, Lee, and Wang (2002) define it as the extent to which the information is sufficiently up-to-date for the task it is used for.

10.3 Evaluation method

While models with high usability might lead to more usable models, without considering the usefulness of a model, models that are effectively designed can be functionally useless (Greenberg & Buxton, 2008). To assess if the proposed model is actually an improvement of the initial model, the usability and usefulness of the models are determined. How the models rate on each dimension can be measured through a 7-point Likert scale, which is widely known to measure the acceptability of a model. Vagias (2006) provide a 7-point Likert scale of acceptability, which will be used to assess how acceptable the usability and usefulness of the models is. The scale is as follows:

1. Totally unacceptable
2. Unacceptable

3. Slightly unacceptable
4. Neutral
5. Slightly acceptable
6. Acceptable
7. Perfectly acceptable

The models are rated on this scale for each dimension of usability and usefulness. A score of a 5 or higher indicates that the model is acceptable. Some dimensions have several features that can be rated. However, as every feature of the dimension needs to be accepted, the lowest rating is used to evaluate that dimension.

Since the initial model has not been fully used yet, and the proposed first needs to be evaluated before it might be used, it is not possible to let the users of the model rate the usability and usefulness. Since this is not possible, but it is necessary to evaluate the acceptability of the model, arguments are stated to support the rating given to each dimension. Some arguments come from discussions held with the BHS designers, others from experience with the model. Even though this is not a solid evaluation of the proposed model, it at least provides an identification of the expected improvement of the usability and usefulness. In reality both models should have been used (at least) multiple times, after which the BHS designers should fill in a survey on these dimensions of usability and usefulness. However, due to time limitations for the duration of this thesis, and time limitations of the BHS designers, this is not possible for this research.

10.4 Evaluating the initial model

Table 10.1 shows how each dimension is rated and why it is rated the way it is for the usability of the model and Table 10.2 for the usefulness.

Table 10.1: The initial model rated for its usability.

Dimension	**Rate**	**Explanation and reason**
Learnability	2	*How easy can the model be leaned?* Without knowledge of coding, it is nearly impossible to run the model. There are two main reasons for this. First, when the model is run for a new airport, in order to run the model as it is designed for, certain information has to be altered inside the the code. Second, when the model has an error, the error message is very basic and difficult to solve. Especially when the user has no coding skills, these errors can be impossible to solve. A manual can be used to guide the user when running the model. The manual explains every step from collecting the right input Excel files, to inserting the terminal shape and running the model. Though, the BHS designers at NACO have mentioned multiple times that they do not understand how to use the model. A reason for this might be that they are hesitant of the model and not willing to learn. However, if they do not understand how to run the model, they will also not be able to learn how to use it, rating the learnability at slightly unacceptable (3).
Efficiency	3	*How efficient is the model in terms of time?* The efficiency of the model mainly depends on the size of the airport that is run. For smaller airports such as Aruba the model on average runs 5 minutes, but for bigger airports such as Singapore or Mexico the model did not complete within a week. As the time to build a conceptual design of a BHS by hand takes about a month, a run time up to a day or maybe even a week is acceptable. However, when for bigger airports the model has not provided outcomes yet, the efficiency of the model is unacceptable.
Memorability	-	*How easy is it to use the model again?* As the model is not yet fully used by the BHS designers, it is difficult to nearly impossible to measure the memorability of the model for the future users. Due to this, the memorability of the model is not taken into account in this analysis.
Errors	3	*What is the error rate?* Even for the developer of the initial model, when running the model for a case study, often several attempts are needed to obtain the desired results. This is due to the fact that a lot of input is needed, which needs to be inserted in the model. If one value is inserted incorrect, the model needs to be run again. However, these errors are quickly visible and usually easy to solve. The future users of the model have been asked to run a case study with the model. A model manual can be used to run the model and is supposed to reduce the number of errors. However, as even for the developer errors are easily made, the number of errors that can be made by the users can be even higher.
Satisfaction	4	*How happy are the users with the model?* As how pleasant the model is to use is subjective, the satisfaction is rated by the BHS designers at NACO. They rated the satisfaction of the model as slightly acceptable. If it is necessary the model can be run in combination with the manual. However, it can still be a difficult task.

Table 10.2: The initial model rated for its usefulness.

Dimension	Rate	Explanation and reason
Relevance	6	*Is the outcome helpful?* The model provides a result, which is also validated by Vijlbrief (2019), that the BHS designers can use as a conceptual design. At the moment, the BHS designers use the outcome to compare it to their own designs. The model is thus conceived as relevant.
Format	7	*Is the format of the model good?* The model is written and executed in Dynamo for Revit. This is a program that is widely used by the company, and therefore should be accepted. Furthermore, output of the model is presented in an Excel file, which is even more acceptable.
Reliability	4	*Is the outcome from a credible source?* The initial model is developed by two previous graduate students, who in collaboration with the BHS designers at NACO, have researched and analyzed conceptual designs of baggage handling systems. Both students graduated with Cum laude results on their thesis. Therefore, it can be concluded that the reliability of the model is perfectly acceptable. However, during a thesis with time limitations, only part of a bigger research problem can be addressed. Due to this, the scope of the model is standard airports and many special characteristics of airports are not considered. Thus, even though the model for these standard airports is fully acceptable, when model is used to build conceptual designs for airports where specific elements are required, the model is rated as neutral.
Level	4	*How is the outcome shown?* The model outcome is presented in an Excel file containing the choice of equipment per subsystem and their parameters, such as the CAPEX, LoA, and number of operators. Even though the outcome is presented in a clear way, the data that is used to obtain these results can only be found in the Dynamo model. This can lead to unnecessary interpretation mistakes.
Timeliness	6	*Is the data up-to-date?* The data used to compute the conceptual designs is researched in detail by Vijlbrief (2019). Furthermore, if a new type of equipment arises, the equipment list can be updated to include the new equipment. The data is thus up-to-date now, and can be kept up-to-date in the future as well. This said, updating the equipment is a task that is more difficult than it sounds. Due to this the timeliness of the model is slightly less acceptable.

10.5 Evaluating the proposed model

Table 10.3 shows how each dimension is rated and why it is rated the way it is for the usability of the model and Table 10.4 for the usefulness.

Table 10.3: The proposed model rated for its usability.

Dimension	**Rate**	**Explanation and reason**
Learnability	5	*How easy can the model be leaned?* It was very hard for a user who did not build the model to change variables that are hard-coded. Therefore it was necessary for the user of the model to be able to run it without going into the code. For instance, in the initial model, in which the order the subsystems are placed in the terminal, had to be manually coded for each airport. Every airport requires research to determine the order of placement. An automated method to determine and code the order would save time and increase the usability of the model. This issue is addressed through expert interviews and is discussed in Chapter 6. This is just one example of how the model is hard coded. The model is adjusted in a way that with basic knowledge of modeling and detailed knowledge of baggage handling systems, the model can be run *and understood* by the BHS designers of NACO. Thus, the designers do not have to go into any code, but only change airport specific values and run the model. Furthermore, to improve the learning process of the BHS designers at NACO, multiple learning sessions were created over the past months. First of all has the model run numerous times with BHS designers present to see how the process goes. Every time the designers had more understanding of the model. Furthermore, also a case study is organized to have the BHS designers use the model by themselves. This case was structured by following a manual, which explains every detail of the model. This case study and manual are presented in Appendix E. This manual is again an improved version of the one of the initial model.
Efficiency	7	*How efficient is the model in terms of time?* The computation time of the model was one of the main constraints of the initial model. Even more since bigger models did not provide any outcomes at all. To improve the computation time, several aspects of the model are addressed which are discussed in Chapter 3. The run time of the model decreased a lot. AUA takes 20 seconds (compared to 5 minutes in the initial model), AAS Area A about 12 minutes, TPE just over 7 hours, CIA 3 hours and 45 minutes, and the biggest airport NAICM just over 13 hours. All airports are thus run within 1 day. As the time to build a conceptual by hand takes about a month, these run times are fully acceptable.
Memorability	-	*How easy is it to use the model again?* The same reason as with the initial model still stands, so the memorability is not taken into account.
Errors	3	*What is the error rate?* The model still has the same input files, even one extra file, so the model is still prone to small mistakes, maybe even more. However, if enough time is taken to carefully insert the right data in the model, and the model manual is used, no mistakes should be made.
Satisfaction	6	*How happy are the users with the model?* Compared to how the initial model was rated, the improved model is more pleasant to evaluate, nothing is hard coded, it is possible to run several scenarios and compare them to each other, detailed transportation is added, the model is preciser, it is possible to include airport specific design decisions, and also brownfield airports can be run. Due to all these added features, of which most were requested by the BHS designers, it can be concluded that the satisfaction has gone up.

Table 10.4: The proposed model rated for its usefulness.

Dimension	Rate	Explanation and reason
Relevance	6	*Is the outcome helpful?* The results are even closer than before. Besides that, it is only a conceptual design and which the BHS designers can use as information. A model for a conceptual design will never replace the BHS designers, it could only guide their design decisions. Since the BHS designers use the outcome and compare it to their own result, the model is perceived as relevant.
Format	7	*Is the format of the model good?* Same reason as in the initial model still stands. Additionally, it is now possible to compare different scenarios through a interactive dashboard in Excel. This makes it even easier for the BHS designers to use the results.
Reliability	6	*Is the outcome from a credible source?* The issue for the reliability of the initial model was the limited scope of the model. Due to the small scope, the model was not reliable for all airports. Broadening the scope was a big part of the improved model. It is now possible to customize the BHS designs (see Chapter 6), also brownfield airports can be run (see Chapter 7), and since the run time of the model decreased, bigger airports can also be addressed. Since the scope of the model expanded, and the basics of the model are still the same as in the previous two models and thus already reliable, the reliability of the model increased.
Level	6	*How is the outcome shown?* Since the dashboard can be used to compare the results, several levels of detail can be analyzed. From just observing the differences between several scenarios and visualizing which settings are used, to a detailed outcome table. Since more levels are added, is is easier to compare results.
Timeliness	6	*Is the data up-to-date?* The same reason as in the initial model still stands.

10.6 Comparing the two models

In the initial model, not all dimensions are rated as acceptable. In order for the BHS designers at NACO to be able to use that model, the model needed to be improved to increase the usability and usefulness of the model. The focus of the thesis was thus to improve the initial model. Every chapter discussed and evaluated one or several improvements, which led to the proposed model.

Both models have been rated on the dimensions of the usability and usefulness of the model, which is shown in Figures 10.1 and 10.2. In the proposed model only one dimension, the errors, is rated as slightly unacceptable. All other dimensions are rated as slightly acceptable or higher. The error rate is still high because the model is complex and a lot of input is needed. If this is reduced, by building a simpler model, a lot of the model features would not be possible, reducing the relevance of the model. Even though the possibility to make errors decreased, the model complexity increased, which open ups the chance for more errors, resulting in the same evaluation of the errors. As this is the only dimension that is rated low, it can be concluded that the model is acceptable.

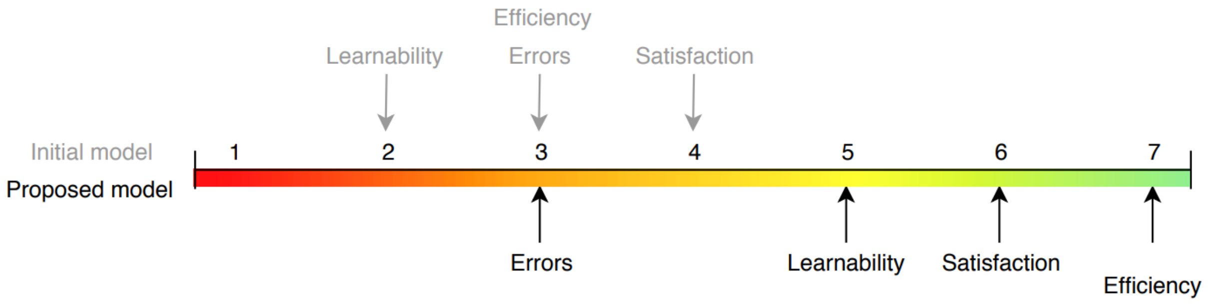


Figure 10.1: The dimensions of usability rated for both models.

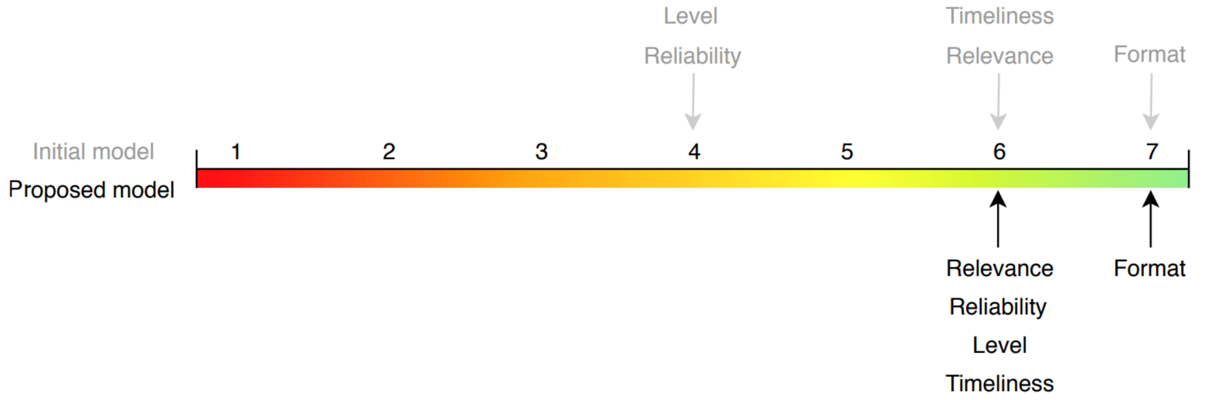


Figure 10.2: The dimensions of usefulness rated for both models.

10.7 Model reflection

Table 10.5 sums up the results of all cases run for this thesis. Two airports have been run during the duration of the research, the last three as tests to validate the model. The table shows all important aspects of the airports and all features that have been improved in this research. As can been seen, the airports range from very small, such as AUA, to very big, such as NAICM. The size of the airport is also reflected in the average run time for the airports. Just as expected, the bigger the airport, the longer the run time. Nevertheless, the relation between the size of the BHS and the run time is different. The bigger the area of the BHS does not necessarily increase the run time. The example of CIA clearly shows this. A reason for this is that the function that causes the long run time is the search for all available spaces. For every subsystem that needs to be done once. CIA is an airport where many pieces of equipment are placed, for which this function only has to be executed once. So concluded from this can be that a large BHS area does not necessarily mean a long run time. Nevertheless, all airports were run within 24 hours. So, the initial goal to have a maximum run time of 24 hours has been reached.

Furthermore, CAPEX calculations fit within the range of the cost cone of uncertainty, except for TPE. However, this is explained by the fact that probably the demand input was too low, resulting in less equipment and less space needed, which decreases the CAPEX. The 4th to the 11th row in the table show which aspects of the model have been used to generate the airport

Table 10.5: Reflection of the model.

	AUA	**AAS**	**TPE**	**CIA**	**NAICM**
Size airport [m^2]	8.100	41.000	165.240	60.000	105.600
Size BHS [m^2]	3.170	5.899	11.929	20.652	9.550
Average run time [h:min:s]	00:00:20	00:08:00	04:52:00	03:44:00	13:21:00
Cost difference [euro]	0.76-1.21	0.81-0.93	0.31-0.34	Unknown	1.19-1.36
Visualization	✓	✓	✓	✓	✓
Detailed transportation	✓		✓		
Placement order	Both	Capacity	Capacity	Capacity	Capacity
Decentralized	✓			✓	✓
Predefined floor level	✓	✓	✓		
Greenfield	✓		✓	✓	✓
Brownfield		✓			
Possible with initial model?	✓	*X*	*X*	*X*	*X*

scenarios. As can be seen every aspect of the model has been tested, and almost all have been tested multiple times.

The last part of the reflection is on if it is possible to do the case studies with the initial model. As can be seen, only AUA is possible with this model. AAS cannot be run since it is a brownfield project. For TPE it is needed to pre-define floor levels. Also CIA is not possible due to the need for decentralized subsystems. Even though a part of NAICM was run with the initial model, as this airport requires decentralized subsystems, the results are not accurate. Moreover, in the initial model TPE, CIA and NAICM probably have a run time which exceed the accepted 24 hours and might not even provide a result due to the needed computation power.

10.8 Other applications

Although the model is designed for BHS at airports, the model can also be used for similar problems. The model consists of a five step framework (see Figure FIG) of which the entire framework can be used, but also only one or a few steps of the framework. For instance, a BHS is of course not the only system at an airport. When designing an airport, every part from passenger screening, airport shops, to even toilets needs to be placed inside a terminal during the conceptual design phase. To be able to customize the designs, by placing subsystems decentralized and choosing the optimal order of placement, is especially important while using the model for other applications at an airport. Due to this there is a lot of room for specification in the problems to make the model applicable to these problems. Not only can the model be used for the conceptual design phase, also in the very beginning can the master planners at NACO (or other companies) use the model while planning the land use at an airport. During the land use planning every area of the airport gets a task, from BHS to terminal area and maintenance.

One of the important input in the model is a flight schedule. Due to this, the full model can only be used for airport placement problems. However, as soon as the demand for each subsystem is calculated, the rest of the model can be used for other placement problems as well. The model also has the option to insert these values manually, which ensures that the model is applicable to these placement problems. Other examples of similar placement problems are harbours, distribution centers and hospitals. Any system that consist of several subsystems that need to be placed in a certain area can be applicable to this model.

If the model is even further generalized, the model could also be applicable for bigger placement problems that exceed one building or area. An example of this is a smart city. As Mohanty, Choppali, and Kougianos (2016) state, "a smart city is a place where traditional networks and services are made more flexible, efficient, and sustainable with the use of information, digital, and telecommunication technologies to improve the city's operations for the benefit of its inhabitants". To become a smart city, the existing physical infrastructure needs to be transformed in an efficient, smart and green manner. Using a model such as the model for this thesis, can be a great way to plan how to transform a city into a smart city.

So, the model or concept behind the model can be used for other placement problems. In addition, also smaller concepts of the model can be used for other applications. Examples of these smaller concepts are the Droplet model and the A* algorithm as implemented in the model. The A* algorithm can be used for any tile based routing problem. An example of a tile based routing problem is a rail or highway network.

In conclusion, the model can be used for multiple other applications as well. It can be used for other placement problems at airports, but also for similar placement problems within a restricted area such a building and even bigger placement problems such as smart cities. Besides using the model for placement problems such as described, also smaller parts of the model, e.g. the Droplet model and the A* algorithm, can be used for other applications.

Chapter 11

Conclusion

Now that all sub-questions are addressed, the main research question can be answered. The main conclusion in Section 11.1 is followed by the discussion in Section 11.2 and the recommendations in Section 11.3.

11.1 Main conclusion

The goal of the research was to improve the existing model that automates the conceptual design phase of a BHS. The existing BHS model has limitations, such as an unacceptable long run time, only applicable to greenfield airports, not specific enough for brownfield airports, and profound uncertainties. The quality of a model can be examined by assessing the usability, e.g. how convenient the model is to use, and usefulness, e.g. the degree to which a model will provide the required results (Buchanan & Salako, 2009; Tsakonas & Papatheodorou, 2006). This led to the following research question: *How can the model for conceptual designs of baggage handling systems be improved, in order to increase the usability and usefulness of the model?*

In the first phase of this research, the model is examined to evaluate which parts of the initial model can be improved, in order to continue to develop the model for efficient use. First, the three most time relevant aspects of the model are renewed, which decreased the run time of the model by 50% to 75%, depending on the size of the airport. Second, a detailed routing algorithm is added in order to include more precise transportation between subsystems. Due to this, less time will be lost on designing and evaluating inadequate scenarios, as the transportation often causes problems in the subsequent BHS design phases. Furthermore, an interactive dashboard is developed to provide the possibility to compare and evaluate scenarios in the this initial stage of a BHS design.

The next research objective was to analyze how changes in the input parameters of the model, effect changes in the output of the model. As often input parameters are based on assumptions and can be uncertain, limiting these uncertainties can improve the model. The Sensitivity Analysis showed that most of the changes in the model outcome can be apportioned to changes in the type of equipment. Many factors can change the type of equipment chosen. However, as these changes can have a major effect, the impact on the outcome can be more significant than desired. Furthermore, another chunk of the changes in the model outcome can be apportioned to a slightly inaccurate optimization framework. The optimization in the model is split up into two phases, the ground equipment and the transportation optimization. The optimal ground equipment is chosen first. The optimal transportation equipment is dependent on these choices, as not all transportation equipment is compatible with every type of ground equipment. Though, the ground equipment of these two optimizations is not chosen based on the combined optimal choice, but on the separate optimal choice. This causes the model to produce somewhat non-optimal solutions. Within the chunk of changes of the variation of the optimization parameters, most of the inaccuracy can be apportioned to the optimization based on the energy consumption values. To reduce these miscalculations, the expected energy consumption of the second optimization is already taken into account in the first optimization.

Since the run time of the model decreased to a desired time, to further improve the model, more design options are added. In order to make the conceptual designs more realistic, the model has to take certain airport specific criteria into account. For instance, usually the optimal location in a terminal is the same for most subsystems. In which order the subsystems are placed, thus rating the importance of a subsystem, has a high impact on the BHS design. Another airport specific criteria is if a subsystem should be placed centralized, all in one central point of the terminal, or decentralized, divided over the area of the terminal. Also, the optimal floor level for a subsystem can be of great importance for a BHS design. These three design rules categories are added to the model as a possibility. Which option of each category is best to choose, can be obtained through the flow diagrams (presented in Chapter 6). These design rules add value to the model as this increases the models applicability to more airports and it is possible to build conceptual designs while taking airport specific characteristics into account.

The last adjustment of the model was to not only design greenfield airports, but also include brownfield airports in the model. As most of the BHS design projects are brownfield airports, this significantly increases the usefulness of the model. A case study is used to test the capability of the adjusted model. If CAPEX of the model outcome is within 50% of the final design, it can be classified as a valid 'conceptual design'. The case showed that the model outcome only differs between 15% and 33% of the final design, thus validating the model. Even though just one brownfield case study is completed, the fact that the outcome is more accurate than desired, could indicate that the developed model is already one step further than a conceptual design.

Until now the research focused on improving the model. Though, research has shown that, no matter how 'good' a model is, only if the user trusts the model, the model will be used for its capabilities. Thus, the rest of the research focused on how models can be trusted and how the trust in a model can be increased. Trust can be evaluated through three categories: dispositional, situational, and learned trust. Only the last two categories can be influenced. Trust in a model can be increased by positive interactions with the model. If an interaction is positive, can depend on the users self confidence and mood, but also on the complexity of the model and if it produces reliable outcomes. The more positive interactions the user has with the model, the higher its trust in the model. Thus, to increase trust in the model, the users should come in contact with it regularly, in a positive and definite manner. This was done for instance by giving a workshop to the future users, where they did a tutorial.

Three case studies have been conducted to test the model, after which both models are evaluated based on the usability and usefulness of the model. The model is proficient for bigger airports and has an acceptable run time. Furthermore, the calculated CAPEX is within range of the cost cone of uncertainty for conceptual designs, validating the model.

The main research question can now be answered: *How can the model for conceptual designs of baggage handling systems be improved, in order to increase the usability and usefulness of the model?* Whether a model is 'good', can be evaluated by assessing the usability and usefulness of the model. Only if the model has an acceptable usability and usefulness, which can be measured through several dimensions, the model will be used. These two concepts are assessed through the 7-point Likert scale of acceptability. A score of a 5 or higher indicates that the model is acceptable. The usability of the initial model was rated between 2 and 4 on a 7-point Likert scale of acceptability, with an average of 3.0. The usefulness of the model was rated between 4 and 7, with an average of 5.4. The improved model was rated between 3 and 7 for the usability, with an average of 5.3. The usefulness was rated from 6 to 7, with an average of 6.2. Thus, both the usability and the usefulness of the model increased on several dimensions (see Figures 11.1 and 11.2), leading to the conclusion that the proposed model is indeed an improvement of the initial model.

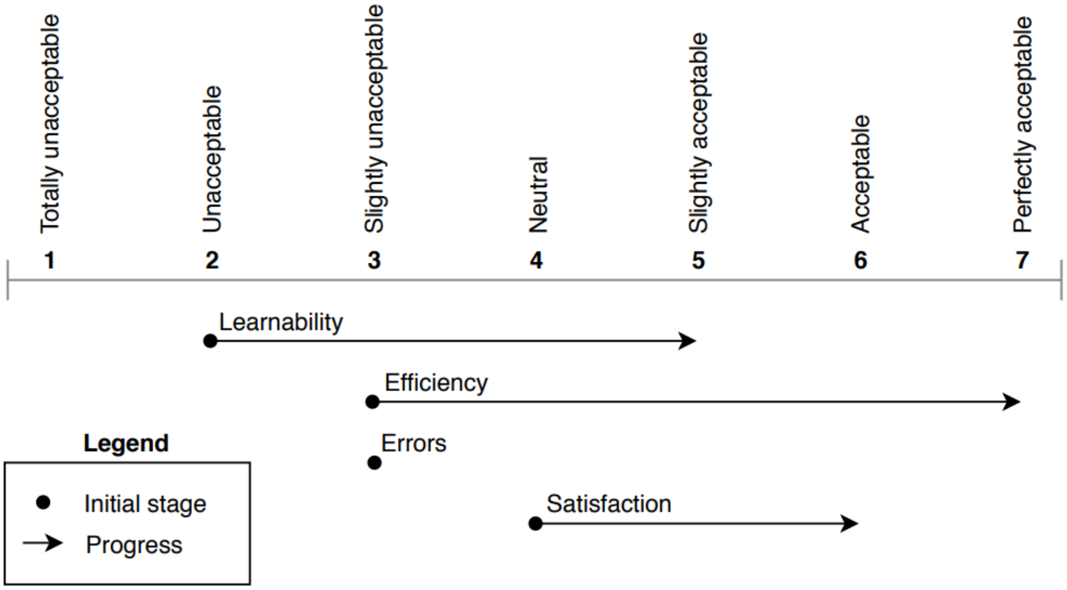


Figure 11.1: The development of the usability of the model.

As the model has reached an acceptable level of usability and usefulness, the chance that the model will be used by the BHS designers to guide their decisions is more likely than with the initial model. However, even if the model is 'good', when a user does not trust the model, he will not use it. Trust in a model can be increased if the user regularly has positive interactions with it. Thus, in order for a model to be used, the model needs to have an acceptable level of

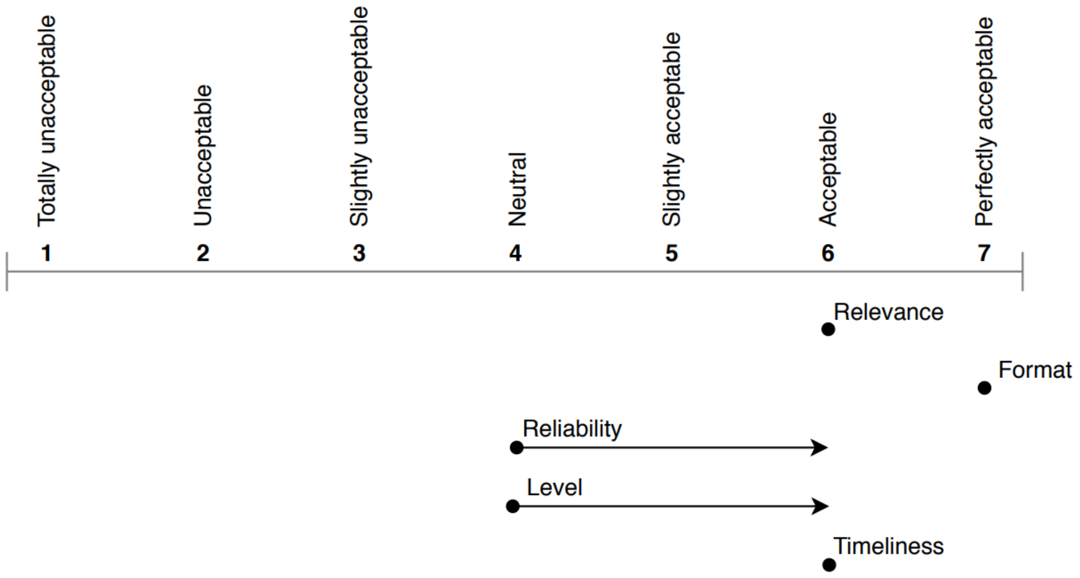


Figure 11.2: The development of the usefulness of the model.

usability *and* usefulness, and the users of the model need to trust it. In order to increase the trust in a model, the model needs to be improved to an acceptable level.

So in conclusion, a model can be improved by increasing both the usability and usefulness of the initial model. Multiple improvements to the initial model have led to the model proposed in this research. The usability has increased due to adjustments in the run time, a manual supporting the model and motivating the users to learn how to work with the model, and adding an interactive dashboard to visualize the results. Due to different improvements, such as expanding the scope of the model, increasing the model precision by limiting uncertainties, and adding levels of detail to the outcome, the usefulness increased. So, it can be concluded that since both facets of the model have increased, leading from the initial model to the proposed model, the goal of this research has been reached.

The work by Noort (2018) can be seen as a proof of concept for automated conceptual designs for a BHS. The further development of this concept by Vijlbrief (2019) brings the research a step further which can be seen as a proof of design. The research conducted in this thesis attempted to continue to develop the model to actually generate conceptual designs. The model has been modified to allow the users of the model to conveniently use it, increase the quality of the model, and broaden the scope to be able to apply it to different types of airport developments. So in the end, a more complete model is developed which can be applied to a wider range of airports.

11.2 Discussion

Just as any model, the model has constraints and restrictions. One of the biggest constraints is the way the optimal starting point for a subsystem in the placement algorithm is incorporated. These starting points have a major effect on the outcome, which is why they are included in many design options. For instance, at a greenfield airport when subsystems are placed decentralized, the starting points are divided over the optimal decentralized places. Meanwhile, when the BHS design is built for a brownfield airport, the optimal starting point is as close as possible to the already existing subsystem. In the meantime, when the subsystems are centralized at a greenfield airport, the optimal starting point depends on the check-in, reclaim and aircraft area, while taking the previously placed subsystem into account. However, only one starting point 'rule' can be chosen at a time. It is thus not possible to decentralize an already existing subsystem at a brownfield airport. Even though this is a limitation to the model, it ensures that the chosen starting points can be traced back. However, this limitation can be taken for granted since first of all these scenarios do not occur often, and second if it does occur, it is very difficult to choose the starting point rule that is more important.

Another restriction of the brownfield model is that it does not consider when it is better to move and rebuild a subsystem at a new location, rather than building the remaining pieces of equipment next to the existing subsystem. Though, as the cost of demolishing an existing subsystem is dependent on that subsystem, this is case specific. As it is not general for all airports, it cannot be considered in the model.

One of the objectives of the research was to make the model user friendly. A model is user friendly if it is easy to use, meaning that it not difficult to learn or understand. Splitting the model into three modules adds some extra steps to the model, which could make the model less user friendly, even if it improves the model. This thus had to be considered. However, the workshop showed that splitting the model did not make the model execution more complicated, but it actually increased the understanding of the model. As the model is executed and explained in modules, it is easier for the user to follow what is happening.

As one of the model improvements a more detailed transportation system is included, as transportation often causes problems in the subsequent phases of the BHS design. The A* algorithm is used to find these optimal transportation routes. The algorithm chooses the first found optimal path, and stops there, even if more routes are just as expensive. This can cause the routes to have many turn. The transportation equipment is more expensive when the baggage needs to turn rather than go straight. However, this is not included in the model. Every tile of transportation equipment in the model is just as expensive. The reason why it is not included is because, while discussing it with the BHS designers at NACO, it appeared that if there is space for routing, this already is detailed enough in the conceptual design phase.

It is very interesting to follow up on previous research. However, it can also complicate the research when it is based on a model developed by previous researchers. As understanding someones code can be complicated and time consuming by itself, using the code to continue the research can result in complications. For instance, in every project, assumptions need to be made. However, if these assumptions are not stated precisely, the research can continue with a different understanding of that assumption. This can cause mistakes in the research.

Furthermore, as it is difficult to have full understanding of all model details, if an error is made in the previous research, it usually continues in the follow up research. For example, every time a growth scenario was computed, the model kept giving an error that there was not enough space in the terminal. Yet, often the terminal was partly empty. After a while a coding error is found, that subtracted too much space for the screening machines. Even though in the end the coding mistake was found, as the code is not written by yourself, this process takes a lot of unnecessary time.

11.3 Recommendations

During this research a conceptual design tool for the BHS is developed which the BHS designers can use. Though, this does not mean the end of this research. To further develop the model and conduct more research on automating conceptual design tools, several recommendation can be done. As this research has been developed together with NACO, the recommendations are split up in further research and NACO specific recommendations.

11.3.1 Recommendations for further research

The type of equipment can change due to changes in demand, redundancy, equipment parameters, the desired sorting system, and the screening rejection rates. Small changes in these parameters can cause the type of equipment that is chosen to change. Though, as these equipment changes have such a major effect, it is interesting to find the 'break points' of when these changes occur. Finding these break points can be of high value, as these points indicate as of when another design is optimal, which provides a lot of valuable information in designing BHS conceptual designs. It is thus recommended to continue this research to find these break points and analyze the effect of them. By analyzing when these break points occur, more insight can be provided of as of when it is better to choose a different design.

Even though the model run time significantly decreased, the model can still take long for big airports such as NAICM. The long run time is mostly due to the function that determines the available spaces in the terminal for a subsystem. This function is added to decrease the run time when many pieces of equipment in one subsystem are placed. The problem with this function is that is searches the entire terminal for the available spaces. Thus, if the terminal is big, there are many spaces available, which takes time to search. To increase the speed of the model even more, the model could be improved to only search M number of available spaces that are closest to the optimal starting point. If no place is found in these available spaces, the model can continue to search the next M number of available spaces. So, another Droplet search.

As previously mentioned in the discussion, the model does not allow the option to tear down and rebuild an existing subsystem at another location. Even though this is not possible as it is airport specific, an improvement to the model would be to if the existing subsystem did not exist let the algorithm search for the optimal location and see if there is a better location. Though, as one of the goals of the model is to have a run time that is as short as possible, it needs to be analyzed if the added precision ways up against the added run time.

Furthermore, to increase the convenience of the model, it would be useful to be able to automatically delete types of equipment from the equipment parameter list. At the moment this needs to be done by hand and the total number of equipment types needs to stay the same. However, this brings up another recommendation. The optimization software that is used in the model is 'Windows Solver Foundation'. This package is relatively old and does not get updated anymore. The maximum number of decision variables that is possible, is limited to the number used in model. This is the reason why there is a maximum number of equipment types. Moreover, this optimization software is also one of the reasons why the model can produce non-optimal scenarios. This is the case because the maximum number of decision variables requires the model optimization to be split into the ground equipment optimization and transport optimization. A big step can be made in improving the model even more by changing the optimization software.

Last, the model develops a BHS design based on a flight schedule. This can be a current or expected future flight schedule. By using a future flight schedule, scenarios can be tested for future airport growth. As the number of equipment increases, assuming that the demand increase in the future, so does the cost. However, airports are unlikely to invest in future growth that is decades away. In addition, it is difficult to anticipate how technological innovations could change the BHS equipment and needs. Another consideration is that the airport at that moment does not need to build all of the future capacity, as it is a large additional investment, and thus may choose to only install some of the equipment. However, the model assumes the system works as a whole, so holding back on the installation of pieces of the equipment, changes the effectivity of the entire system. Thus, building part of a future system is not good option. Real Options Analysis (ROA) is a method that is used to reserve space for uncertain future implementation (Bowman & Moskowitz, 2001). This method can be used to incorporate future growth in the scenarios, without fully planning this growth, so that the growth scenarios are still flexible. It is recommended to research future growth of BHS designs with ROA.

11.3.2 Recommendations for NACO

The model designed for NACO works and can be used by the BHS designers. Though, this does not mean that the development of the model should stop. Besides the recommendations mentioned in the previous section, there are multiple ways the use of the model can be make broadly applicable. For instance, the model can be useful for other departments at NACO, such as the terminal planners, and even outside of NACO. It is thus recommended to search for links with the model between each department. Furthermore, the placement algorithm can be applicable for any grid-based placement problem. Even parts of this algorithm, such as the A* algorithm, can be used for other grid based routing problems.

Last, to further develop the model, it is recommended to link the terminal shape from Revit to Dynamo. As designing a BHS is only part of an airport design, the terminal is often already specified in Revit. This design is not only more accurate, it also saves time when using the model, as the shape does not have to be designed by hand.

References

Airbus. (2014). *Global Market Forecasts 2014-2033.* Toulousse: Airbus.

Anbuselvi, R., & Phil, M. (2013). Path Finding Solutions For Grid Based Graph. *Advanced Computing: An International Journal (ACIJ)*, *4*(2), 51–60.

Aruba Airport Authority N.V. (2019). *Aeropuerto Internacional Reina Beatrix.* Retrieved from `https://www.airportaruba.com`

Asman, A., & Srikanth, R. (2016). *A Top Domain Ontology For Software Testing* (Unpublished doctoral dissertation).

Astrup, R., Coates, K. D., & Hall, E. (2008). Finding the appropriate level of complexity for a simulation model: An example with a forest growth model. *Forest Ecology and Management*, *256*(10), 1659–1665. doi: https://doi.org/10.1016/j.foreco.2008.07.016

Belobaba, P., Odoni, A., & Barnhart, C. (2015). *The Global Airline Industry.* Wiley.

Boehm, B. W. (1984). Software Engineering Economics. *IEEE Transactions on Software Engineering*, *SE-10*(1), 4–21. doi: 10.1109/TSE.1984.5010193

Boeing. (2015). *Current Market OUtlook 2015-2033.* Seattle: Boeing.

Bowman, E. H., & Moskowitz, G. T. (2001, 12). Real Options Analysis and Strategic Decision Making. *Organization Science*, *12*(6), 772–777. doi: 10.1287/orsc.12.6.772.10080

Buchanan, S., & Salako, A. (2009, 10). Evaluating the usability and usefulness of a digital library. *Library Review*, *58*, 638–651. doi: 10.1108/00242530910997928

Camp, L. J. (2003). Designing for Trust. In R. Falcone, S. Barber, L. Korba, & M. Singh (Eds.), *Trust, reputation, and security: Theories and practice* (pp. 15–29). Berlin, Heidelberg: Springer Berlin Heidelberg.

Cavada, J. P., Cortés, C. E., & Rey, P. A. (2017). A simulation approach to modelling baggage handling systems at an international airport. *Simulation Modelling Practice and Theory*, *75*, 146–164. doi: https://doi.org/10.1016/j.simpat.2017.01.006

Chin, R., & Lee, B. Y. (2008). Chapter 15 - Analysis of Data. In R. Chin & B. Y. Lee (Eds.), *Principles and practice of clinical trial medicine* (pp. 325–359). New York: Academic Press. doi: https://doi.org/10.1016/B978-0-12-373695-6.00015-6

Chwif, L., Banks, J., & Pereira-Barretto, M. (2011). Estimating the implementation time for discrete-event simulation model building. In *Proceedings - winter simulation conference* (pp. 1774–1785). doi: 10.1109/WSC.2010.5678891

Chwif, L., Barretto, M. R. P., & Paul, R. J. (2000). On Simulation Model Complexity. In *Proceedings of the 32nd conference on winter simulation* (pp. 449–455). San Diego, CA, USA: Society for Computer Simulation International.

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly*, *13*(3), 319–340. doi: 10.2307/249008

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, *1*(1), 269–271. doi: 10.1007/BF01386390

Federal Aviation Administration. (2015). *Aviation Emissions, Impacts and Mitigation: A Primar.*

Frey, C., & Patil, S. (2002). Identification and Review of Sensitivity Analysis Methods. *Risk Analysis*, *22*(3), 553–578. doi: 10.1111/0272-4332.00039

Greenberg, S., & Buxton, B. (2008). Usability Evaluation Considered Harmful (Some of the Time). In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 111–120). New York, NY, USA: ACM. doi: 10.1145/1357054.1357074

Grigoras, C., D.R. & Hoede. (2007). *Design of a baggage handling system.*

Hart, N. N., P., & Raphael, B. (1968). A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Transactions Systems Science and Cybernetics*, *4*, 100–107.

Hoff, K. A., & Bashir, M. (2015). Trust in Automation: Integrating Empirical Evidence on Factors That Influence Trust. *Human Factors*, *57*(3), 407–434. doi: 10.1177/0018720814547570

Hoops, S., Hontecillas, R., Abedi, V., Leber, A., Philipson, C., Carbo, A., & Bassaganya-Riera, J. (2016). Chapter 5 - Ordinary Differential Equations (ODEs) Based Modeling. In J. Bassaganya-Riera (Ed.), *Computational immunology* (pp. 63–78). Academic Press. doi: https://doi.org/10.1016/B978-0-12-803697-6.00005-9

Hsu, W., & Liu, B. (2000). Conceptual design: issues and challenges. *Computer-Aided Design*, *32*(14), 849–850. doi: https://doi.org/10.1016/S0010-4485(00)00074-9

Hu, W.-L., Akash, K., Jain, N., & Reid, T. (2016). Real-Time Sensing of Trust in Human-Machine Interactions. *IFAC-PapersOnLine*, *49*(32), 48–53. doi: https://doi.org/10.1016/j.ifacol.2016.12.188

IATA. (2016). *IATA Forecasts Passenger Demand to Double Over 20 Years.* Retrieved from `https://www.iata.org/pressroom/pr/Pages/2016-10-18-02.aspx`

Inagaki, T. (2008). Smart collaboration between humans and machines based on mutual understanding. *Annual Reviews in Control*, *32*(2), 253–261. doi: https://doi.org/10.1016/j.arcontrol.2008.07.003

Iooss, B., & Lemaître, P. (2015). A Review on Global Sensitivity Analysis Methods. In G. Dellino & C. Meloni (Eds.), *Uncertainty management in simulation-optimization of complex systems: Algorithms and applications* (pp. 101–122). Boston, MA: Springer US. doi: 10.1007/978-1-4899-7547-8{_}5

Kazda, T., & Caves, B. (2015). *Airport Design and Operation* (C. Bob, A. Kazda, & R. E. Caves, Eds.). Emerald Group Publishing Limited. doi: 10.1108/978-1-78441-870-020153001

Khosravi, A., Nahavandi, S., & Creighton, D. (2009). Interpreting and modeling baggage handling system as a System of Systems. In *2009 ieee international conference on industrial technology* (pp. 1–6). doi: 10.1109/ICIT.2009.4939627

Kumar, V. (2002). *Introduction to Parallel Computing* (2nd ed.). Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc.

Kunze, A., Summerskill, S., Marshall, R., & Filtness, A. (2017). Enhancing Driving Safety and User Experience Through Unobtrusive and Function-Specific Feedback.. doi: 10.1145/3131726.3131762

Kwakkel, J., & Haasnoot, M. (2018). Supporting decision making under deep uncertainty: a synthesis of approaches and techniques. In *Decision making under deep uncertainty - from* *theory to practice* (chap. 17).

Kwakkel, J., & Pruyt, E. (2013). Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. *Technological Forecasting and Social Change*, *80*(3), 419–431. doi: https://doi.org/10.1016/j.techfore.2012.10.005

Lee, J. D., & See, K. A. (2004). Trust in Automation: Designing for Appropriate Reliance. *Human Factors*, *46*(1), 50–80. doi: 10.1518/hfes.46.1.50-30392

Lee, W. (2017). *Taiwan Taoyuan Int'l Airport named best airport in Asia-Pacific.* Retrieved from `https://www.taiwannews.com.tw/en/news/3110507`

Lemain, T. (2002). *Get the bag on the right track! 'Development of a new methodology for baggage handling system design' (MSc Thesis).*

Lim, S. K. (2008). *Practical Problems in VLSI Physical Design Automation.* Springer Netherlands.

Mapaila, M. (2012). *Efficient path finding for 2D tile-based games.* (Tech. Rep.). Cape Town, South Africa: University of CapeTown Rondebosch.

Mathew, G. E. (2015). Direction Based Heuristic for Pathfinding in Video Games. *Procedia Computer Science*, *47*, 262–271. doi: https://doi.org/10.1016/j.procs.2015.03.206

Mohanty, S. P., Choppali, U., & Kougianos, E. (2016). Everything you wanted to know about smart cities: The Internet of things is the backbone. *IEEE Consumer Electronics Magazine*, *5*(3), 60–70. doi: 10.1109/MCE.2016.2556879

Muir, B. M. (1987). Trust between humans and machines, and the design of decision aids. *International Journal of Man-Machine Studies*, *27*(5), 527–539. doi: https://doi.org/10.1016/S0020-7373(87)80013-5

NACO. (2018). *Terminal 3 Taiwan Taoyuan int. Airport.* Retrieved from `https://www.ibelingsvantilburg.nl/website/wp-content/uploads/2016/01/1771-I.pdf`

Neufville, R. d. (1994). The baggage system at Denver: prospects and lessons. *Journal of Air Transport Management*, *1*(4), 229–236. doi: https://doi.org/10.1016/0969-6997(94)90014-0

Nezamaldin, D. (2019). *Parametric design with Visual programming in Dynamo with Revit: The conversion from CAD models to BIM and the design of analytical applications* (No. 467).

Nielsen, J. (1993). *Usability Engineering.* San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.

Nievergelt, J. (2000). Exhaustive Search, Combinatorial Optimization and Enumeration: Exploring the Potential of Raw Computing Power. In V. Hlaváč, K. G. Jeffery, & J. Wiedermann (Eds.), *Sofsem 2000: Theory and practice of informatics* (pp. 18–35). Berlin, Heidelberg: Springer Berlin Heidelberg.

Noort, L. (2018). *Design of a Mathematical Model for Automated Generation of Baggage Handling System Concept Designs (MSc Thesis).*

Noyes, J., Cook, M., & Masakowski, Y. (2007). *Decision Making in Complex Environments.* Abingdon, United Kingdom: Chapman & Hall/CRC Press.

Ölvander, J., Lundén, B., & Gavel, H. (2009). A computerized optimization framework for the morphological matrix applied to aircraft conceptual design. *Computer-Aided Design*, *41*(3), 187–196. doi: https://doi.org/10.1016/j.cad.2008.06.005

O'Connor, T., Yang, X., Tian, G., Chatterjee, S., & Lee, S. (2017). Quality risk management for pharmaceutical manufacturing: The role of process modeling and simulations. In P. Pandey & R. Bharadwaj (Eds.), *Predictive modeling of pharmaceutical unit operations* (pp. 15–37).

Woodhead Publishing. doi: https://doi.org/10.1016/B978-0-08-100154-7.00002-8

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering design: a systematic approach LK* (3rd ed. NV ed.). London: Springer.

Peffers, K., Tuunanen, T., Rothenberger, M., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, *24*, 45–77.

Pielage, B. (2005). *Conceptual design of automated freight transport systems.*

Pipino, L. L., Lee, Y. W., & Wang, R. Y. (2002, 4). Data Quality Assessment. *Commun. ACM*, *45*(4), 211–218. doi: 10.1145/505248.506010

Potdar, G., & Thool, R. (2014). Comparison Of Various Heuristic Search Techniques For Finding Shortest Path. *International Journal of Artificial Intelligence & Applications (IJAIA)*, *5*(4), 63–74.

Reddy, H. (2013). Path finding - Dijkstra's and A* Algorithm's.. Retrieved from `http://cs.indstate.edu/hgopireddy/algor.pdf`

Rengelink, W., & Saanen, Y. A. (2002). Improving the quality of controls and reducing costs for on-site adjustments with emulation:an example of emulation in baggage handling. In *Proceedings of the winter simulation conference* (Vol. 2, pp. 1689–1694). doi: 10.1109/WSC.2002.1166452

Russell, S., Norvig, P., Canny, J., Malik, J., & Edwards, D. (1991). Gordian: VLSI placement by quadratic programming and slicing optimization. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, *10*(3), 356–365. doi: 10.1109/43.67789

Russell, S., Norvig, P., Canny, J., Malik, J., & Edwards, D. (1995). *Artificial Intelligence: A Modern Approach.* Upper Saddle River, N.J.: Prentice Hall, Englewood Cliffs.

Saltelli, A., Chan, K., & Scott, E. M. (2009). *Sensitivity Analysis.* New York: Willey.

Schiphol. (2018). *Key figures 2018.* Retrieved from `https://downloads.ctfassets.net/biom0eqyyi6b/3hKtd12g8MKy9N4z4sEk4B/cb72fcedb870e474e755943d61c305c2/95652_SPL_Media_Facts___Figures_2018_boekje_MEI_2.pdf`

Seffah, A., Donyaee, M., Kline, R. B., & Padda, H. K. (2006). Usability measurement and metrics: A consolidated model. *Software Quality Journal*, *14*(2), 159–178. doi: 10.1007/s11219-006-7600-8

Shanks, N., & Bradley, A. (2005). Hold Baggage Screening. In *Handbook of checked baggage screening: Advanced airport security operation* (pp. 7–53). London: John Wiley & Sons.

Silven, A. (2018). *Autonomous Transport Robots in Baggage Handling Systems: A study on the use of autonomous individual transport robots in baggage handling systems at medium-sized regional airports operating in a point-to-point network (MSc thesis).*

Stanley Dicks, R. (2002). *Mis-usability: on the uses and misuses of usability testing.* doi: 10.1145/584955.584960

Tombros, A., Ruthven, I., & Jose, J. M. (2005, 2). How users assess Web pages for information seeking. *Journal of the American Society for Information Science and Technology*, *56*(4), 327–344. doi: 10.1002/asi.20106

Tsakonas, G., & Papatheodorou, C. (2006, 6). Analysing and evaluating usefulness and usability in electronic information services. *Journal of Information Science*, *32*(5), 400–419. doi: 10.1177/0165551506065934

Vagias, W. M. (2006). *Likert-type scale response anchors* (Tech. Rep.). Clemson International Institute for Tourism & Research Development, Department of Parks, Recreation and

Tourism Management.

Vijlbrief, M. (2019). *Automation of the conceptual design stage for material handling systems (MSc Thesis).*

Wang, L., Shen, W., Xie, H., Neelamkavil, J., & Pardasani, A. (2002). Collaborative conceptual design—state of the art and future trends. *Computer-Aided Design*, *34*(13), 981–996. doi: https://doi.org/10.1016/S0010-4485(01)00157-9

Yang, S., Tian, W., Cubi, E., Meng, Q., Liu, Y., & Wei, L. (2016). Comparison of Sensitivity Analysis Methods in Building Energy Assessment. *Procedia Engineering*, *146*, 174–181. doi: https://doi.org/10.1016/j.proeng.2016.06.369

Yang, Z., Cai, S., Zhou, Z., & Zhou, N. (2005). Development and validation of an instrument to measure user perceived service quality of information presenting Web portals. *Information & Management*, *42*(4), 575–589. doi: https://doi.org/10.1016/j.im.2004.03.001

Zissis, D., & Lekkas, D. (2012). Addressing cloud computing security issues. *Future Generation Computer Systems*, *28*(3), 583–592. doi: https://doi.org/10.1016/j.future.2010.12.006

Part I

Appendices

Appendix A

Confidential appendix

This appendix is intentionally left blank due to confidentiality reasons.

Appendix B

Baggage Handling System Equipment

Vijlbrief (2019) analyzed in detail which parameters are needed to develop a BHS concept design (for NACO). This appendix summarizes his findings, which are needed to understand the concept BHS design. The parameters are discussed and improved with input from the members of the Baggage Handling Team at NACO. Each subsystem from Figure 1.1 will be discussed.

Each type of equipment has certain characteristics or parameters. They have dimensions (height, length and width), a capacity (in bags/hour, positions or MUPs), a CAPEX (in Euro or Euro/meter), how many operators are needed per equipment element, the energy consumption of the machine (in Kwh), the level of automation (ranked from 1, totally manual, to 7 fully automated), the amount of time a bag spends in the system (in minutes or meter/second), and sometimes a transportation speed.

B.1 Check-in

At check-in the departing passengers drop off their bags and the bags are loaded into the BHS. There are three types of equipment that can be used for the BHS design:

- **Staffed counter:** The passengers check in their bags at a counter which is manned by one operator.
- **One-step-drop-off:** This is a self service check-in, where the passenger checks-in, tags his bag and drops it off himself. Only one operator is necessary per 5 check-in machines.
- **Two-step-drop-off:** This is also a self service check-in, but the check-in and drop off of bags is done through separate machines.

B.2 Hold Baggage Screening

The hold baggage screening (also HBS) is the security system for baggage at the airport. As Shanks and Bradley (2005) define it, "the application of technical or other means which are

Figure B.1: Staffed counter.

Figure B.2: One-step-drop-off.

Figure B.3: Two-step-drop-off.

intended to detect weapons, explosives or other dangerous devices which may be used to commit an act of unlawful interference."

The HBS is divided into 3 levels (shown in Figure B.4). From check-in, all bags go through an automated explosive detection system (EDS). These machines automatically check for irregularities by measuring for explosive substances. If a bag passes the EDS check, it goes straight to the sorting system. If the bag did not pass the check, it goes to level 2 screening. At level 2, operators check the images of the bags using on-screen resolution (OSR) tools, within 45 seconds of leaving the EDS machines. Again, if the bag is accepted, it goes straight to sorting, otherwise to screening level 3. In this last stage the bag is checked manually using explosives trace detection (ETD) equipment. If the bag is still rejected at this point, it leaves the BHS.

As each level of screening uses different equipment, the equipment is categorized per level of screening:

- ***EDS:*** Automated machines check for explosives and provide a three-dimensional view of the bag's contents. The machines are categorized based on their capacity.
  - **High speed EDS:** A high speed EDS is an in-line EDS. It is the fastest machine.
  - **Medium speed EDS:** This is also an in-line EDS, but it has a slight reduced speed.
  - **Low speed EDS:** A low speed EDS is a stand-alone EDS. It is the simplest system. The screeners have to manually load the bags in and out of the EDS unit.
- ***OSR:*** An operator who is trained to analyze the EDS images, checks the bags. The OSR machines are categorized by one equipment type.
- ***ETD:*** An operator takes a sample of the bag and checks it for explosives. There are two types of searches.
  - **ETD normal search:** An operator searches the bag by swiping the outside for explosives.
  - **ETD full search:** An operator opens the bag and searches and swipes the whole bag or part of the bag that seems irregular.

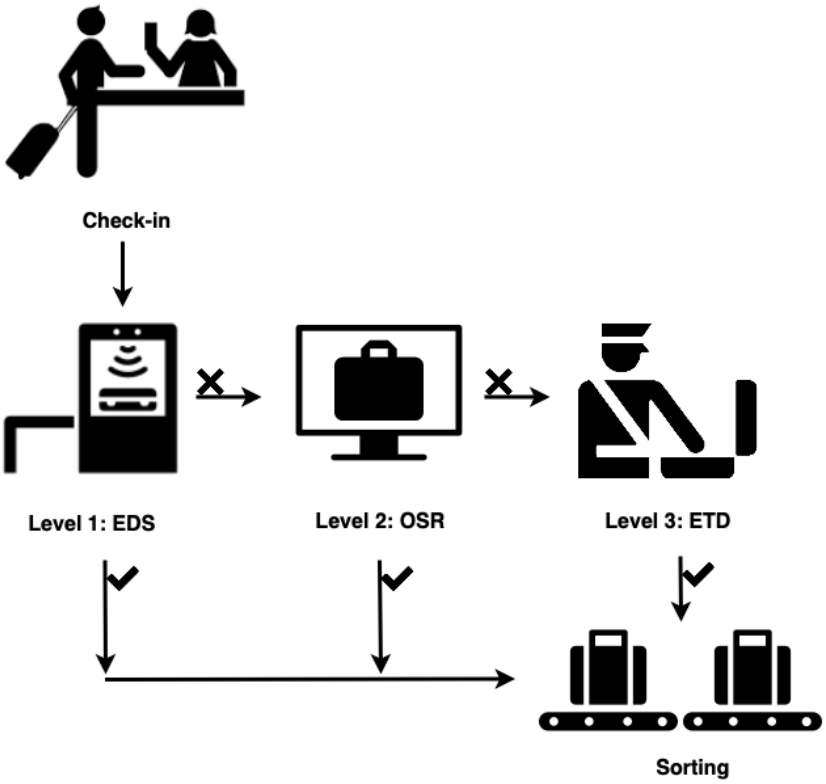


Figure B.4: Hold Baggage Screening process.

B.3 Transport

Baggage needs to be transported from one system to another. However, in this research transportation is referred to the transportation between screening, sorting and make-up. After screening, which is discussed in the previous section, the baggage is transported to the sorting area. Vijlbrief (2019) divided the transportation equipment into four types:

- **Belt conveyor:** Bags are loaded onto a conveyor belt and transported over the belt.
- **Destination Coded Tray (DCT):** Bags are loaded into trays, which are transported through a conveyor system.
- **Destination Coded Vehicle (DCV):** Bags are loaded into individual carts (instead of trays), that are individually powered.
  - **DCV type 1:** Self propelled carts that are equipped with a conveyor belt, and so the carts can load and unload themselves.
  - **DCV type 2:** External propelled carts that are not equipped with a conveyor belt, so they need additional loading devices.

Figure B.5: Belt conveyor.

Figure B.6: DCT.

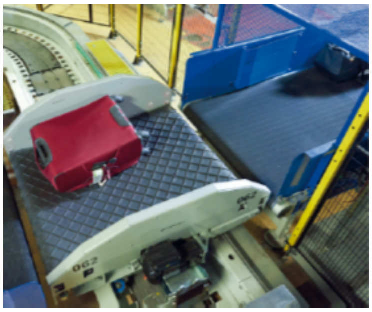


Figure B.7: DCV type 1.

Figure B.8: DCV type 2.

B.4 Sorting

After screening the bags are transported to the sorting area. In the sorting process, bags are sent to the right make-up position or if bags are in the system early, to Early Baggage Storage (EBS). The sorting usually happens through sorting loops, of which the loops consist of one of the transportation equipment types discussed in Section B.3. Each sorting equipment type is discussed per transport type.

- ***Belt conveyor***
  - **Cross belt sorter:** The conveyor consists of individual carriages, which are linked together to form a loop. Each carriage has a smaller belt conveyor that is perpendicular to the travel direction.
  - **Push tray:** The conveyor consists of an ongoing chain of trays, where bags are pushed off by sliders.
  - **Tilt tray:** Also this conveyor consists of an ongoing chain of trays, but here the bags are removed by tilting the tray towards the desired output.
  - **Pusher low speed:** A machine that pushes the baggage at low speed.
  - **Pusher high speed:** A machine that pushes the baggage at high speed.
- ***DCT***

  - **Static discharge:** The tray or cart comes to a complete stop before discharging the bag.
  - **Dynamic discharge:** The bag is discharged while the tray or cart is still travelling.

- ***DCV type 1:*** Since the conveyor can load and unload automatically, no additional sorting equipment is needed. However, there are different types of unloading configurations.
  - **Chute:** Bags are unloaded onto a chute while the cart is still moving.
  - **Parallel:** Bags are unloaded onto a parallel conveyor belt while the cart is still moving.
  - **Single:** Static discharge, where individual bags are unloaded while the cart stands still.
  - **Double:** Static discharge, where two bags are unloaded at the same time, while the carts stands still, into the same conveyor. The carts are parallel to each other.
- ***DCV type 2***
  - **Single:** See previous description.
  - **Double:** See previous description.

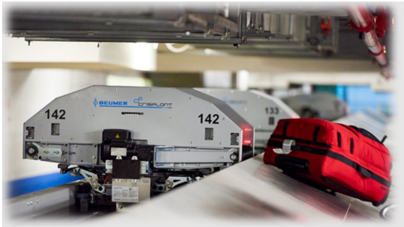


Figure B.9: Cross belt sorter.


Figure B.10: Push tray.

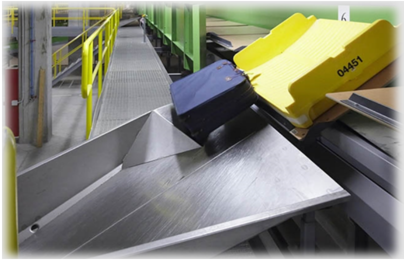


Figure B.11: Tilt tray.


Figure B.12: Pusher.


Figure B.13: Chute.

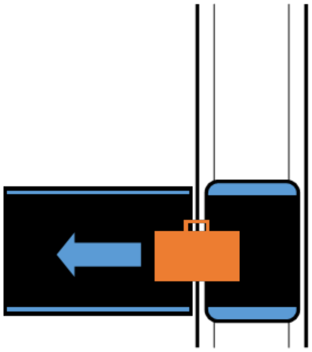


Figure B.14: Single.

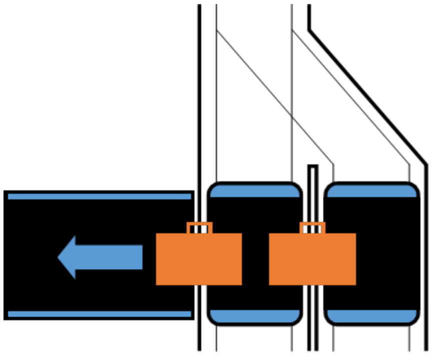


Figure B.15: Double.

B.5 Make-up

The baggage can leave the BHS in two ways. For arriving passengers it leaves the system through reclaim, for departing and transfer passengers through make-up. Make-up consists of two steps, the loading and the outlet. First the outgoing baggage is loaded into load units (the loading part), after which the unit load devices (ULDs) are transported to vehicles which take them to the aircraft (the outlet part).

The capacity of make-up is not defined by the amount of baggage, but by the amount of make-up points (MUPs) needed. A MUP is a point in the make-up area where bags of a certain flight are stalled for loading. The amount of MUPs needed depends on the size of an aircraft. There are three aircraft types: wide-body (WB), narrow-body (NB) and regional jets (RJ). The amount of MUPs needed per aircraft type differs per airport, as every airport applies their own rules.

In the outlet part, the transportation can happen in two ways. It can be directly at the MUP, where the ULDs are already connected to the vehicle when they are loaded at the MUP. The operator then fills the ULDs and the vehicle drives away when the operators are finished. However, for this method the make-up area needs to be big enough for the vehicles to drive and turn. The second way the transportation can happen is through automated load unit transportation (ALT). The ULDs are on a roller conveyor. The conveyors are placed next to the MUPs and are connected to external discharge stations. When an operator has filled an ULD, it is transported to the external output and connected to the vehicles. As the vehicles do not need to enter the make-up area, less space is required.

The equipment that is used for make-up is divided into the two parts:

- ***Make-up loading***
  - **Chute:** The most basic equipment type that is available. It is an inclined surface which can accumulate several bags. One chute equals 1 MUP and requires one operator.
  - **Lateral:** A lateral is a straight conveyor belt. Multiple bags can accumulate over the

belt and operators take the bags off the belt. One lateral equals 4 MUPs and has up to two operators.

- **Carousel:** A carousel is a lateral loop, so a loop of made of conveyor belt. One carousal equals 12 MUPs and can have up to four operators.
- **Robot:** An operator can be replaced by a robot. However, the robots can only handle bag containers and work in fenced off areas. One robot equals 1 MUP. For every couple of robots an operator is needed to help if a robot cannot load a bag.

- ***Make-up outlet***
  - **Train:** A vehicle located at the MUP, where an operator loads it.
  - **Non-driven ALT:** Operators push the ULDs over the roller deck.
  - **Driven ALT:** The rollers are driven and transport the ULDs.
  - **Tranfser vehicle ALT:** Transport vehicles individually transport ULDs through the system, like automated guided vehicles.

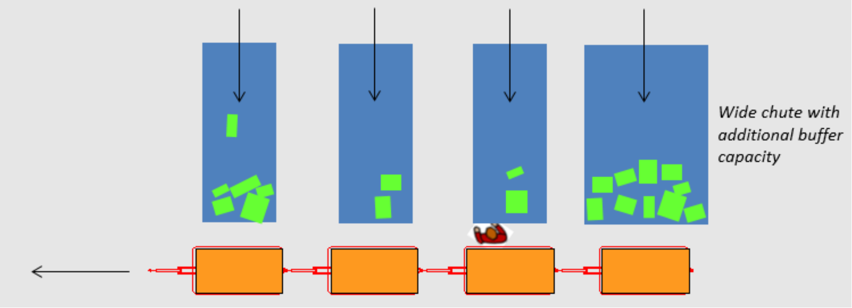


Figure B.16: Chute.

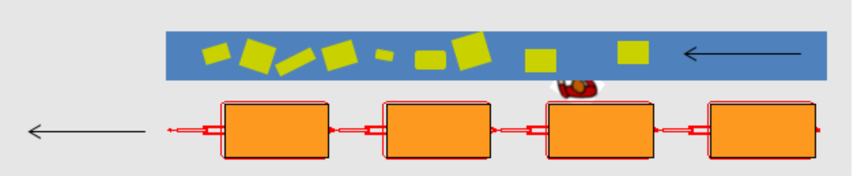


Figure B.17: Lateral.

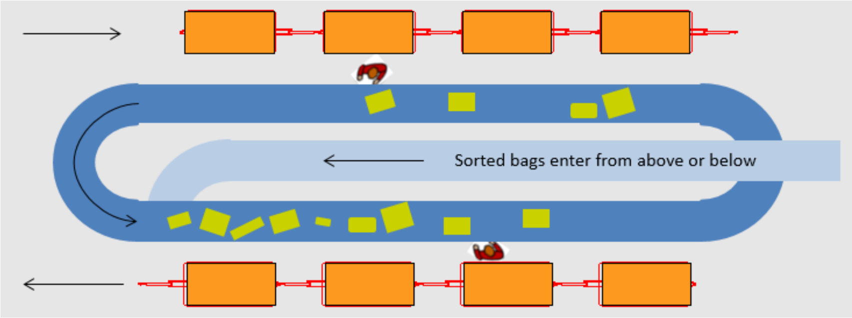


Figure B.18: Carousel.

Figure B.19: Train.

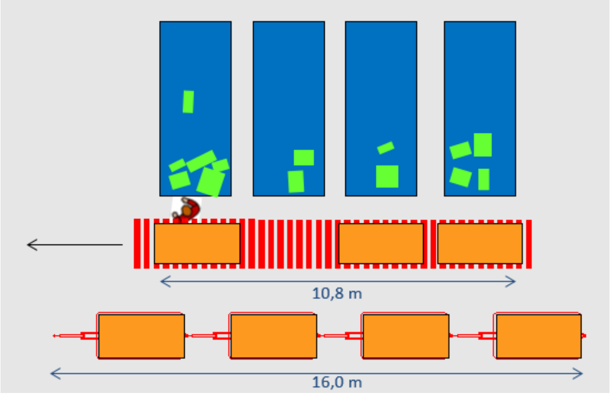


Figure B.20: ALT.

B.6 Early baggage storage

Big airports often use early baggage storage (EBS). In EBS, bags which arrive at the sorting system before any MUPs are assigned to their flight, are stored here. There are three types of equipment:

- **Lane:** Lanes of conveyor belts are assigned to flights. If bags arrive early, they go to that lane. As soon as a flights MUP opens, the late is unloaded into the sorting system.
- **Individual:** Bags are loaded onto individual storage units, which have a conveyor belt.
- **Rack:** Bags are loaded onto treys, which are then loaded into a rack. There are two kinds of racks:
  - **Shuttle rack:** Can only move vertically along the rack.
  - **Shuttle rack:** Can move both ways along the rack, horizontal and vertical.

Figure B.21: Lane.

Figure B.22: Individual.

Figure B.23: Rack.

B.7 Offloading

The baggage from the transfer and arriving passengers enter the BHS through offloading. The bags arrive in ULDs and are unloaded on a conveyor belt. This conveyor takes the bags further into the system. Except for the conveyor belt, no other equipment is used during offloading. However, the offloading process can be automated when using a bag tipper. This device shakes and tilts the ULDs, so that the bags slide out and land on the conveyor belt.

B.8 Reclaim

Reclaim is the second output point of the BHS. This is where the arriving passengers retrieve their bags from a reclaim unit. Almost all airports use reclaim carousels. There are two different types of reclaim carousels:

- **Flat belt:** Can hold one bag along the width.
- **Tilted belt:** Can hold two bags along the width.

Figure B.24: Flat belt.

Figure B.25: Tilted belt.

Appendix C

Placement functions

This appendix describes the functions that are used to place the subsystems.

General functions

- **CoorToTile(x,y):** Changes coordinates to a tile number. This is the numbering system that is used in the entire placement code.
- **MidPoint(System):** Calculates the middle tile of one subsystem containing several equipment's.
- **CenterEquipment(OneEquip):** Calculates the middle tile of one equipment.
- **CenterEquipments(Sub):** Calculates the middle tile between several types of equipment in one subsystem. This function is different from the 'MidPoint'-function because it will calculate the middle when not all equipment's in a subsystem are placed yet. It is needed to find the new starting point for the next equipment that will be placed.
- **MidStart(System1,System2):** Calculates the middle tile *between* two subsystems. If the ideal place for a subsystem is in between two others, this function is used to find the best tile.
- **MidFixed(Fix):** Calculates the middle point between one of the fixed points (aircraft point, reclaim point or check-in). These fixed points are the entrance and outlet points of a BHS. This function is used when a subsystem needs to be centralized, but there are several in- or outpoints and the subsystem needs to be placed in the middle of it.
- **EquipmentDirection(Equipment):** Determines the direction in which an equipment should be placed. The equipment is placed modular. Thus, if the terminal width is larger than the length, the equipment is placed in the way that the width is smaller than the length.

Make grid

- **CreateGrid():** Make the grid, e.g. the terminal, in tile numbers.
- **OpenGrid():** Get all the spaces in the grid that are blocked by shapeblocks and delete these from the grid. Shapeblocks are spaces in the grid that cannot be used for the BHS or fall outside of the terminal. Due to modeling purposes the grid is always a rectangle. If the terminal is not a rectangle, this is rectified by placing shapeblocks.

- **OpenGrid2(Placed):** Removes tiles of already placed subsystems.

Determine the available spaces

- **EliminateSpaces(Equip,level):** Gets all the available spaces for a subsystem. So if three blocks next to each other are not available, but they are not available, but they are needed, that space is deleted from the available spaces.

Droplet model

- **Droplet(Startpoint,N,floor):** Gives all the tiles of circle N that are still available in the OpenGrid. Section 1.4.4 describes in more detail how this function works.

Placement of a subsystem

- **PlaceEquipment(Start,AvailableSpacesAll,floor):** The placement of one equipment in a subsystem. This function searches for the first best location to place an equipment. Figure 3.5 shows how this function works.
- **PlaceSubsystem(Startpoint,Equip,Placed,floor):** The placement of an entire subsystem. This function executes the function 'PlaceEquipment' for every equipment in a subsystem. Figure 3.5 also shows how this function works.
- **NextLevel(Equip,floor,Start,AvailableSpacesAll):** If there is no space available on the optimal floor level, the search for a place moves up to the next level. This continues until a place is found or there is no space on any of the floor levels (and the function returns "No space found").

Routing

- **PlaceLift(Sys1,Sys2,EquipLift):** If two subsequent subsystems (thus two subsystems that need routing in between) are not on the same floor level, a lift is placed in order to be able to connect the two subsystems.
- **SurroundingTiles(Sys,All=False):** Provides a list of the tiles directly next to the subsystem. There are two options. First, the function can be used to find *all* the surrounding tiles, even if some tiles are not available anymore. This is used to determine if two subsystems are directly next to each other. Second, the function is used to find all the surrounding tiles that are still available. This is used for the actual routing.
- **StartingTiles(SurTiles1,SurTiles2):** Gets the starting and ending tiles which are needed for routing.
- **Routing(SurTiles1,SurTiles2):** Finds routes between two subsystems, based on the A* algorithm. It searches for the best route out of the tiles that are still available.
- **PlaceTransport(Subs):** This function actually places the transportation that is needed between the subsystems.

Equipment calculations

- **CalcEDS():** Placement of the EDS machines (screening level 1). This function calls the function 'PlaceSubsystem' to actually place the subsystem. The EDS machines can be placed centralized or decentralized, depending on which switch is turned on.
- **CalcMU():** Placement of make-up, by calling the function 'PlaceSubsystem', which can also be centralized or decentralized.
- **CalcQuayT():** Placement of offloading transfer equipment (by calling the function 'PlaceSubsystem'). Again it can be centralized or decentralized.
- **CalcEBS():** Placement of the early baggage storage (by calling the function 'PlaceSubsystem').
- **CalcETD():** Placement of the ETD machines (by calling the function 'PlaceSubsystem').
- **CalcOSR():** Placement of the OSR machines (by calling the function 'PlaceSubsystem').
- **CalcSort():** Placement of the sorting equipment (by calling the function 'PlaceSubsystem').

Convert data to Dynamo input

- **PlaceBlock(PlacedEquip,Equip,lift=False):** Converts the equipment & lift data to the right input data, that can be used in Dynamo.
- **Tlength(Sys1,Sys2):** Calculates the transportation distance between two subsystems.
- **Circumference(Sys):** Calculates the circumference of a subsystem.
- **TransportCalc():** Calculates the transportation distances that are needed to calculate the transportation cost in the next phase.

Appendix D

Interviews

In order to find the important design decisions that are made when designing a BHS in a terminal, several interviews were held. These interviews helped in defining which topics have a big influence on the design and thus are important to consider when modeling a concept design. The ideal model can design a scenario specific built for that airports' characteristics, but still able to design different scenarios. A balance needs to be found in designing realistic though still original scenarios. In other words, the scenario space needs to be limited to scenarios that fit a certain airport, but not limited to much to be able to only design tunnel vision scenarios. This appendix provides a summary of the interviews that were held to discover the important design rules that are implemented into the model.

D.1 Interview 1

The first interview was held with Piet Ringersma on April 10, 2019. Ringersma is one of NACO's airport functional planners. Ringersma is involved in the initial terminal design, among other things reserving spaces for all the different airport systems. He is the first person to think about the placement of systems. As this line of thought effects the system, it is important to incorporate this into the design process. The main findings of the interview with Ringersma are as follows:

Check-in and reclaim

- If there are multiple floors, the reclaim area should be placed below the check-in area. Actually it is preferred if reclaim has a double ceiling (thus takes two levels) for the space to feel open. So if there is enough space and at least 3 levels, reclaim should be placed two levels below check-in.
- Check-in is are preferably not placed on the same level as baggage screening. The reason for this is that if the systems are placed on the same level, the baggage needs to go to another floor to transport between the two systems and then back to the same floor. The same goes for reclaim and offload.

Screening

- If all baggage in the system needs to be 'clean' (meaning that it already needs to be screened and cleared before it enters the rest of the system (i.e. EBS or sorting), an extra HBS is needed for the transfer bags. If the baggage does not need be be clean, it can be offloaded into the sorting system which will direct it to HBS.

Sorting, make up and offloading

- Sorting is preferred above make up rather than below make up because of three reasons:
  1. This is the way to utilize the space above make up.
  2. In this manner one supplier for the systems can be in one room instead of having to move between floors.
  3. The tender for baggage is often done before the tender for the building. Due to this it is very difficult to reserve room for sorting in a basement, because often just a part of the basement is then used (based on the efficiency of the tender). If sorting is above MU, the space that is left over can be used for something else.
- Make up and offloading are preferably placed on the same level.
- The the airport is not willing to drive on a ramp between make up and the aircraft, make up has to be on the same level as airside. If the airport is willing to drive on a ramp, make up can be placed a floor level below airside.

EBS

- If the demand for EBS is high, the EBS is often placed in a different part and can thus be placed last.

Remaining findings

- Airport systems are preferably placed modular (i.e. in the other direction that the terminal is). If the systems are placed modular the airport is more flexible which is useful during airport expansions.
- If the terminal layout is finger piers, linear or transporter, the systems are often centralized. If the terminal layout is satellites or midfield, the systems are often decentralized.
- The level of airside and landside has an effect on which systems or optimal on which floor level.

D.2 Interview 2

The second interview was held with Henk Brandsma on April 10, 2019. Brandsma is a senior technical consultant at NACO. His job is to find and integrate effective procedures and BHS systems to support the airport, airlines and handlers. Brandsma has a lot of detailed knowledge about baggage handling systems and equipment. The main findings of the interview with Brandsma are as follows:

Screening

- If there are a lot of transfer passengers inside a terminal, HBS level 1 can be decentralized.
- If make up is decentralized, HBS level 1 can be decentralized.
- If the baggage from transfer passengers does not need be screened, it can be offloaded directly into the sorting system which will direct it to HBS. This option is cheaper qua equipment because less equipment is needed.

Sorting, make up and offloading

- All operations including driving vehicles, thus make up and offloading, are preferably placed on the same level.
- If the client has no preference in floor level for make up and offloading, the systems are preferably placed on apron level. If there is not enough space for both subsystems, it is more important that make up is placed on apron level as make up is time critical. Additionally, if make up is on apron level and offloading a level below, the 'full' vehicles (filled with suitcases) do not have to drive uphill.
- Make up is time critical, and therefor needs to be as close as possible to the point where baggage exits the building to the aircraft.
- The terminal layout has effect on if make-up and offloading is decentralized or centralized. In principle, finger piers, linear or transporter (remote stands) is a centralized system. Satellite or midfield is a decentralized system.

EBS

- If it is possible, the EBS can also be used as storage (for multiple processes), not just 'early' baggage. Different placement rules then hold:
  - EBS can be decentralized, because early baggage is not time critical.
  - If possible baggage storage should be close to sorting, because baggage is also stored for other reasons.
- The bigger the airport, the higher the change that it is required to have an (E)BS.
- The optimal location to route the baggage to an (E)BS is part of the sorting process, as this reduces the number of times baggage needs to be sorted.

Remaining findings

- Odd size baggage is not taken into account in this model, but accounts for approximately 5% of the baggage. This baggage also needs to be processed and thus space needs to be reserved for these systems, and actually needs to be placed in the terminal. Odd size baggage consists of all baggage that cannot go through the normal baggage process, such as heavy bags, odd size, animals, etc.
- If the terminal is a low cost carrier, the entire system is likely to be centralized. This is the case because there are no transfer bags.
- The trade-off between a centralized or a decentralized system is how big the distance for baggage handling is.

- The importance in order of placement is make up, offload, HBS level 1, and then the rest.
- Transport between subsystems is best to connect between center points of the subsystems.

D.3 Interview 3

The third interview was held with Alisa Silven on May 8, 2019. Alisa is an airport consultant at NACO for special airport systems, mainly baggage handling systems. The main findings of the interview with Silven are as follows:

Check-in and reclaim

- The location for the check-in system is very important since it involves passengers. Even though the model does not place the check-in system, it would be handy to be able to place it.

Screening

- Screening machines are extremely heavy, and therefor preferably need to be placed on a concrete floor.
- Screening level 1 does not have first priority in placement order, but it is preferred if it is placed sooner rather than later.
- Preferably HBS level 1 is placed near the outer walls of an airport. This is preferred because replacing these systems is already really hard (very heavy and big, need to be moved by forklift truck) and if system is in the middle, the forklift truck first needs to pass the other rooms in order to reach the screening system. Furthermore, as it requires a truck to replace a HBS machine, a big door needs to be implemented, so that the forklift truck can enter the HBS space.
- If the baggage needs to be cleared or not should not cause screening level 1 to be decentralized. If the baggage needs to be cleared, a vehicle can be used to directly bring the baggage to HBS.

Sorting, make up and offloading

- Offload does not need to be placed very early in the process. If the offload area is further away from the aircraft input point, vehicles can drive to this area. This might even be cheaper as the routing distance (i.e. baggage belts) is shorter this way.
- Make up should be the first system to place.

EBS

- It is difficult to determine if EBS is necessary or not. If the airport has a lot of transfer passengers, EBS is very useful. If there are not a lot of transfer passengers, the client or designer should make this decision.

- If there are a lot of *long* transfer passengers (i.e. passengers with a layover of a couple of hours), EBS can be placed in a separate building. However, it is difficult to determine the number of transfer passengers with a long layover, as this is not provided in a flight schedule. A good indication to use is to check if the airport has a night curvew. If the airport has a night curvew, there is a big change that there are many long layovers.

Remaining findings

- Preferably all systems are placed as a centralized system because machines are expensive. Furthermore, the system needs to be redundant. A redundant decentralized system needs even more machines, as at least two of everything is required. However, if a centralized system creates a gigantic spaghetti of transportation lines, a decentralized system can be more efficient.
- The trade-off between a centralized and decentralized system is the distance that baggage needs to travel and the number of transfer bags. The longer the handling distance and the larger the amount of transfer bags, the higher the chance is that a decentralized system performs better than a centralized system.
- The amount of (transfer) passengers is the determining factor between a centralized or decentralized system. Not the terminal layout of the airport.
- Baggage from OD passengers is routed from screening to EBS or sorting, depending on the remaining time before a flight. This baggage does not go back from sorting to EBS. Baggage from transfer passengers either goes directly to HBS level 1 or it can go into sorting and then to HBS level 1.

D.4 Interview 4

The fourth interview was held with Niels Ridderbos on May 14, 2019. Ridderbos is a junior consultant airport security and baggage handling. The main findings of the interview with Ridderbos are as follows:

Check-in and reclaim

- Check-in and reclaim are usually the first systems that are placed. Check-in should be the first though, because it should be optimal for passengers.

Screening

- The placement of screening is also important. First of all often because of legal requirements, but also because the screening equipment can be very space consuming.
- All three levels of screening should be placed close to each other. They could even be placed as one system, rather than three separate equipment types.
- Screening needs to be placed near check-in. If a bag is not cleared and the passenger needs to come down to open the bag, the passenger should not have to walk through the entire baggage hall.

- If there are several piers at an airport, a decentralized HBS can be useful. This facilitates the process when a passenger needs to come done to open the baggage. The bigger the surface area of an airport, the handier it is that HBS is decentralized.
- Screening is preferably places on the ground floor due to three reasons:
  1. the equipment is very heavy,
  2. if the bag contains an explosive, it needs to be brought outside as fast as possible,
  3. and if a machine needs to be replaced, you do not have to pass other subsystems first to be able to reach the machine.

Sorting, make up and offloading

- It is important that make up is placed as close a possible to the aircraft. Not only because make up is time critical, but also because you don't want the CO2 emissions from the vehicles inside the terminal. Thus, make up needs to be placed as soon as possible.
- The placement of sorting is the most flexible and thus can be placed last.
- Arrivals offloading should be close to reclaim. Transfer offloading should be close to the rest of the baggage system. Offload depends on what the client/airport wants, if the baggage needs to be customs cleared or not.
- If there are two or more handling operators at one airport, which is often the case if there are several alliances at an airport, make up is often decentralized.
- In principle, if make up fits on the ground level, also transfer offload quays will fit. Offload is just a couple of belts and does not take up a lot of space.

EBS

- As EBS is meant for storage, the location in the terminal is not as important, and can thus be placed last.
- It does not matter that much on which floor EBS is placed. If there is room on the first floor, start searching there.
- The EBS is useful if there are a lot of transfer passengers and if the transfer passengers have a long layover.
- It is beneficial if the EBS can be placed close to make-up.
- EBS is also useful for batch processing operations.

Remaining findings

- The capacity of a subsystem could be a determining factor in the order of placement. As a system cannot exceed the IST, which is linked to capacity.
- The required space hangs together with the capacity, as usually a system with a higher capacity requires more space. However, also this could be used to determine the order of placement.
- If a baggage handling system should be centralized or decentralized depends on three things:

   1. the terminal shape,
   2. the gate layout,
   3. and the number of handling operators.
- Make up, offload and screening can all be decentralized.

Appendix E

Case study

E.1 Aruba

Queen Beatrix International Airport (AUA) is an international airport located in Oranjestad, Aruba. It is the main and only airport on the Caribbean island of Aruba. AUA transported more than 2,5 million passengers in 2018. A new BHS needs to be installed as part of a terminal expansion. Use the model to build a BHS concept design for AUA. This case manual will guide you through it.

E.2 Files

Before starting, make sure the Excel files are present. These files are:

- *Flight schedule.* This file is needed to calculate the capacity that the BHS is required to meet. The flight schedule needs to be converted to a 'model version', which is explained in Section 3. File name: *Airport.xlsx*
- *Input parameters.* These values are used to specify the requirements of the airport. What each parameter means is explained in Section 3. File name: *Inputdata_Airport.xlsx*
- *Scenario file.* This is the file that contains the output from the model and is used to compare scenarios. File name: *Scenarios_Airport.xls**m***
- *Output file.* This file shows the detailed output data from one scenario, containing all possible equipment's rather than only the chosen equipment. File name: *Outputdata_Airport.xlsx*
- *Parameter file.* This file contains all the equipment options that the model chooses from. The same file is used for every airport. If necessary, more equipment options can be added to this file. File name: *Parameters2.1.xlsx*
- *Placement output file.* This file is needed for modelling purposes. It is an empty Excel file of which the placement data is read into. File name: *Placementoutput_Airport.xlsx*

Three other files are needed to run the model. First, is a Revit file, named 'Space Plan', which is used to show the placement of the concept design. This is the same file for every airport.

Furthermore, the model in Dynamo and the model in Jupyter Notebook are needed. These files will be explained in the next chapters.

E.3 Model preparation

To run the model, several types of input need to be gathered. This section describes which input is needed and how the data should be presented.

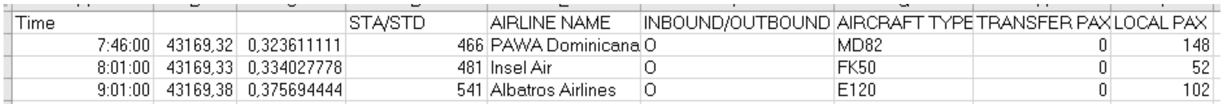
E.3.1 Flight schedule

Although different templates are available for flight schedules, the same data must be extracted in the same way to determine the BHS demand. In total six different sets of data should be retrieved from the schedule for each flight. These six sets are:

- **STA/STD:** The scheduled time of arrival (STA) or scheduled time of departure (STD) is needed to be able to determine the daily demand. This value is calculated by converting the time the aircraft leaves from a ‘time’-variable to a ‘general’-variable (changing the number format in Excel). Next, these numbers need to be converted to decimal fractions, numbers between 0 and 1. For example, 12:00 has a value of 0.5 because it is half of 24 hours. If the time also has a date (when the converted variable is not a number between 0 and 1), the starting date needs to be deducted. The starting date, ‘January 1st, 1900’ in Excel, is the number before the decimal point. Last, you have to convert this number to the number of minutes in a 24-hour period by multiplying the fraction by 60 minutes and 24 hours.
- **Airline:** To make the link between how many bags on average passengers take per airline, the airline needs to be known. The codes/names used for the airline need to be precisely the same as the codes/names used for the airline-bag ratio in the ‘InputdataAirport.xlsx’-file.
- **Flight direction:** The direction of the flight is needed to determine which demand is influenced by the flight. The direction can either be inbound or outbound and determines if the time value given in the beginning is a STA or STD.
- **Aircraft type:** For the MUP demand it should be known if the aircraft used is a WB, NB or RJ. If the exact aircraft is not known, an aircraft of the same type can be used.
- **Transfer PAX:** The number of passengers on the flight which transfer at the airport.
- **Local PAX:** The number of passengers on the flight which are O&D passengers.

To run the model, the flight schedule file needs to have a sheet named “Converted” containing these variables. All the above-mentioned data should be given in a column, each of equal length, with the following titles: STA/STD, AIRLINE NAME, INBOUND/OUTBOUND, AIRCRAFT TYPE, TRANSFER PAX, LOCAL PAX. Within the sheet other data can be added as columns, as long as they do not have the same title as one of the above. Figure E.1 shows the first three rows for the converted flight schedule of Aruba.

Aruba Case Study: To speed up the process of the case, the sheet ‘Converted’ has already been added with most of the data. Before continuing to the next step, you still need to get the calculate the STA/STD from the Time variable.



Time			STA/STD	AIRLINE NAME	INBOUND/OUTBOUND	AIRCRAFT TYPE	TRANSFER PAX	LOCAL PAX
7:46:00	43169,32	0,323611111	466	PAWA Dominicana	O	MD82	0	148
8:01:00	43169,33	0,334027778	481	Insel Air	O	FK50	0	52
9:01:00	43169,38	0,375694444	541	Albatros Airlines	O	E120	0	102

Figure E.1: Converted flight schedule for Aruba.

E.3.2 Input parameters

The next step is to fill in the input file. At first, this file consists of four sheets that you need to fill in. These sheets will be discussed in the following sections.

Input data sheet

The first sheet is the 'InputData'-sheet that contains some airport specific parameters. Table E.1 on the next page describes each variable.

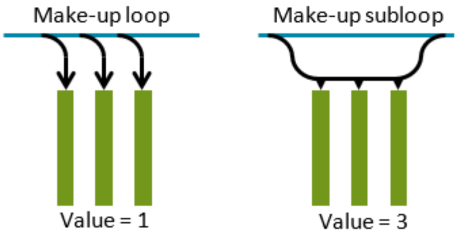
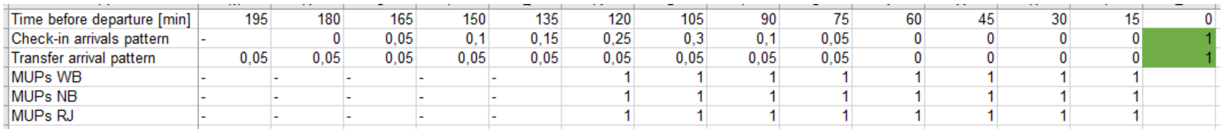


Figure E.2: The difference between a make-up loop and a make-up subloop.

Distribution pattern sheet

In this sheet, named "Distributions", the distributions used in the model can be found (see Figure E.3). This sheet often stays the same. Only if specific information from the airport is available, this can be used to specify it for that airport.



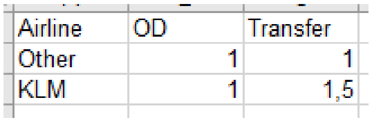
Time before departure [min]	195	180	165	150	135	120	105	90	75	60	45	30	15	0
Check-in arrivals pattern	-	0	0,05	0,1	0,15	0,25	0,3	0,1	0,05	0	0	0	0	1
Transfer arrival pattern	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0	0	0	0	1
MUPs WB	-	-	-	-	-	1	1	1	1	1	1	1	1	
MUPs NB	-	-	-	-	-	1	1	1	1	1	1	1	1	
MUPs RJ	-	-	-	-	-	1	1	1	1	1	1	1	1	

Figure E.3: Distributions sheet in Excel.

The first two distributions are the arrival distributions of the check-in and transfer passengers. The last three are of the make-up position (MUP) usage of each aircraft type. The model can recognize when the distribution starts, meaning that the first time a number is used instead of a "-". The model knows the distribution started at that point. The check-in and make-up opening times are also defined by this. If a 0 is used instead of a "-", the model will think the check-in or make-up already open at that point. For the MUP distributions, the model will assign positions to the equipment and not flight, meaning that for a lateral (4 MUP's) multiple flight can be assigned.

Airline-bag ratio sheet

This sheet has all the airline to bag ratios of the passengers (see Figure E.4). This is the average number of bags that one passenger brings on a flight. The model checks if the airline from the flight schedule is specified in this list. If it is, the model uses that airline-bag ratio. If the airline is not in the list, it will use the ratio defined in “Other”. The airline names used here should precisely (also upper and lower case) match those of the flight schedule to be recognized. So, if KLM is used in the flight schedule, KLM needs to be used in the airline-bag ratio. If the flight schedule uses KL, KL should be used in this list.



Airline	OD	Transfer
Other	1	1
KLM	1	1,5

Figure E.4: Airline-bag ratio sheet in Excel.

Aircraft list sheet

The aircraft list sheet should contain all the aircraft that can be found in the flight schedule, if any aircraft is missing, the model will show an error in the first model step (demand calculations). During the model preparation nothing needs to be done with this sheet. Airlines only need to be added when the model shows the error. If the right block in Figure E.5 turns yellow (e.g. an error), it shows the list of airlines that needs to be added to this list.

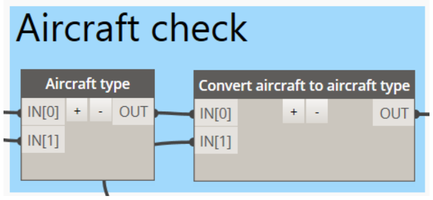
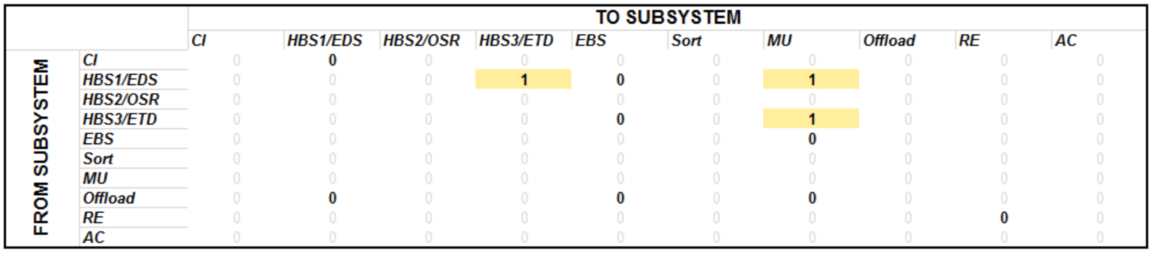


Figure E.5: Model error to show when an airline is missing in the aircraft list in Excel.

Routing sheet

This sheet is used to define the routing between subsystems (see Figure E.6). If routing is needed from subsystem A to subsystem B, the value needs to be changed from 0 to 1. It is only possible to change the routing between the bold and black squares, which are: HBS1-HBS3, HBS1-EBS, HBS1-MU, HBS3-EBS, HBS3-MU, EBS-MU, offload transfer-HBS1, offload transfer-EBS, and offload transfer-MU. For modeling purposes routing that goes to sorting, goes straight to make-up in this table. No routing goes to sorting (in this table). However, in the outcome the route goes from subsystem A, through sorting, to make-up. Furthermore, in the model HBS2 (OSR) is just a computer screen where the bag stays in HBS1. So, there is no routing to and from HBS2.

Aruba Case Study: For Aruba Airport several input parameters are different than the standard:



		TO SUBSYSTEM									
		CI	HBS1/EDS	HBS2/OSR	HBS3/ETD	EBS	Sort	MU	Offload	RE	AC
FROM SUBSYSTEM	CI	0	0	0	0	0	0	0	0	0	0
	HBS1/EDS	0	0	0	1	0	0	1	0	0	0
	HBS2/OSR	0	0	0	0	0	0	0	0	0	0
	HBS3/ETD	0	0	0	0	0	0	1	0	0	0
	EBS	0	0	0	0	0	0	0	0	0	0
	Sort	0	0	0	0	0	0	0	0	0	0
	MU	0	0	0	0	0	0	0	0	0	0
	Offload	0	0	0	0	0	0	0	0	0	0
	RE	0	0	0	0	0	0	0	0	0	0
	AC	0	0	0	0	0	0	0	0	0	0

Figure E.6: Define the routing between subsystems in Excel.

- There are 7 check-in desks per side.
- The HBS level 1 rejection rate is 0.25.
- he HBS level 2 rejection rate is 0.5.
- Aruba does ETD normal search.
- Aruba does not include baggage train turn circles.
- Aruba wants loop sorting.
- Aruba does not use make-up subloops.
- Aruba has 2 reclaim carousels.
- The Airline-Bag ratio for United Airlines is 1 for OD and 1.2 for transfer BAX.
- Routing is needed from HBS1-HBS3 and HBS3-MU.

E.3.3 Model specification

After the input files are organized, the model can be opened. To open the model, open the program 'Revit 2018'. In the screen that pops up, click on 'Open...' in the Projects part, and select the file 'Space Plan'. In the next screen that pops up, click on the 'Manage' tab. Next, click on Dynamo Visual Programming in the top right corner and select Dynamo version 2.0.2. Last, select the model for the airport you want to build the concept design. If this is the first time you run the model for this airport, select the standard file to build your own.

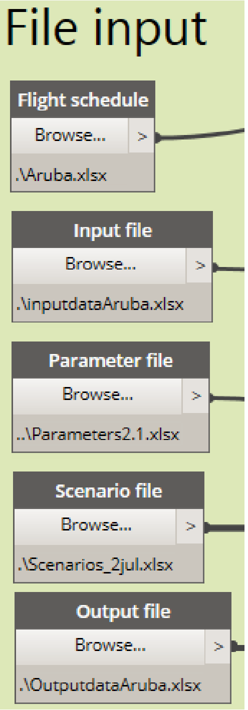
When starting up, the green squares should be adjusted to fit the airport. Every model specification will be discussed in this section.

File input

In the file input section (see Figure E.7), the corresponding files discussed before should be selected. This can be done by pressing the Browse button. Which file should be selected at which block is shown in the blocks title.

Terminal dimensions

The next step is to define the terminal dimensions (see Figure E.8). First, the main data (terminal width, length, height and the number of floor levels) need to be inserted at (1). This is to develop a square with the outside boundaries of the terminal part that is available for BHS.


File input

Flight schedule
Browse... >
.\Aruba.xlsx

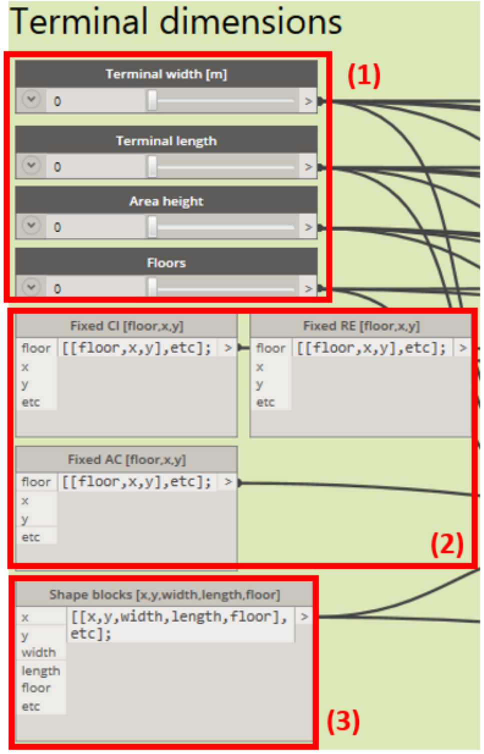
Input file
Browse... >
.\inputdataAruba.xlsx

Parameter file
Browse... >
..\Parameters2.1.xlsx

Scenario file
Browse... >
.\Scenarios_2jul.xlsx

Output file
Browse... >
.\OutputdataAruba.xlsx

Figure E.7: File input in Dynamo.


Terminal dimensions

Terminal width [m]: 0

Terminal length: 0

Area height: 0

Floors: 0

Fixed CI [floor,x,y]
floor, x, y, etc: `[[floor,x,y],etc];`

Fixed RE [floor,x,y]
floor, x, y, etc: `[[floor,x,y],etc];`

Fixed AC [floor,x,y]
floor, x, y, etc: `[[floor,x,y],etc];`

Shape blocks [x,y,width,length,floor]
x, y, width, length, floor, etc: `[[x,y,width,length,floor], etc];`

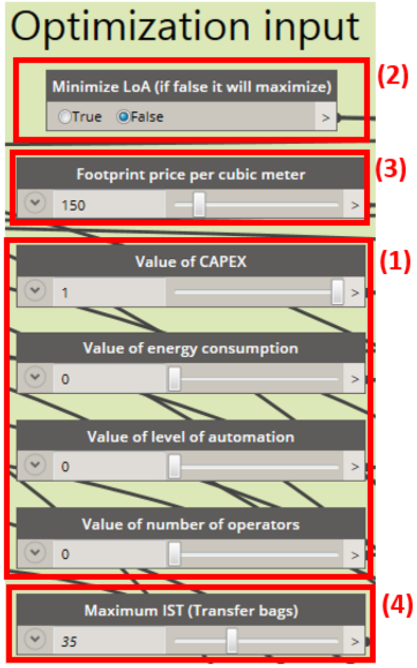
Figure E.8: Terminal dimensions in Dynamo.

In (2), the important input points of the terminal are defined. These are the reclaim (RE), check-in (CI) and aircraft (AC) points. The reclaim and check-in point define were these systems are connected or located in the building. The aircraft point is where the trains leave the terminal to travel to the aircraft (make-up is usually located here). If there are several entrance/exit points, these can also be added. If a subsystem is placed following a centralized structure, the middle point between the points is used. If a subsystem is decentralized, the equipment's are divided over these points.

At (3) shape blocks can be added. This can be done by adding a list to the block which contains the x/y coordinates, the width and length of the shape, and the floor it is placed on. The coordinates are the center point of the blocks and the width and length the total of length of the block. If multiple blocks are needed, a "," should be used between the lists.

Optimization input

The optimization settings need to be chosen. Figure E.9 shows these settings. First, there are four optimization options (see (1)): CAPEX, energy consumption, level of automation (LoA), and the number of operators. The model can be optimized on one value or on a combination of values. These values, meaning the weights of the trade-off, must add up to 1 (otherwise the model will crash). If the model is optimized on the LoA or number of operators, the first block (2) also needs to be set. This block defines if the LoA is minimized (True) or maximized (False). If the LoA is minimized, the number of operators is maximized and the other way around. Next, the footprint price per cubic meter needs to be inserted (see (3)). The cubic room price is the value of 1 cubic meter of BHS. In the last block (4), the maximum in-system-time of a transfer bag should be given in minutes. This model will choose the equipment without exceeding this time limit.



Optimization input

Minimize LoA (if false it will maximize): ○ True ● False

Footprint price per cubic meter: 150

Value of CAPEX: 1

Value of energy consumption: 0

Value of level of automation: 0

Value of number of operators: 0

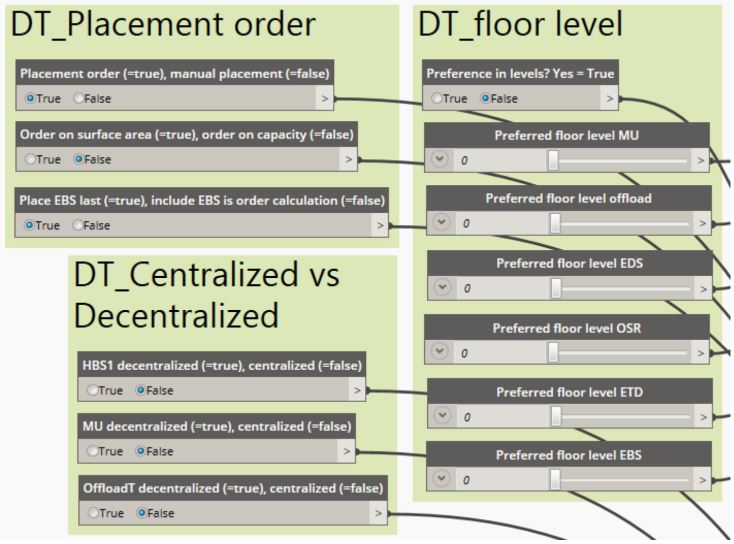
Maximum IST (Transfer bags): 35

Figure E.9: Optimization input in Dynamo.

Design decisions

The model can be specified by selecting design decisions (see Figure E.10). There are three design categories: in which order the subsystems are placed, if several subsystems are centralized or decentralized, and if there is a preference in placing subsystems on certain floor levels. Each category is briefly discussed.

Placement order Figure 6.2 in Chapter 6 shows the placement rules in a flow diagram which can be used to determine the order of placement. The diagram goes as follows. If the client has a specific preference in order, follow the order of the preference. This needs to be modelled by hand. If not, first make up (MU) is placed which is followed by the first phase of screening (HBS1). The next decision is to choose a placement order system, either capacity or space requirements. To determine the placement order, another decision needs to be made about the


DT_Placement order

Placement order (=true), manual placement (=false)
● True ○ False

Order on surface area (=true), order on capacity (=false)
○ True ● False

Place EBS last (=true), include EBS is order calculation (=false)
● True ○ False

DT_Centralized vs Decentralized

HBS1 decentralized (=true), centralized (=false)
○ True ● False

MU decentralized (=true), centralized (=false)
○ True ● False

OffloadT decentralized (=true), centralized (=false)
○ True ● False

DT_floor level

Preference in levels? Yes = True
○ True ● False

Preferred floor level MU: 0

Preferred floor level offload: 0

Preferred floor level EDS: 0

Preferred floor level OSR: 0

Preferred floor level ETD: 0

Preferred floor level EBS: 0

Figure E.10: Specifying design decisions in Dynamo.

placement of the EBS. These two decisions lead to one of the four placement orders.

Centralized versus Decentralized Figure 6.3 in Chapter 6 shows the flow diagram which can be used determine when a decentralized system is best versus a centralized system. If the client has a preference for a decentralized system, follow the preference of the client. If not, if there are no transfer passengers, keep the entire system centralized. If there are transfer passengers, the next questions is how long the handling distance is. If the distance from transfer offload through screening and back to make-up is big, it is useful to decentralized make-up, offload and screening level 1. If the distance is small the follow up question is if the baggage needs to be clean before it enters the BHS. This is an airport specific requirement. If baggage needs to be clean, baggage screening level 1 should be decentralized, otherwise the entire system can be centralized.

Floor level Each airport is different, this leads to different subsystem layouts for every airport. However, there are a lot of similarities between airports on which level each subsystem is placed. Figure 6.5 in Chapter 6 shows the flow diagram which can be used to determine on which floor level the model is going to try and find a location. The diagram can be read as follows. If the client has a preference in floor level, that preference should be followed. If not, the number of levels the terminal has available for baggage handling systems is the changing factor. Which floor level is optimal for each subsystem can be found in Figure L. Furthermore, each floor level is ordered based on importance. For instance, in a two level terminal on the ground floor (level aircraft) the most important system that should be placed on that floor is make up, followed by offload, screening and EBS.

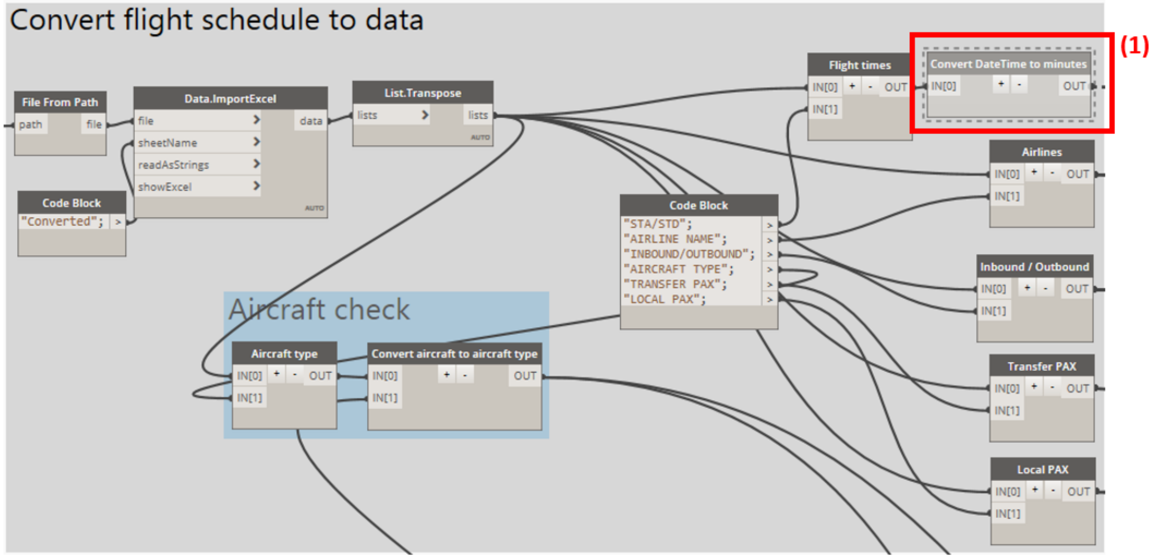
Aruba Case Study: The BHS terminal layout for Aruba is as in Figure 5.2 in Chapter 5. Use this information to get the input for the terminal dimensions. Furthermore, choose the optimization input and design decisions for 3 scenarios. The client does not have a preference, choose as you think fits the airport the best. The footprint price per cubic meter is 375 dollar and the maximum IST is 35 minutes. This information needs to be filled in during the step ‘Run the model’ in Section E.4.

E.4 Run the model

The model is split up into three phases (see Figure 3.4 in Chapter 3). Phase 1 and 3 are executed in Dynamo (with some preparation in Excel), phase 2 is executed in Jupyter Notebook (online version of Python). This section will explain how to run the model following these phases.

E.4.1 Phase 1

The first phase consists of three steps. In step one, the system capacity is defined using the flight schedule of an airport in conjunction with the input parameters. Before doing this however, the flight schedule is checked to see if all aircraft are known (in the blue square). Before running the model make sure that the right top block ‘Convert DateTime to minutes’ in the group ‘Convert flight schedule to data’ is frozen (see (1) in Figure E.11). This will prevent the model from running if there is a mistake in the beginning. Freeze a block by right-clicking on that block and select ‘Freeze’. If a block is frozen it turns light grew.



```
"Converted";
```

```
"STA/STD";
"AIRLINE NAME";
"INBOUND/OUTBOUND";
"AIRCRAFT TYPE";
"TRANSFER PAX";
"LOCAL PAX";
```

Figure E.11: Check if all aircraft are already known.

If an aircraft is missing, the right block in the blue group will tell which aircraft names are missing. These can then be added to the aircraft list from the input file, which should then be saved. After saving, the connection between the input file node and the file from path node of the previous section should be disconnected by clicking the path block input and pressing escape. The model should be run (which gives an error) and the two blocks should be reconnected. Do not ask me why but every time an excel file is changed and the model has been run, this process should be performed for that file to use the new values.

If all aircraft are in the list, the output of the blue blocks should become a long list containing the words NB, WB and RJ. Now, the block indicated by (1) should be unfrozen. This is done by right clicking the block and then left click freeze. Before running the model again, make sure that the node ‘Equipment to amount2’ in the block ‘Calculate required ground equipment space and elements’ is frozen.

Calculate system demand

When running the model, the capacity is calculated for each subsystem. The capacity of a subsystem per hour is based on the busiest 15 minutes of a day. The output file gets updated with the demand graphs.

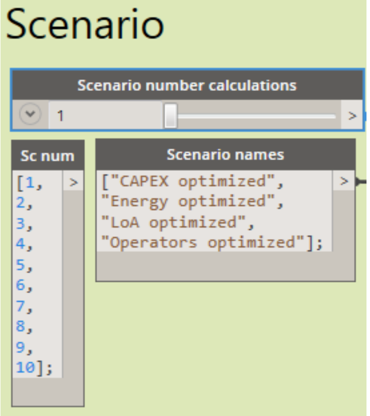
The watch nodes will show the value of the required capacity for each system part (see Figure E.12). In the slider blocks in the ‘Demand input’ group, these watch values can be inserted. However, if other values need to be used the watch blocks can be used as an indicator. If for example, only 25% of the demand should be developed, you can insert 25% of the value given by the watch block. This data is then used to define the system requirements.

Figure E.12: Demand input in Dynamo.

If all values are correct, the ‘Equipment to amount2’ node can be unfrozen. Make sure that the ‘FullOptimization. FinalOptimization’ node in the ‘Optimise and choose ground equipment’ block is frozen. Run the model again. This will update the ground equipment sheet of the output file which will show all the data for each possible equipment type.

Define scenarios

The next step is to define the scenarios. Every variable can be changed to define a scenario, the demand, input parameters, optimization choice, design decision, etc. To be able to recognize the scenarios a name should be given (see Figure E.13). You need to input the scenario number of the scenario you are running. A maximum of 10 scenarios can be run. The data from each scenario is added to the 'Scenarios_Airport.xlsm' file.



```
[1,
2,
3,
4,
5,
6,
7,
8,
9,
10];
```

```
["CAPEX optimized",
"Energy optimized",
"LoA optimized",
"Operators optimized"];
```

Figure E.13: Scenario input in Dynamo.

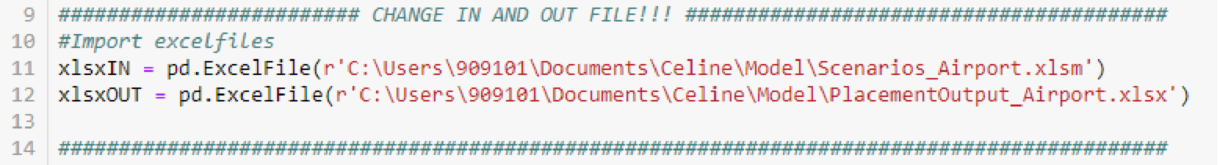
The model dashboard can be used to compare and evaluate the scenarios at a first glance. The dashboard provides an overview of the differences between the scenarios. Choose the scenarios you want to evaluate in the top left corner by ticking the boxes. The demand histograms show the demand that is used as input. The switches histogram shows how big the scenario space is you evaluated. The equipment histogram shows how often each type of equipment is chosen. The boxplots show the range in which the scenarios differ from each other. The radar plot of the scenario output variables shows the achievement of each decision variable. The radar plot of the capacity shows how big capacity of the chosen equipment per scenario is. The closer a scenario is to the outside ring, the better that scenario scores on that variable.

The next modelling step is the part that can take a several hours. If a scenario does not look promising in the dashboard, deleting this scenario can help to shorten the run time.

E.4.2 Phase 2

The next phase is to run the placement model in Jupyter Notebook. Open Anaconda and launch Jupyter Notebook. Select the Placement file. Select the correct Excel files by changing the file paths in the first block (see Figure E.14). Be aware, *Jupyter notebook can only run if the Excel files are closed!*

Run the first block by pressing shift-enter. If there is no error message, do the same for the second block to run the model. The optimal placement configuration for every scenario will be searched. This can take a while, ranging between minutes for smaller airports to hours for bigger



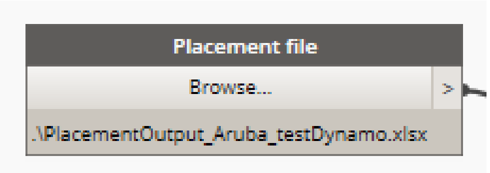
```
######################### CHANGE IN AND OUT FILE!!! ########################################
#Import excelfiles
xlsxIN = pd.ExcelFile(r'C:\Users\909101\Documents\Celine\Model\Scenarios_Airport.xlsm')
xlsxOUT = pd.ExcelFile(r'C:\Users\909101\Documents\Celine\Model\PlacementOutput_Airport.xlsx')

############################################################################################
```

Figure E.14: Change the file paths in Jupyter Notebook.

airports. Do not turn your computer off and make sure you are connected to the internet. At the bottom of the page you can see the progress of the model. As soon as the model prints "Placement is finished", the model is finished and the placement data has been exported to the empty Excel file. Open the Excel file ‘Placementoutput_Airport.xlsx’ to check if the data is exported correctly.

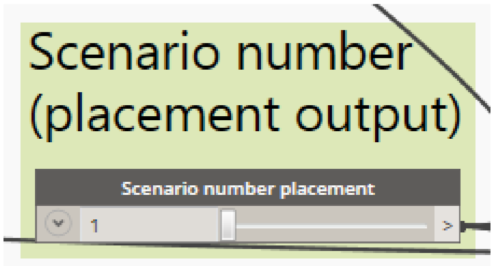
E.4.3 Phase 3

The last step is to visualize the placement output and optimize the transport equipment. At the moment it is not possible to see the output of all scenario’s at once. However, just a couple of extra actions are needed to get the output. Select the correct placement file from phase 2 (see Figure E.15). Input the scenario number of the scenario you want to see the placement (see Figure E.16). Run the model and within seconds 3D drawing is visible in Revit. To see the output of the next scenario, change the scenario number and run the model again.



..\PlacementOutput_Aruba_testDynamo.xlsx

Figure E.15: Placement output file in Dynamo.



Scenario number placement: 1

Figure E.16: Scenario number in Dynamo.

The other Excel files are also updated with the transport equipment after this run/these runs. The ‘Scenarios_Airport.xlsm’ file in combination with the 3D Revit drawing should contain enough information to compare the different scenarios.

Table E.1: Explanation of the input data sheet in Excel.

Parameter	**Explanation**	**Unit**	**Average**
Amount of Check-in systems	Represents the number of check-in-systems. If check-in is centralized, this value is 1. If check-in is decentralized, this value is 2 or higher and represents over how many areas it is decentralized.	-	1 or higher
Redundancy	The redundancy of the entire BHS.	%	75
Check-in desks per side	The number of check-in desks that are in a row next to each other. Thus, the desks per island side, not the full island. If the check-in configuration is linear, a high value can be given which results in a long row of desks.	-	9
Distance between check-in sides	The distances between the different check-in islands. Thus the width of the waiting line.	Meter	26
HBS level 1 rejection rate	The fraction of bags which get send to from level 1 baggage screening (EDS) to level 2 screening (OSR).	Fraction	Between 0 and 1
HBS level 2 rejection rate	The fraction of bags which get send to from level 2 baggage screening (OSR) to level 3 screening (ETD).	Fraction	Between 0 and 1
ETD full or normal search	The search method that the airport uses for baggage screening level 3. It can be 'full' or 'normal' (written like this with lower case letters).	-	full/normal
Include baggage train turn circles	If at make-up the trains need to make a turn within the make-up area, baggage train turn circles need to be added. If this is the case (answering this question with 'yes'), 6 meter is added to the make-up equipment in both the width and length to make it possible for the trains (tugs/tractors) to turn.	-	yes/no
Road width	The width of the road that is needed at make-up to transport the trains/carts. If ALT is not used, space for a road (with this width) is reserved.	Meter	3
Average of bags in a NB cart	This value represents the average number of bags that goes into a baggage cart of a narrow-body or regional jet flight.	Bags	35
Average of bags in a WB ULD	This value represents the average number of bags that goes into a baggage ULD of a wide-body flight.	Bags	35
Train occupancy	The average time that it takes operators to unload the bags for an arriving aircraft (for all three types of aircraft).	Minutes	30
Maximum of Carts/ULDs per train inside	The number of baggage carts that a train is allowed to tow inside the make-up area (same for ULDs).	Carts	2
Maximum of Carts/ULDs per train outside	The number of baggage carts that a train is allowed to tow on the apron (same for ULDs).	Carts	4
Train departure time	The time before a flight that a train is sent to the gate of an arriving flight.	Minutes	15
Loop sorting	Is there a make-up loop or not?	-	yes/no
MUPs per subloop	Are all the make-up equipment's connected directly to the loop (value is 1) or are there any subloops? Figure E.2 shows this difference.	-	1 or higher
Single bag access	Do you need single bag access for the EBS (US CBP)? If single bag access is needed, lane storage is excluded for the equipment options.	-	yes/no
Amount of reclaim carousels	The amount of reclaim carousels which can be found in the airport for O&D passengers	-	1 or higher
Length of reclaim carousels	The length of a reclaim carousel. The model calculates one offload quay per 60 meter. So, if this value is 70, it will calculate that twice the number of offload quays is needed for O&D offloading quays. If this value is 130, it is three times.	Meter	60

Appendix F

Technical appendix

This appendix shows the full results of all model tests and runs. The important information is summarized in bullet points.

F.1 Sensitivity analysis

DEMAND

- The demand input for the SA is shown in Table F.1.
- Figure F.1 shows the equipment choice of the SA for the demand. Only the make-up loading equipment changes.
- Figure F.2 shows the size of the capacity per subsystem per scenario of the SA for the demand. Due to a alteration in make-up equipment, the CAPEX of scenario 3 is lower than the other two scenarios.
- The placement of the subsystems per scenario is shown in Figure F.3. A decrease in demand causes the shape of EBS to change. Because of this the EBS does not fit on the first floor anymore and is moved to the second (see (b)). The alteration in make-up equipment is shown in (c).
- Table F.2 shows the outcome of the decision variables of the SA for the demand.

AIRPORT SPECIFIC INPUT PARAMETERS

- Figure F.4 shows the change in placement due to a reduced redundancy (SA B). Due to an extra HBS machine, screening level 2 and 3, transfer offloading and O&D offloading moved.
- Figure F.5 shows the effect of the SA of the rejection rate on HBS.

OPTIMIZATION PARAMETERS

- Figures F.6-F.11 show all the scenarios that are run for the optimization SA.
- Figures F.12 and F.13 show that a wide solution space is explored while maximizing or minimizing the optimization parameters. Most types of equipment are chosen and a wide range of every decision variable is found.

- Figure F.14 shows how maximizing and minimizing the optimization parameters greatly affected the placement of the subsystems for AUA. However, this is as expected since the entire scenario changed.

- Figure F.15 shows how the scenarios of the SA of the CAPEX versus the energy consumption score for all decision variables. Figure F.16 shows the placement of these scenarios. These placements show the break points of this SA for AUA.

- Figure F.17 shows the placement of the third SA (CAPEX versus minimizing the number of operators). The break point for this SA for AUA is from scenario 5 to 6 and from scenario 9 to 10.

- Figures F.18 and F.19 show the placement of the last SA, the former minimizing the LoA, the latter maximizing the LoA. Also these placements show the break points of these scenarios.

Table F.1: Demand for the SA of AUA.

	Scenario 1: Base case	**Scenario 2: -10% demand**	**Scenario 2: +10% demand**
Transfer arrival	0	0	0
Screening	642	578	706
Check-in	642	578	706
Sorting	642	578	706
Make-up	26	23	29
EBS	429	386	472
Trains outside	17	15	19
Trains inside	14	13	15

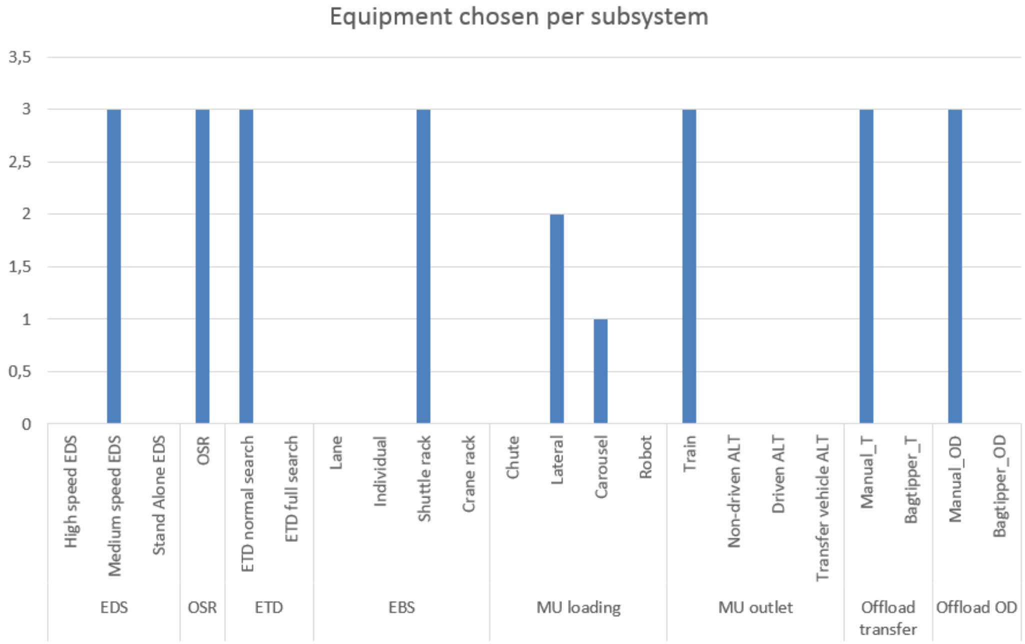


Figure F.1: Equipment choice of SA demand scenarios of AUA.

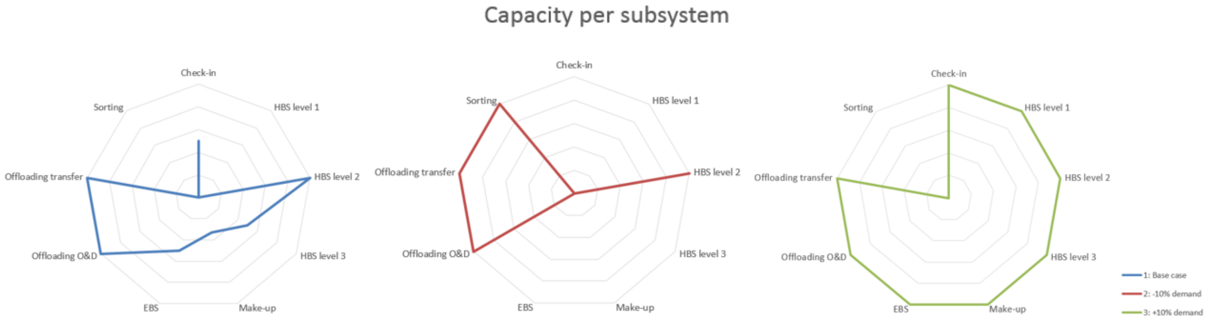
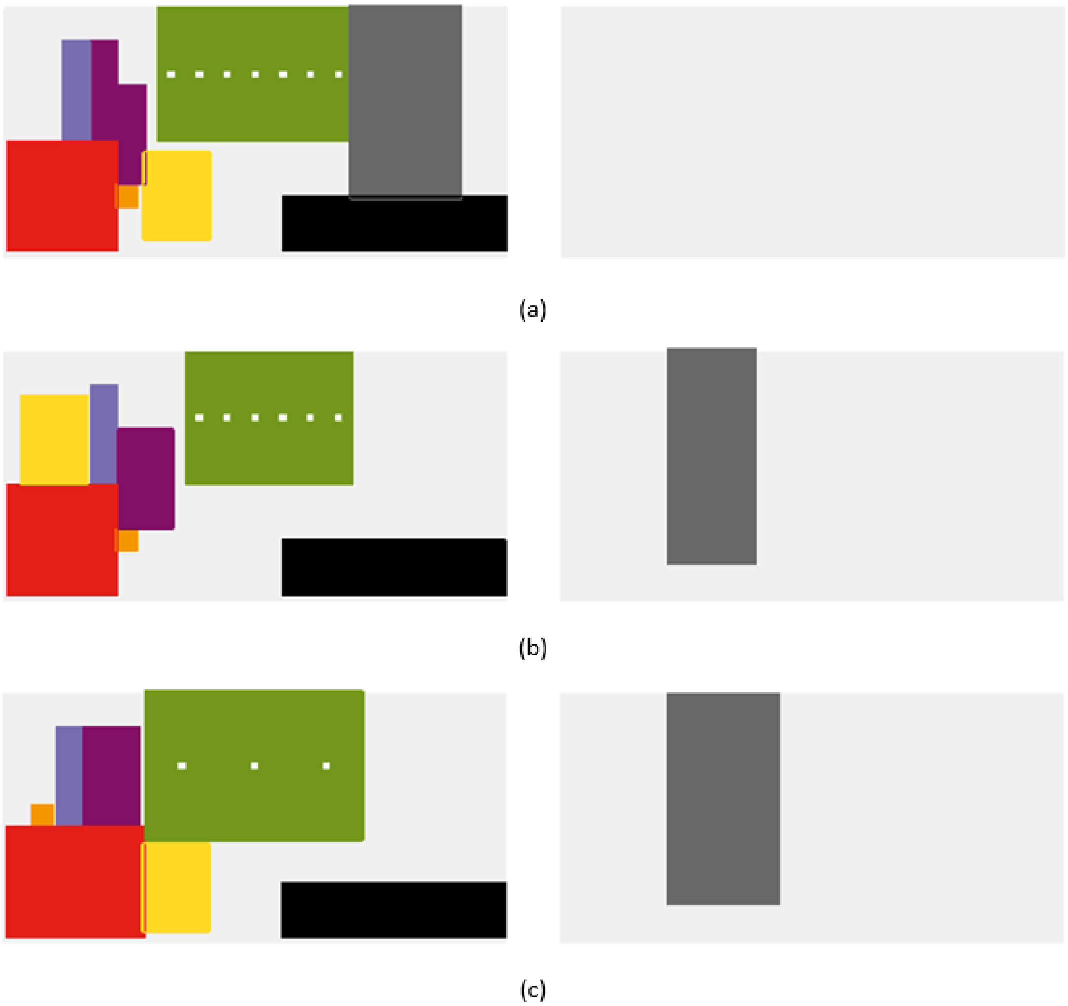


Figure F.2: Radar chart of equipment capacity of SA demand scenarios of AUA.



(a)

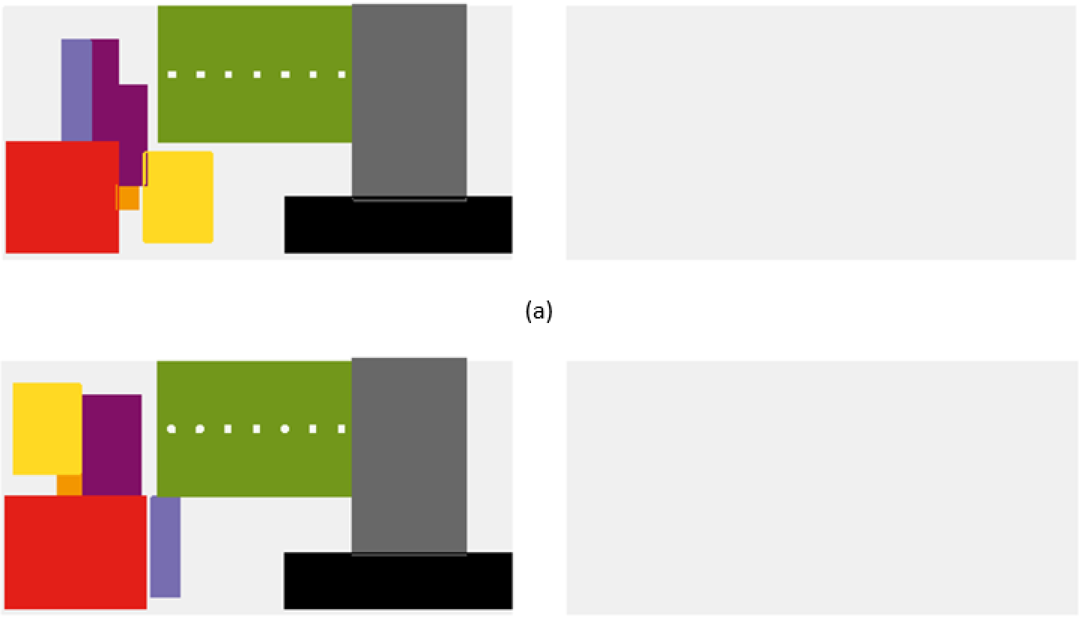
(b)

(c)

Figure F.3: Placement output of SA demand scenarios of AUA, where (a) is scenario 1, (b) is scenario 2, and (c) is scenario 3.

Table F.2: Outcome of the demand SA of AUA.

	Scenario 1: Base case	**Scenario 2: -10% demand**	**Scenario 3: +10% demand**
System area [m^2]	5789	5230	6354
CAPEX	€ 12.399.320,00	€ 10.809.320,00	€ 9.879.320,00
Operators	64	58	69
Energy consumption	2755,6	1885,2	1289,2
LoA	4,6	4,5	4,6



(a)

(b)

Figure F.4: Placement output of the SA of the redundancy of AUA, where (a) is scenario SA B1 and SA B2, and (b) is scenario SA B3.

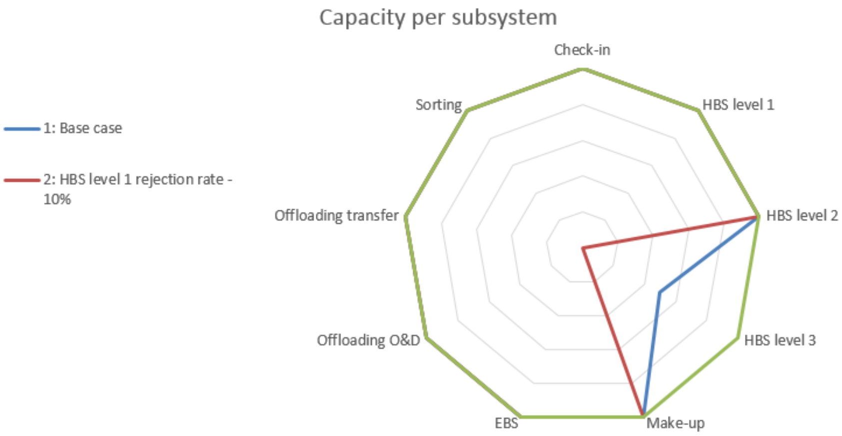
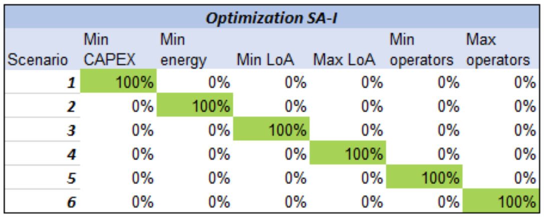


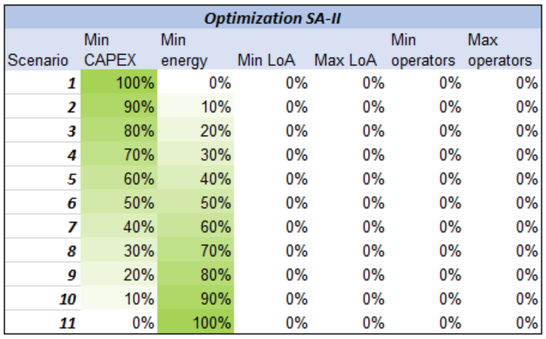
Figure F.5: Radar chart of equipment capacity of SA of the rejection rate of HBS of AUA.



Optimization SA-I

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	0%	100%	0%	0%	0%	0%
3	0%	0%	100%	0%	0%	0%
4	0%	0%	0%	100%	0%	0%
5	0%	0%	0%	0%	100%	0%
6	0%	0%	0%	0%	0%	100%

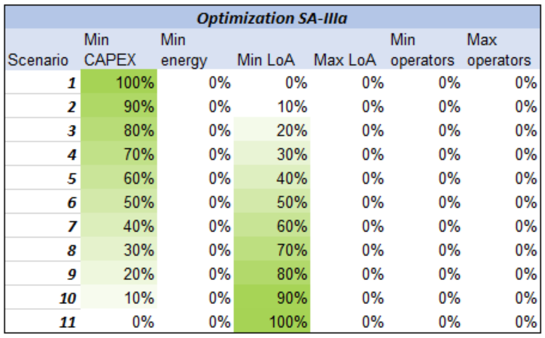
Figure F.6: Optimization SA I scenarios.



Optimization SA-II

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	90%	10%	0%	0%	0%	0%
3	80%	20%	0%	0%	0%	0%
4	70%	30%	0%	0%	0%	0%
5	60%	40%	0%	0%	0%	0%
6	50%	50%	0%	0%	0%	0%
7	40%	60%	0%	0%	0%	0%
8	30%	70%	0%	0%	0%	0%
9	20%	80%	0%	0%	0%	0%
10	10%	90%	0%	0%	0%	0%
11	0%	100%	0%	0%	0%	0%

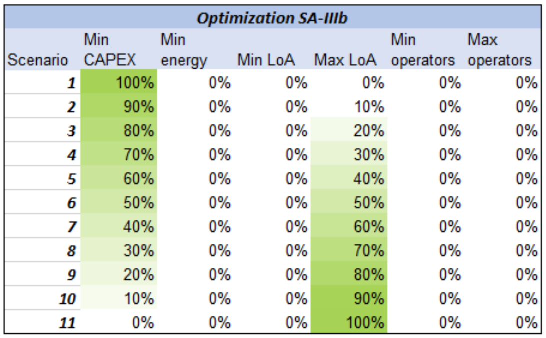
Figure F.7: Optimization SA II scenarios.



Optimization SA-IIIa

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	90%	0%	10%	0%	0%	0%
3	80%	0%	20%	0%	0%	0%
4	70%	0%	30%	0%	0%	0%
5	60%	0%	40%	0%	0%	0%
6	50%	0%	50%	0%	0%	0%
7	40%	0%	60%	0%	0%	0%
8	30%	0%	70%	0%	0%	0%
9	20%	0%	80%	0%	0%	0%
10	10%	0%	90%	0%	0%	0%
11	0%	0%	100%	0%	0%	0%

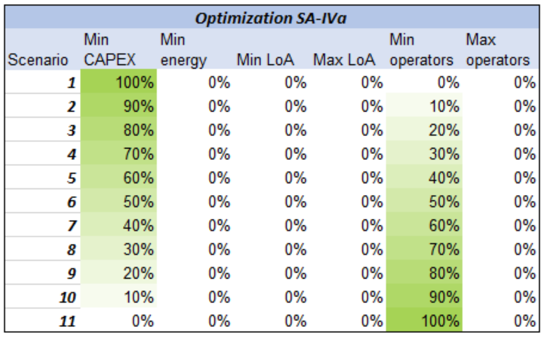
Figure F.8: Optimization SA IIIa scenarios.



Optimization SA-IIIb

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	90%	0%	0%	10%	0%	0%
3	80%	0%	0%	20%	0%	0%
4	70%	0%	0%	30%	0%	0%
5	60%	0%	0%	40%	0%	0%
6	50%	0%	0%	50%	0%	0%
7	40%	0%	0%	60%	0%	0%
8	30%	0%	0%	70%	0%	0%
9	20%	0%	0%	80%	0%	0%
10	10%	0%	0%	90%	0%	0%
11	0%	0%	0%	100%	0%	0%

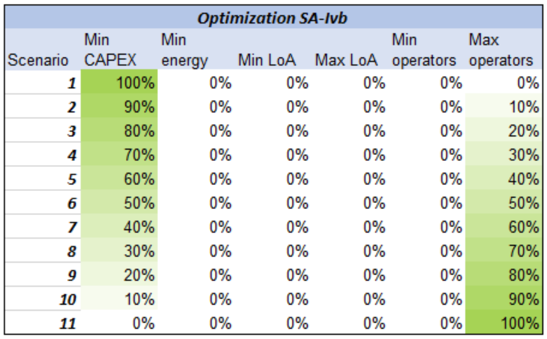
Figure F.9: Optimization SA IIIb scenarios.



Optimization SA-IVa

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	90%	0%	0%	0%	10%	0%
3	80%	0%	0%	0%	20%	0%
4	70%	0%	0%	0%	30%	0%
5	60%	0%	0%	0%	40%	0%
6	50%	0%	0%	0%	50%	0%
7	40%	0%	0%	0%	60%	0%
8	30%	0%	0%	0%	70%	0%
9	20%	0%	0%	0%	80%	0%
10	10%	0%	0%	0%	90%	0%
11	0%	0%	0%	0%	100%	0%

Figure F.10: Optimization SA IVa scenarios.



Optimization SA-Ivb

Scenario	Min CAPEX	Min energy	Min LoA	Max LoA	Min operators	Max operators
1	100%	0%	0%	0%	0%	0%
2	90%	0%	0%	0%	0%	10%
3	80%	0%	0%	0%	0%	20%
4	70%	0%	0%	0%	0%	30%
5	60%	0%	0%	0%	0%	40%
6	50%	0%	0%	0%	0%	50%
7	40%	0%	0%	0%	0%	60%
8	30%	0%	0%	0%	0%	70%
9	20%	0%	0%	0%	0%	80%
10	10%	0%	0%	0%	0%	90%
11	0%	0%	0%	0%	0%	100%

Figure F.11: Optimization SA IVb scenarios.

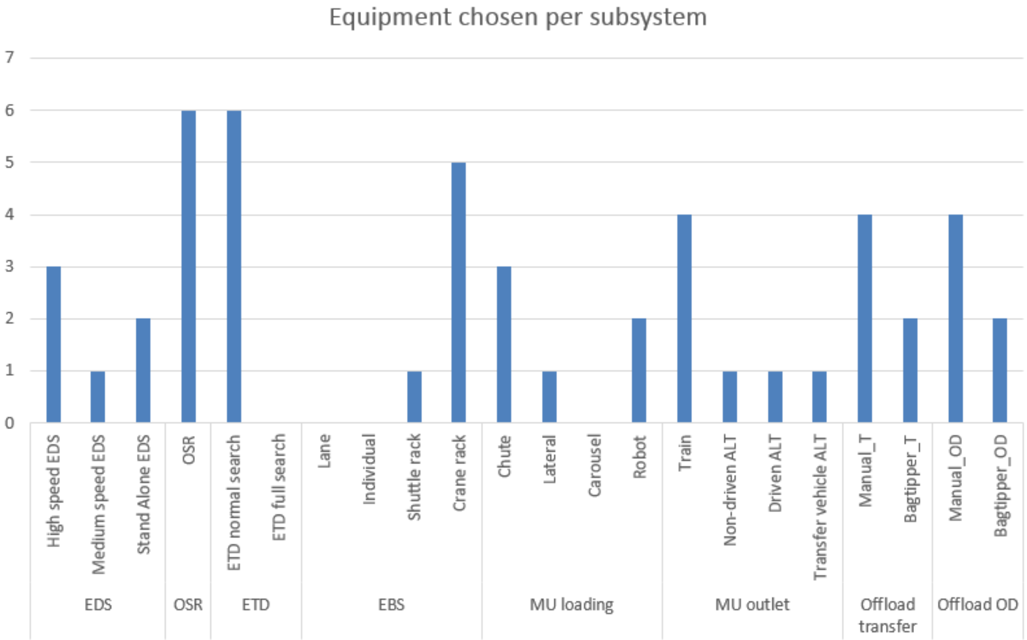


Figure F.12: The equipment that is chosen while minimizing or maximizing the optimization parameters for AUA.

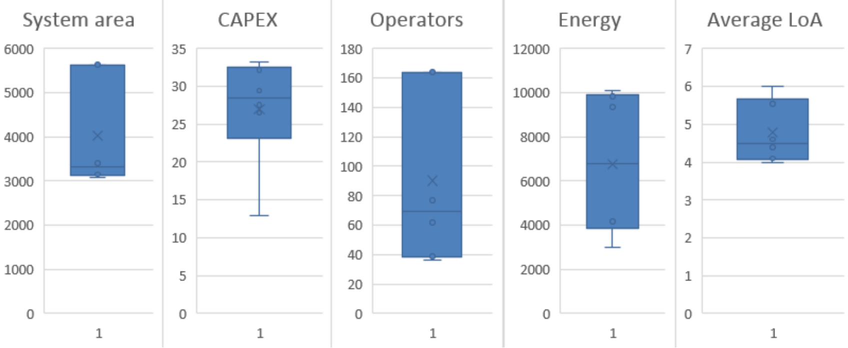
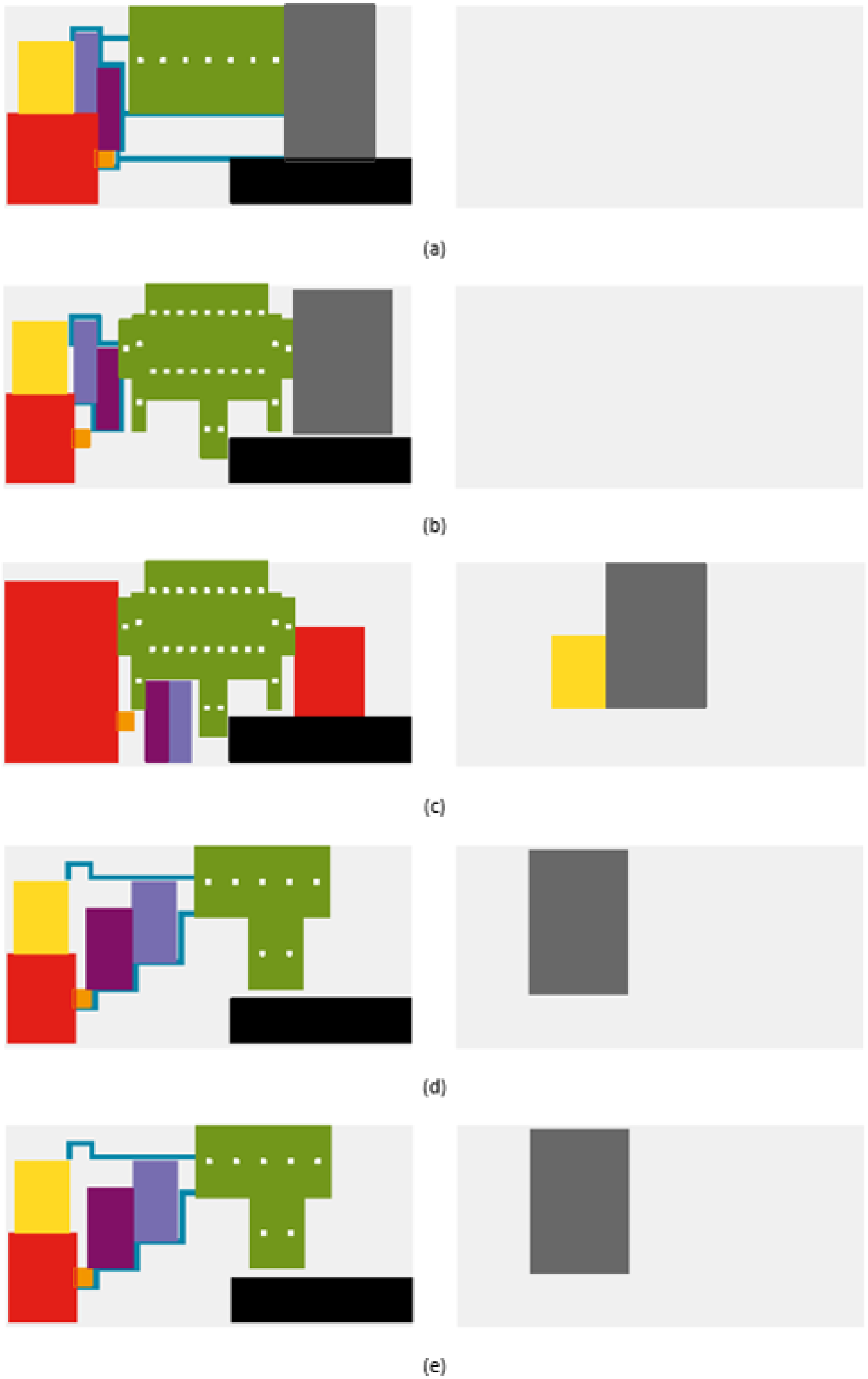


Figure F.13: The range of the decision variables while minimizing or maximizing the optimization parameters for AUA visualized in box plots.



(a)

(b)

(c)

(d)

(e)

Figure F.14: Placement output of the SA while maximizing or minimizing the optimization parameters for AUA, where (a) is scenario 1, (b) is scenario 2, (c) is scenario 3 and 5, (d) is scenario 4, and (e) is scenario 6.

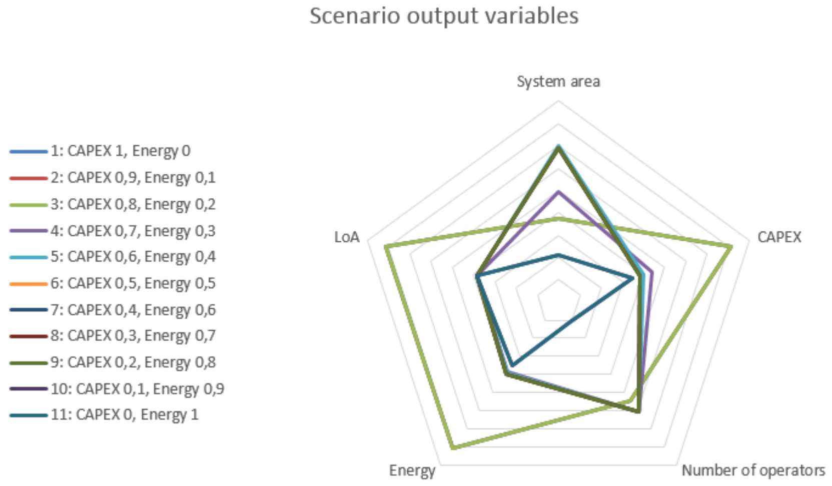
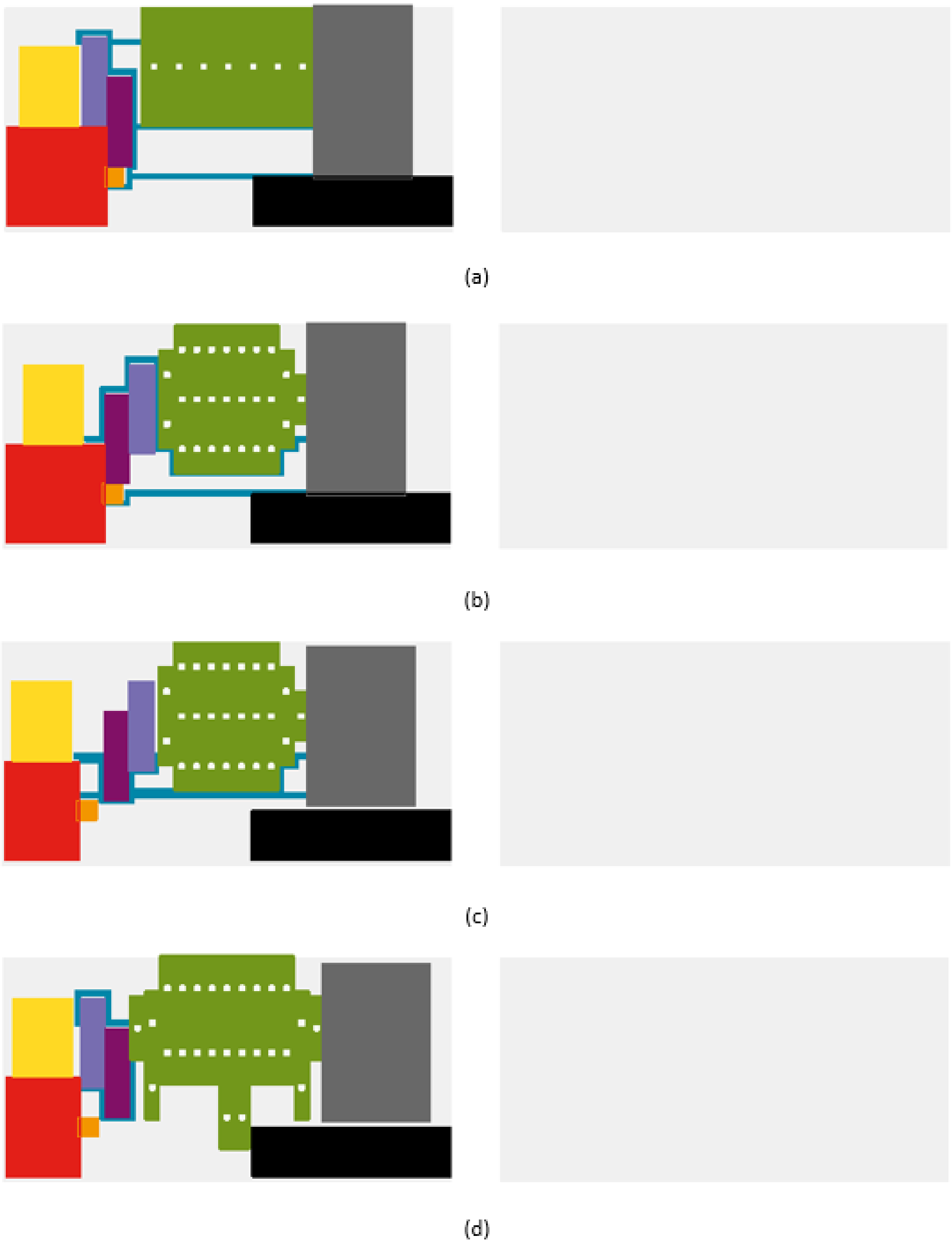


Figure F.15: Radar chart of the decision variables of the SA of the CAPEX versus energy consumption for AUA.

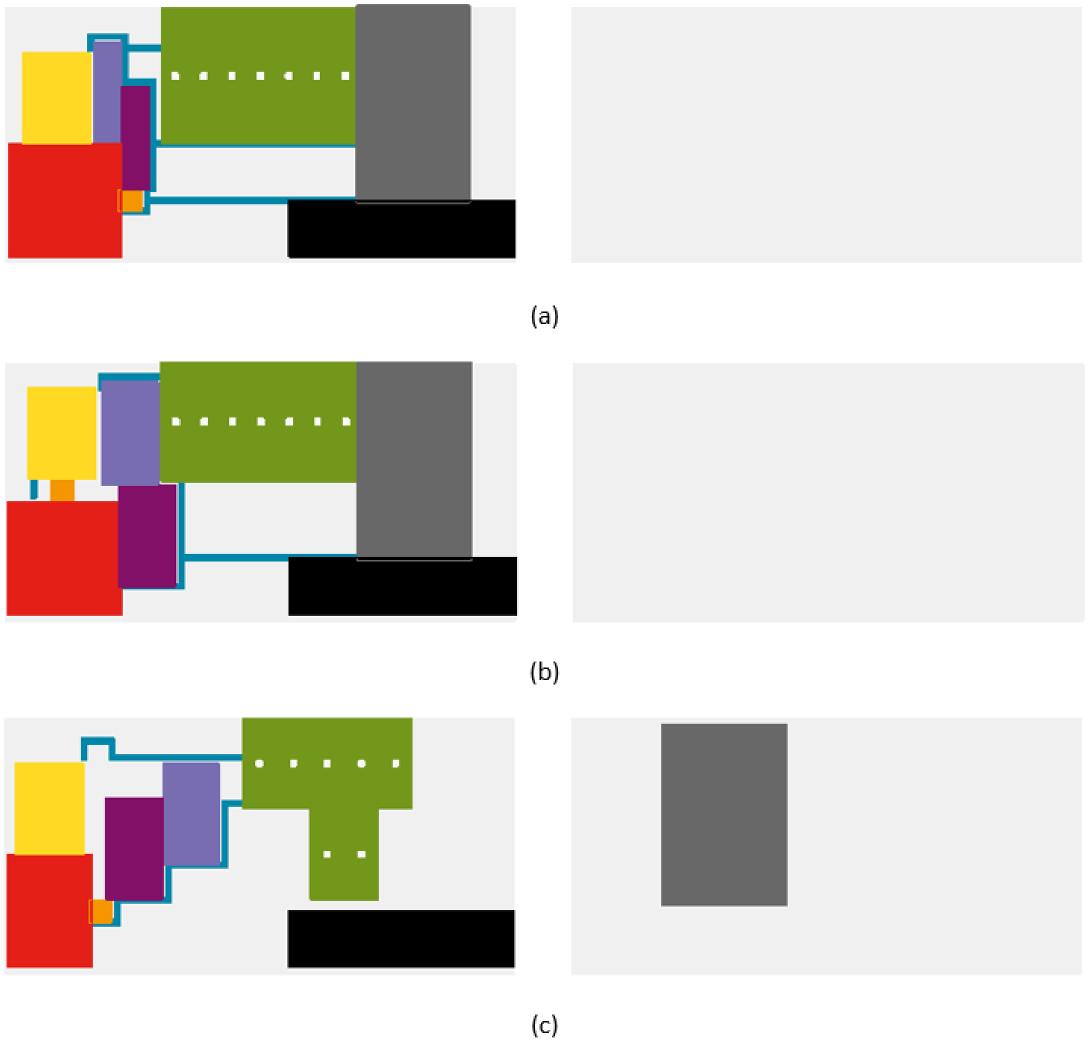

(a)

(b)

(c)

(d)

Figure F.16: Placement output of the SA of the CAPEX versus the energy consumption for AUA, where (a) is scenario 1-3, (b) is scenario 4, (c) is scenario 5-9, and (d) is scenario 10-11.

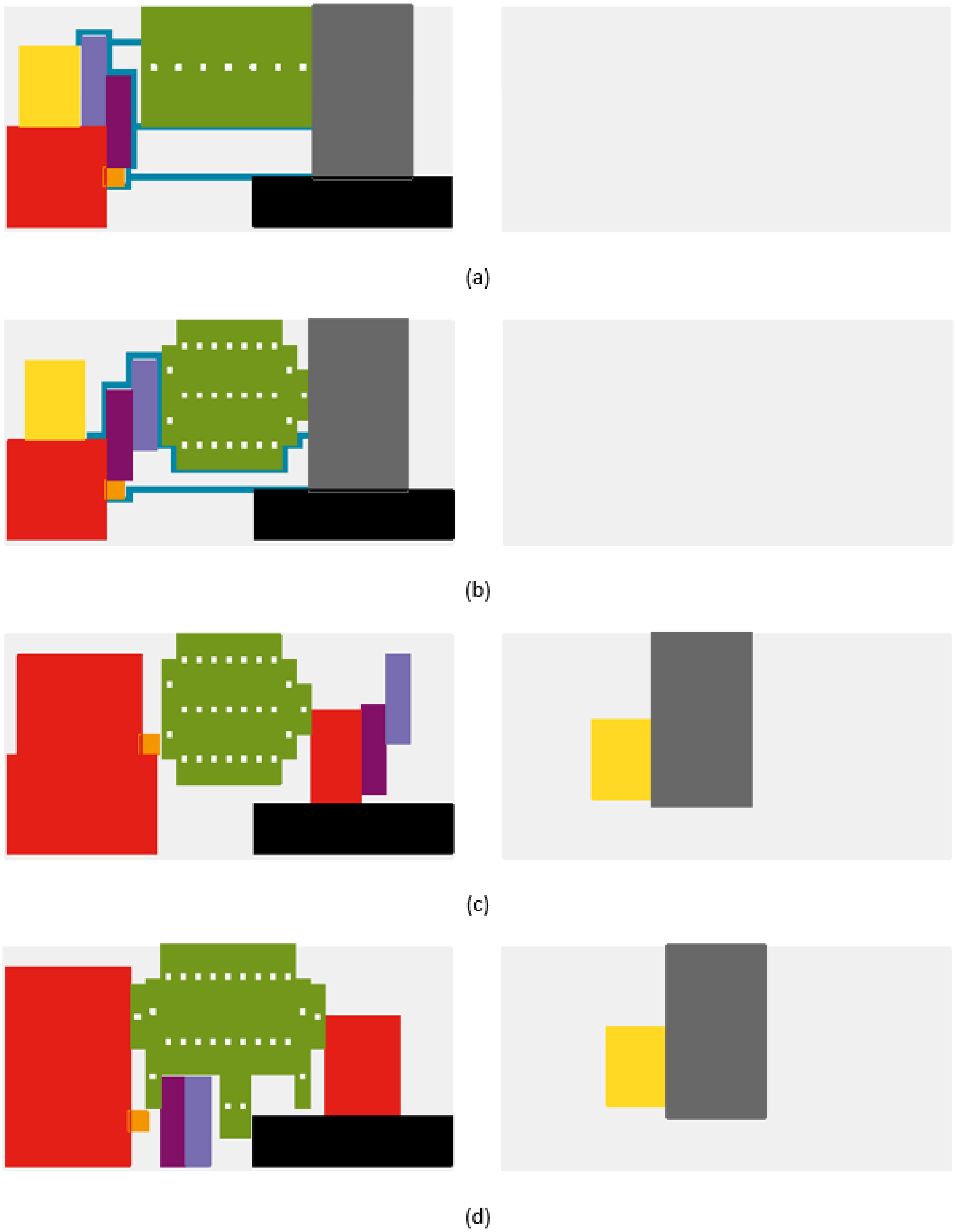


(a)

(b)

(c)

Figure F.17: Placement output of the SA of the CAPEX versus the minimizing the number of operators for AUA, where (a) is scenario 1-5, (b) is scenario 6-9, and (c) is scenario 10-11.



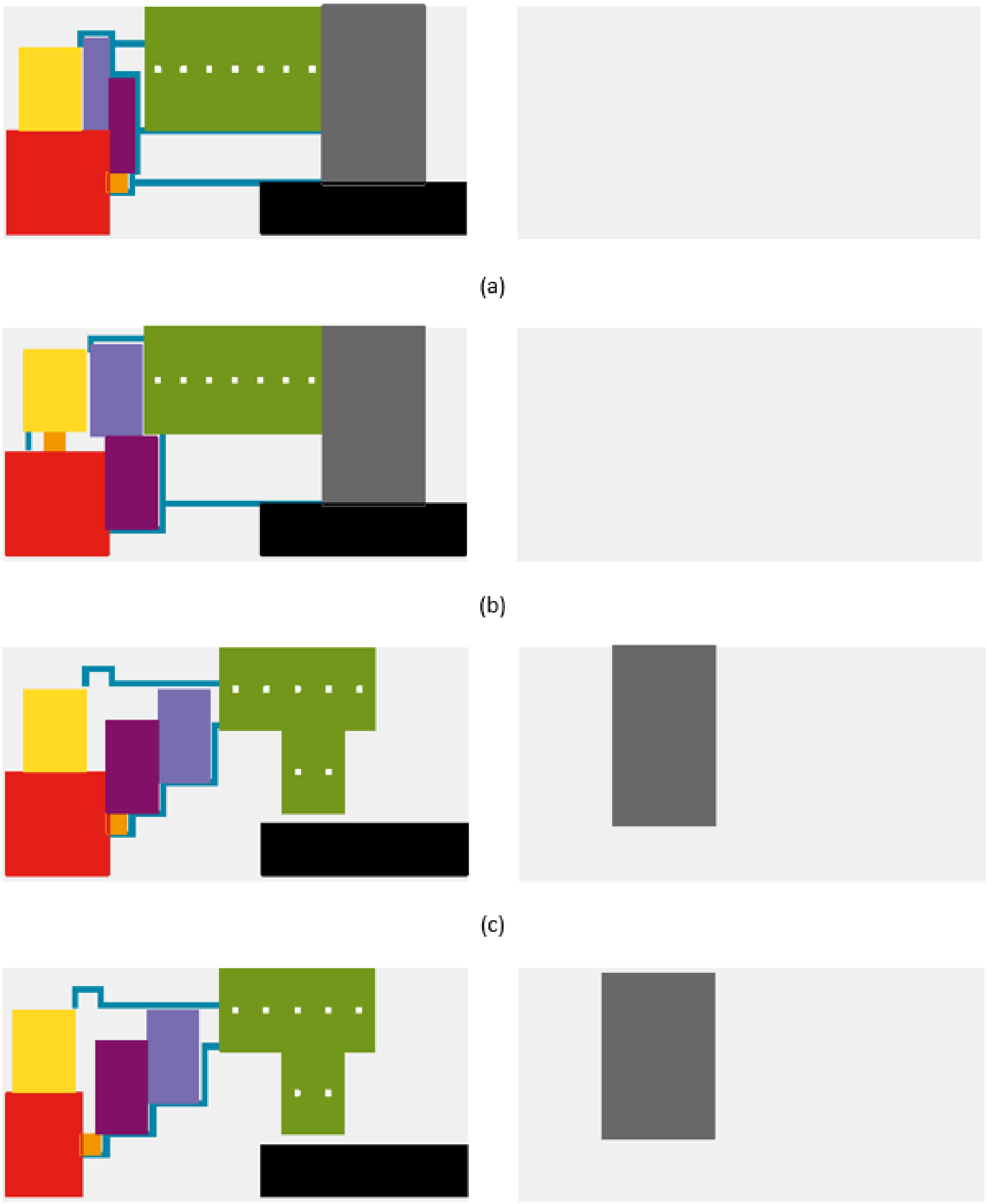
(a)

(b)

(c)

(d)

Figure F.18: Placement output of the SA of the CAPEX versus the minimizing the LoA for AUA, where (a) is scenario 1-4, (b) is scenario 5-6, (c) is scenario 7-9, and (d) is scenario 10-11.



(a)

(b)

(c)

(d)

Figure F.19: Placement output of the SA of the CAPEX versus the maximizing the LoA for AUA, where (a) is scenario 1-3, (b) is scenario 4-9, (c) is scenario 10, and (d) is scenario 11.

F.2 Design decisions

- To validate the model switches and to test if the model acts as expected (which are explained in detail in Chapter 6), the switches are tested for Aruba Airport. The demand that is used for the scenarios is constant (the same for every scenario) and is calculated via a flight schedule.

- First the switches that determine the placement are tested. Figure F.20 shows these settings. If the switch is turned on for a scenario, the square is green.

- The switches are tested for four optimization choices: 100% CAPEX, 100% energy, 100% LoA and 100% operators. For every optimization choice six scenarios are run with a varying set of switches. Figure F.21 shows how often each switch was turned on or off for each of the four optimization scenario groups.

- The type of equipment per subsystem varied between the optimization groups, but was the same within a group. Table F.3 shows the differences in equipment per optimization group.

- Figures F.22-F.25 show the placement results from the test. Of each figure, (a) is the placement of scenario 1 and 2, (b) of scenario 3 and 4, (c) of scenario 5 and (d) of scenario 6.

- Notable is that scenario 1 and 2 provide the same placement outcome. The same applies to scenario 3 and 4. This can be explained by the fact the EBS is placed in a spot that is not desired by the other subsystems, for instance in the top right corner or second floor.

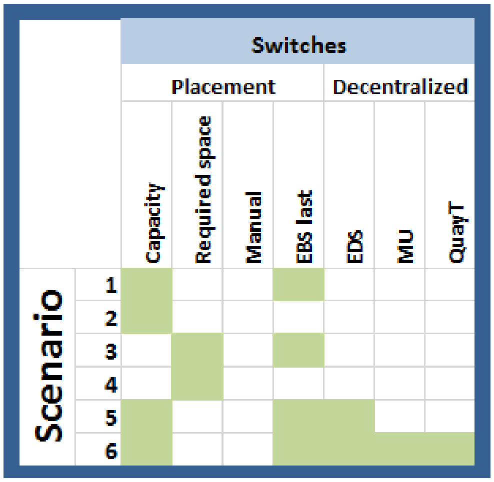
- In Figure F.22 the difference between (a) and (b), which is ordered based on capacity versus required space, is that in (a) the ETD (yellow) is placed last while in (b) it is the fourth subsystem to be placed.

- The third placement, (c), shows that the screening level 1 is decentralized. Two machines are placed near check-in (bottom-left corner, 1st floor) and one at each aircraft point (top-left and top-right corner, 1st floor).

- In the last placement (d) also make-up is decentralized, closer to the aircraft points than screening level one. Also offloading is decentralized, but since their is only one offloading machine, it is placed at the first aircraft point.

- The other placement figures show similar results to the CAPEX optimized results previously discussed.

- Also the preference to place subsystems on a selected floor level is tested. Figure F.26 shows the result that every requested subsystem can be placed on a required floor level. These scenarios are tested with the standard settings and show no odd results.



		Switches						
		Placement				Decentralized		
		Capacity	Required space	Manual	EBS last	EDS	MU	QuayT
Scenario	1	🟩			🟩			
	2	🟩						
	3		🟩		🟩			
	4		🟩					
	5	🟩			🟩	🟩		
	6	🟩			🟩	🟩	🟩	🟩

Figure F.20: Scenarios run to test the model switches.

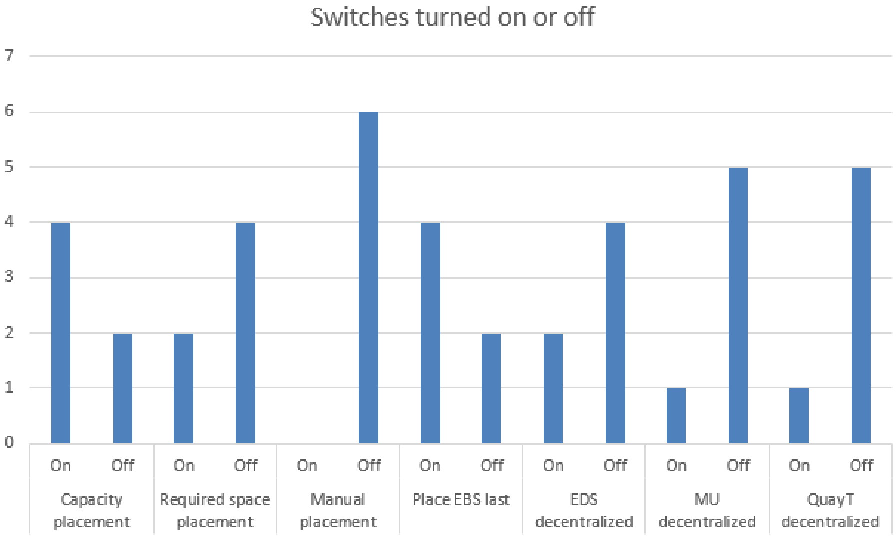
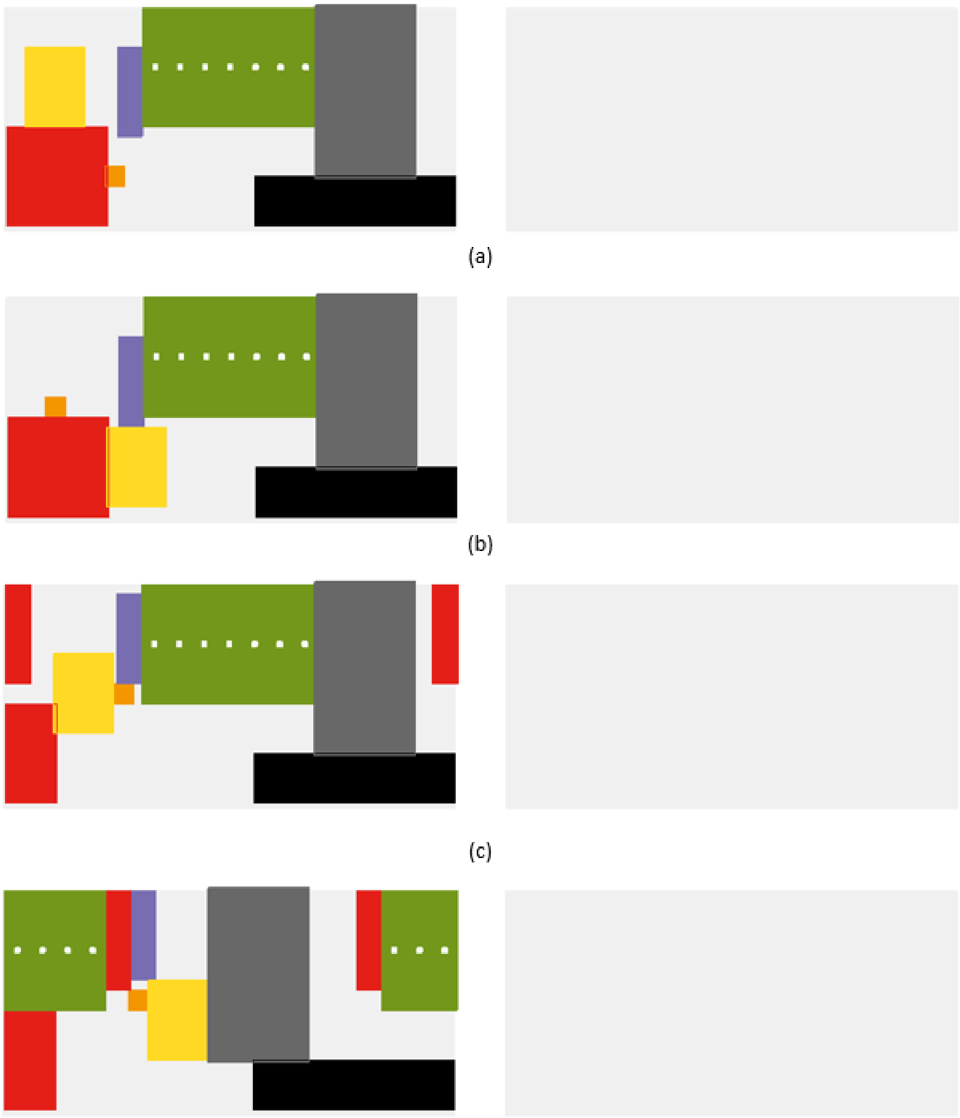


Figure F.21: Histogram of switches.

Table F.3: Equipment choices.

	Optimized based on: **CAPEX**	**Energy**	**LoA**	**Operators**
Check-in	Two-Step-Drop-Off	Two-Step-Drop-Off	Staffed	Staffed
HBS level 1	Medium speed EDS	High speed EDS	Stand Alone EDS	Stand Alone EDS
HBS level 2	OSR	OSR	OSR	OSR
HBS level 3	ETD normal search	ETD normal search	ETD normal search	ETD normal search
Make-up	Lateral+Train	Chute+Train	Chute+Train	Chute+Train
EBS	Shuttle rack	Crane rack	Crane rack	Crane rack
Offloading OD	Manual_OD	Manual_OD	Manual_OD	Manual_OD
Offloading T	Manual_T	Manual_T	Manual_T	Manual_T



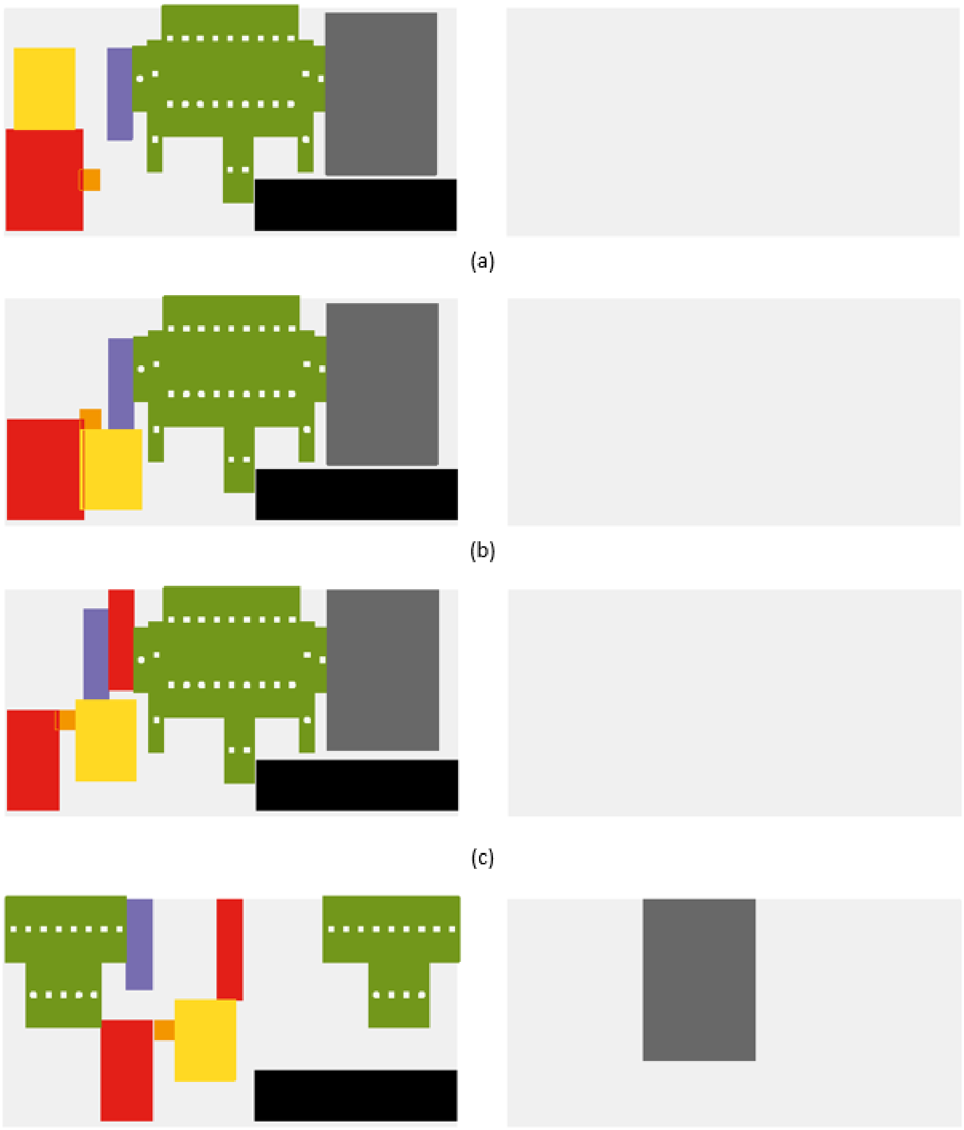
(a)

(b)

(c)

(d)

Figure F.22: Concept design, optimized based on the CAPEX.



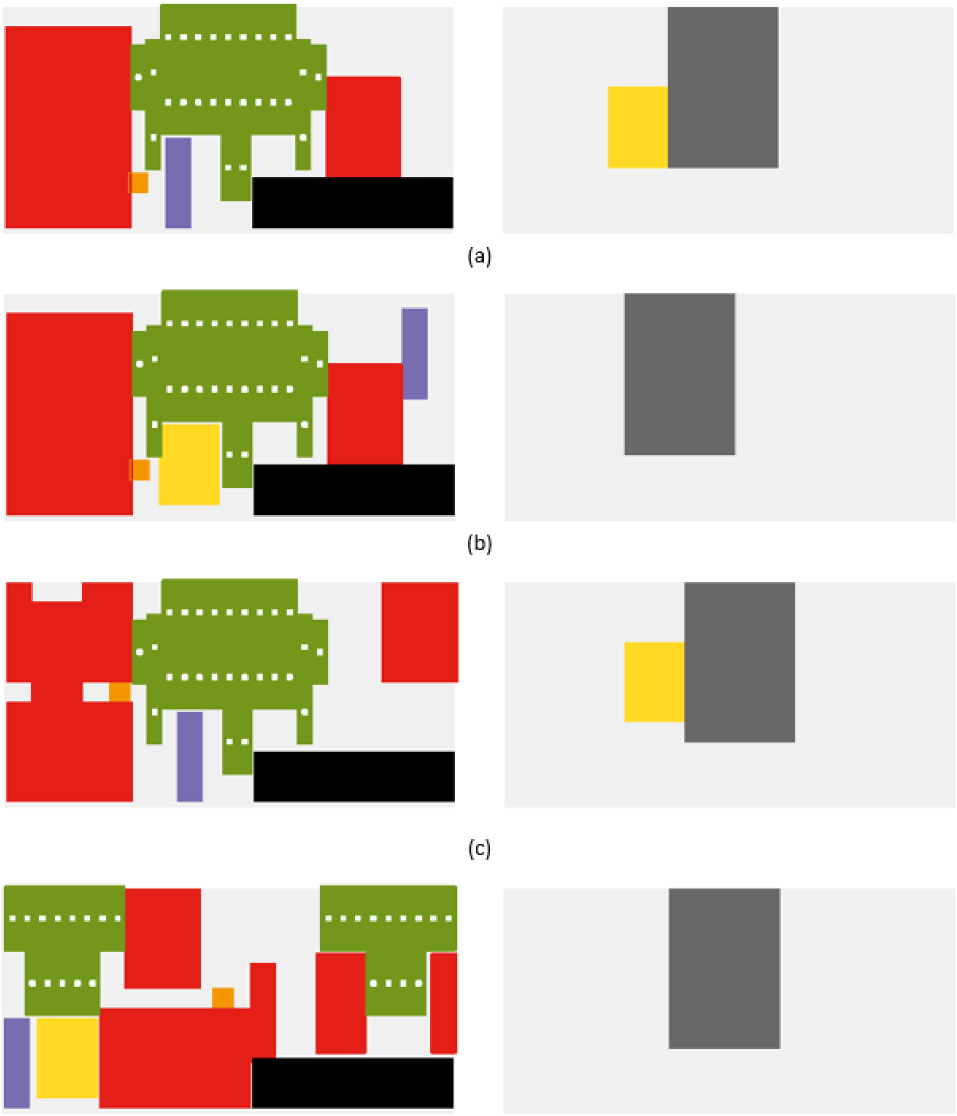
(a)

(b)

(c)

(d)

Figure F.23: Concept design, optimized based on the energy consumption.



(a)

(b)

(c)

(d)

Figure F.24: Concept design, optimized based on the LoA.

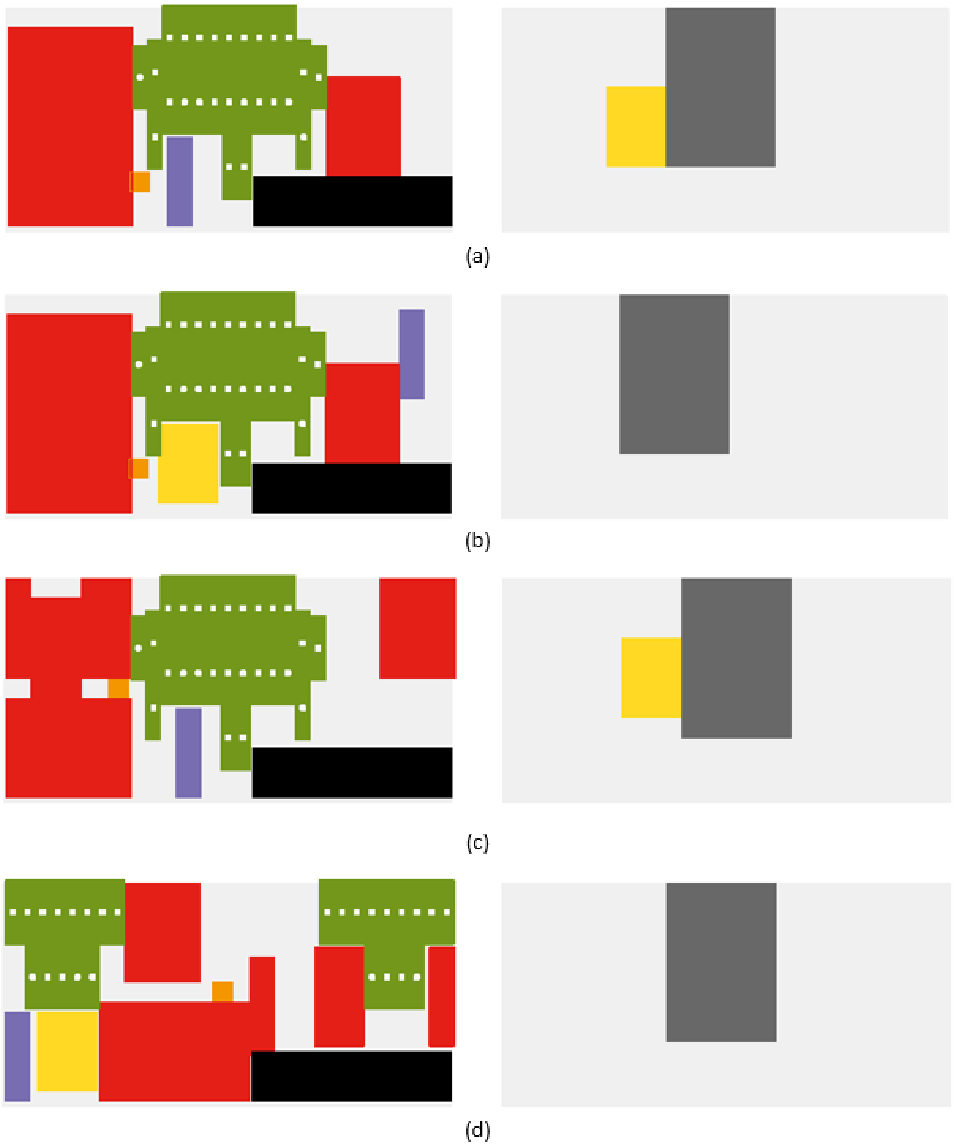


Figure F.25: Concept design, optimized based on the number of operators.

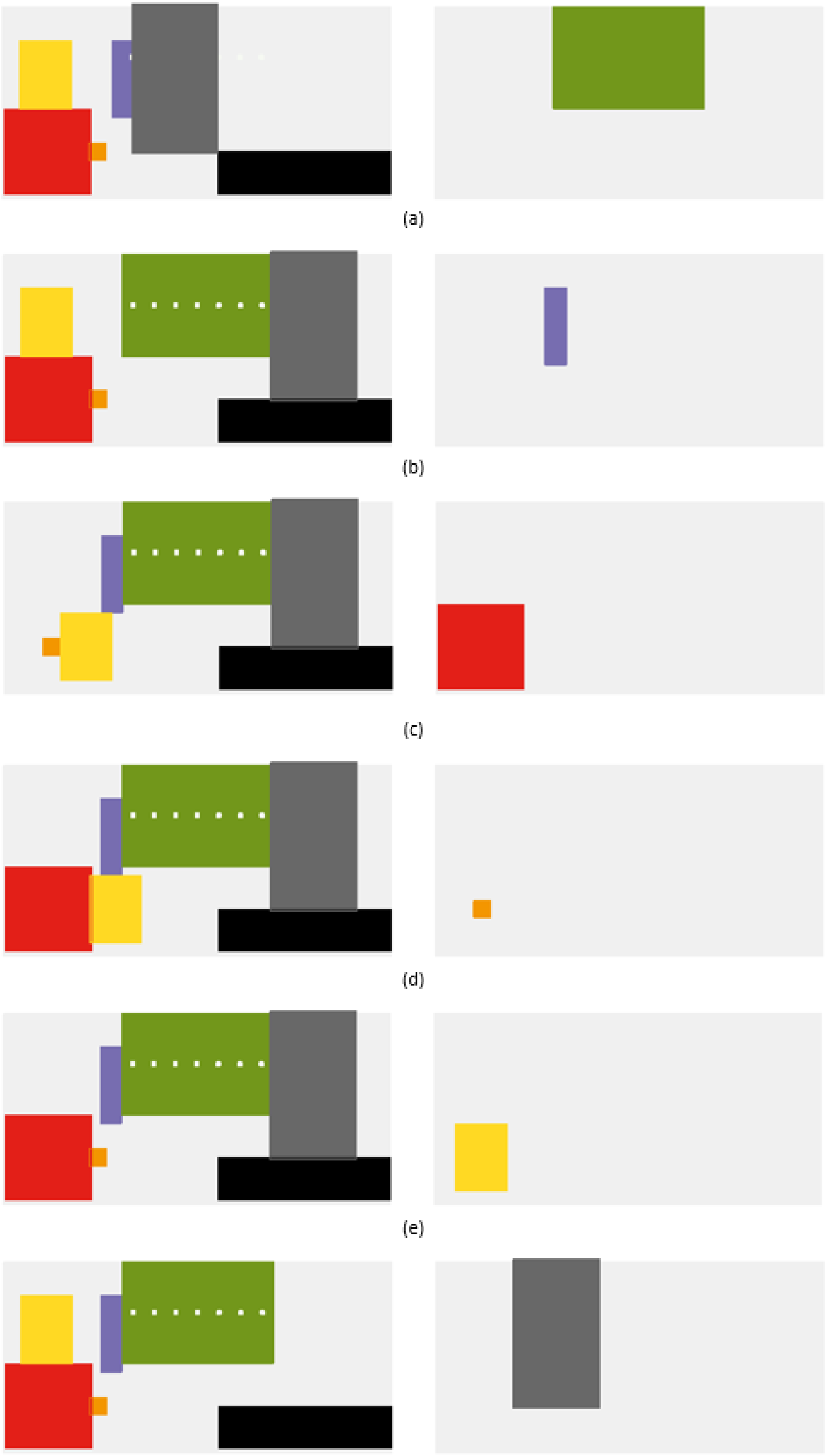

(a)
(b)
(c)
(d)
(e)
(f)

Figure F.26: Test floor level of the concept design.

F.3 Brownfield model

- To validate the brownfield model and to test if the model acts as expected, the model is tested for Amsterdam Airport Schiphol.
- Figure F.27 shows the demand that is used for the scenarios. Figure F.28 shows the settings that are used to test the brownfield model.
- All other results are discussed in Chapter 7.

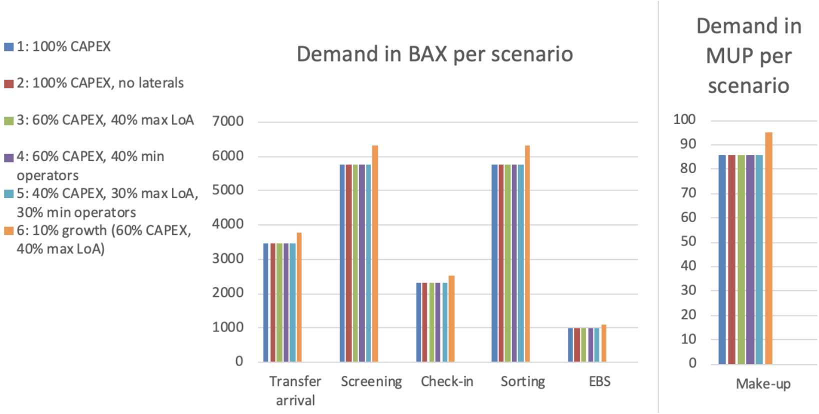


Figure F.27: Demand of the scenarios of AAS South terminal and Area A BHS.

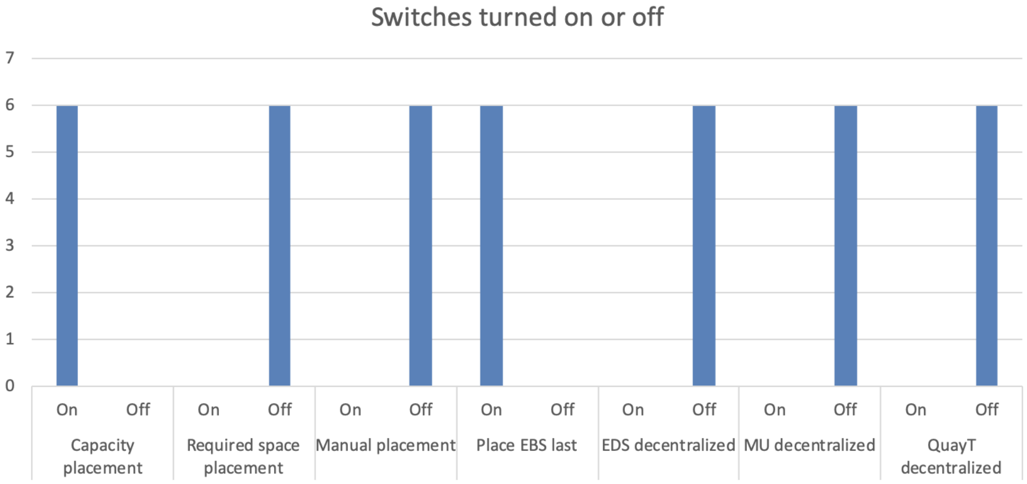


Figure F.28: Settings of the scenarios of AAS South terminal and Area A BHS.