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Automation of the conceptual design stage for material handling systems

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Automation of the conceptual design stage for material handling systems

Development of an automated design model for the conceptual design phase of baggage handling systems

By

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Preface

This thesis is the result of my graduation assignment at NACO. During a 7 month period I developed a conceptual design tool for the Special Airport Systems department of NACO. Ever since my minor "Airport of the future", I have been intrigued by the logistics around airport. So, performing my thesis at one of the world-leading airport consultancy has therefore been a privilege.

I would like to thank my university supervisor Wouter Beelaerts van Blokland for introducing me to NACO and his interest into this project and Dingema Schott for her honest feedback during each meeting. Special thanks go out to my NACO supervisors, Taco Spoor and Niels Ridderbos. I would like to thank Taco Spoor for his guidance during the process and giving me the freedom to perform this research however I wanted. And I would like to thank Niels Ridderbos for always being able to help me whenever needed. At last, I would like to thank the entire SAS team for always being supportive and helping me when needed.

There are many people involved during the process which I could thank. As the list would be to long to give here, I would therefore like to thank everybody else involved in this thesis. This includes the rest of NACO and Royal HashkoningDHV, my friend and last but not least my family.

Mark Vijlbrief
Den Haag, February 2019

Abstract

Baggage handling systems (BHS) are unknown to most people but are a vital part of an airport. They are material handling systems which transport the bags of passengers to the aircraft and back. A famous example of the importance of a BHS is Denver International Airport, were a failure of the system delayed the airports opening by 16 months costing roughly $500 million. To prevent such failure, the design process of a BHS is of importance. Usually at the beginning of the design process, tools are lacking. This research therefore aims at developing a design tool for the very first stage of BHS design: the conceptual design phase. In this phase, a first estimate of the amount of equipment is calculated and a floorplan is made for spacial reservation.

First automated design of material handling system in general were researched. From this research a generalized design framework was developed for material handling system. The first step of this framework is to take the supply data and operational requirements of the system to define the required capacity of each subsystem. Next, for each possible equipment type, the amount and corresponding equipment data is calculated based on the desired capacity. In the third step, based on the stakeholders desires and the terminal dimensions, the equipment is chosen. In the fourth and final step, called facility sizing, each piece of equipment is placed within the terminal. If this framework is followed, a concept design can be developed.

The work of a previous graduate already provides a basis for the first three steps of the framework, however, for the facility sizing an extra research is done. This research is on very large scale integration (VLSI) placement models, were the Gordian placement model is seen as the most suitable for BHS applications. However, with VLSI placement, the placement is performed based on the amount of connections each subsystem has while the facility sizing is based on the capacity of each connection. So a second placement model is introduced, the droplet model. This model works by finding the best location for a piece of equipment and then search the closest possible location were the unit can be placed. This search algorithm propagates through the area similar to a wave created when a droplet hits a liquid surface.

With the models framework defined, the desired output was researched. This is done by first finding the involved stakeholders, then define their important trade-offs. Based on the latter it was decided which output can be used to show the effect of each trade-offs to the stakeholders. It is concluded that the best data visualization methods are a 2D graph showing the relation between different trade-offs, a table representation showing the individual data of each sub system and a 3D model showing the placement of the BHS subsystems.

Next, the input parameters needed to develop a BHS conceptual design were researched. As research on entire BHS is lacking, each subsystem was looked at separately. Then, by combining all information, the important input parameter for the conceptual design phase were filtered out. This resulted in a total of 38 input parameters and 38 possible types of equipment which can be used for BHS.

With all the facets of the model defined, it could be fully developed. Before doing this, the Gordian and droplet models were put to the test. As expected, the Gordian model cannot be used for facility

sizing. The droplet model performs better so this model was chosen to be used in the final model. The model is then tested in a few test cases. Each test case was successful, so the next step was to apply the model in several test cases. These studies were on Aruba International Airport, Qatar's Hamad International Airport and the New Mexico City International Airport. From the test cases it became clear that the model is able to develop a feasible solution, but has limitations. These limitations are mainly caused by the fact that the four step framework cannot be followed. The model works with a five step framework were the transport related equipment is chosen after the facility sizing. This has to do with the fact that the transport equipment is dependent of the placement of each subsystem. However, the model was able to provide a feasible solution.

Besides BHS, a few case studies were performed on other material handling systems. These cases are highly simplified, but show the possibilities of the model. It shows that the framework behind the model is not only applicable to BHS, but to material handling systems in general. This highlights the applicability of the design framework developed in this research and opens space for new research.

In conclusion, a model is proposed which is able to aid in the development of BHS concept designs. A design is created based on different stakeholder trade-offs. This model is able to show the impact of certain design decisions and is able to develop a 3D model which takes into account the terminal shape and size. As shown by the case studies, it can also be applied to different types of airports. Limitations to the model are still present, but the outcome of the model is usable. Were the work of the previous graduate provided a proof-of-concept for a possible design tool, this thesis provides a fully functional model for the conceptual design stage of BHS which can be used in the field.

Abstract (Dutch)

Onbekend voor meeste reizigers, maar bagage afhandeling systemen (BHS) vormen een cruciaal deel van een vliegveld. Het zijn materiaal afhandeling systemen die bagage van reizigers naar het vliegtuig brengen en andersom. Een berucht voorbeeld van het belang van een BHS is Denver International Airport waar een storing van het systeem de opening van het vliegveld met 16 maanden vertraagde en een kosten van ongeveer $500 miljoen veroorzaakten. Om zulke storingen te voorkomen is het ontwerpproces van BHS van groot belang. Echter, aan het begin van het ontwerpproces zijn er vaak weinig hulpmiddelen te vinden. Dit onderzoek is daarom gericht op het ontwikkelen van een hulpmiddel voor het allereerste ontwerpproces van een BHS: de conceptuele ontwerpfase. Tijdens deze fase wordt een eerste schatting gemaakt van de hoeveelheid machines die nodig zijn en een plattegrond is ontwikkeld voor ruimte reservering.

Sinds BHS, materiaal afhandeling systemen zijn, werd geautomatiseerd ontwerpen in het algemeen eerst onderzocht. Hieruit volgde een gegeneraliseerd ontwerpproces voor materiaal afhandeling systemen. De eerste stap is om aanvoer data en de operationele vereisten van het systeem te gebruiken om de benodigde capaciteit van elk subsysteem te bepalen. Vervolgens wordt voor elk mogelijk type machine de hoeveelheid en corresponderende data te berekenen gebaseerd op de benodigde capaciteit. In de derde stap, gebaseerd op de stakeholders verlangens en de terminals afmetingen, word een machine keuzes gemaakt. In de vierde en laatste stap, genaamd de facility sizing, word elke machine in de terminal geplaatst. Als dit proces wordt gevolgd kan een conceptueel ontwerp worden ontwikkeld.

Het werk van een vorige afstudeerster levert al een basis voor de eerste drie stappen van het proces. Echter, voor de facility sizing is een extra onderzoek nodig. Dit onderzoek is gericht op very large scale integration (VLSI) plaatsing modellen waar het Gordian placement model wordt gezien als het meest geschikt voor BHS-applicaties. Echter, bij VLSI-plaatsing wordt de plaatsing gedaan op basis van de hoeveelheid connecties tussen elk systeem terwijl voor facility sizing de capaciteit van elke verbinding belangrijker is. Daarom wordt een tweede plaatsing model geïntroduceerd, het droplet model. Dit model werk door de beste locatie te vinden voor een machine en vervolgens de dichtstbijzijnde locatie te vinden waar de machine geplaatst kan worden. Dit zoek algoritme verspreid zich over het oppervlak vergelijkbaar met een golf die gecreëerd wordt door een druppel (droplet) die het oppervlak van een vloeistof breekt.

Met het model proces gedefinieerd, kan de gewenste output worden onderzocht. Dit onderzoek begon door eerst alle stakeholders te vinden en vervolgens de belangrijkste afwegingen voor hen te definiëren. Gebaseerd op de afwegingen werd de mogelijke output vormen te vinden die het effect van de verschillende afwegingen in kaart gebracht. De beste visualisatie methodes die gevonden zijn, zijn een 2D grafiek die de relatie tussen verschillende afwegingen, een tabel die data voor elk subsysteem laat zien en een 3D model die de plaatsing van elke machine laat zien.

Vervolgens werden de input parameters onderzocht die nodig zijn om een conceptueel ontwerp te ontwikkelen. Sinds onderzoek in het ontwerp van BHS in het geheel weinig voorkomt, word elk systeem apart onderzocht. Hierna wordt alle data gecombineerd om de belangrijkste parameter voor de conceptuele ontwerpfase eruit gefilterd. Dit resulteerde in totaal 38 input parameters en 38 verschillende machine types die gebruikt kunnen worden voor BHS.

Met al de aspecten van het model gedefinieerd kan het model ontwikkeld worden. Voordat dit gedaan wordt, word eerst het Gordian en droplet model getest. Zoals verwacht kan het Gordian model niet worden gebruikt voor facility sizing. Het droplet model presteert beter dus dit model wordt gebruikt voor de facility sizing van het uiteindelijke model. Het model wordt vervolgens getest in een paar test situaties en sinds deze testen succesvol zijn, word het model toegepast op drie test casussen. Deze casussen zijn Aruba International Airport, Qatars Hamad International Airport en New Mexico-City International Airport. Uit deze tests wordt het duidelijk dat het model haalbare oplossingen kan creëren maar het model maar met beperkingen. Deze beperkingen komen voornamelijk voort uit het feit dat het vier stappen proces niet gevolgd kan worden. Het model ontwikkeld werkt met een vijf stappen proces waar de transport gerelateerde machines na de facility sizing. Dit heeft te maken met het feit dat het transportsysteem afhankelijk is van de plaatsing van elk systeem. Echter, het model is wel in staat een haalbaar ontwerp te leveren.

Naast BHS, zijn er een paar casussen uitgevoerd voor andere materiaal afhandeling systemen. Deze casussen zijn gesimplificeerd maar laten wel de mogelijkheden van het model zien. Het laat zien dat het proces achter het model niet alleen toepasbaar is voor BHS, maar ook voor materiaal afhandeling system in het algemeen. Dit markeert de toepasbaarheid van het ontwerpproces dat in dit onderzoek ontworpen is en opent ruimte voor nieuw onderzoek.

In conclusie, een model is voorgelegd wat in staat is om een conceptueel ontwerp voor BHS te ontwikkelen gebaseerd op verschillende afwegingen van de stakeholders. Dit model kan de impact van verschillende ontwerp keuzes en is in staat om een 3D model te ontwikkelen die rekening houdt met de vorm en grootte van een terminal. Zoals de casussen laten zien is het ook toepasbaar op verschillende type luchthavens. Het model heeft beperkingen maar levert een bruikbaar resultaat. Waar het werk van de vorige afstudeerster een proof of concept als resultaat had heeft dit onderzoek geleid tot een functioneel model voor de conceptuele ontwerpfase van BHS die gebruikt kan worden in de praktijk.

List of Figures

List of Tables

List of Abbreviations

AAS	Amsterdam Airport Schiphol
AGV	Automated guided vehicle
ALT	Automated load unit transportation
AUA	Queen Betarix International Airport
BHS	Baggage handling system
BIP	Binary linear programming
CAPEX	Capital expenditure
CBRA	Checked baggage resolution area
DCT	Destination coded tray
DCV	Destination coded vehicle
DOH	Hamad International Airport
DOM	Domestic flight
EBS	Early baggage storage
ECAC	European Civil Aviation Conference
EDD	Explosive detection dogs
FIFO	First in first out
HBS	Hold baggage screening
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILP	Integer linear programming
INT	International flight
IST	In-system-time
LoA	Level of automation
LoS	Level of service
MCT	Minimum connection time
MUP	Make-up position

NACO	Netherlands Airport Consultants
NAICM	Nuevo Aeropuerto Internacional de la Ciudad de México
NB	Narrow-body aircraft
O&D	Origin and destination
OPEX	Operational expenditure
OSR	On-screen resolution
PPV	Physical programming visualization
QP	Quadratic programming
RJ	Regional jet
SAS	Special Airport Systems
STA	Scheduled time of arrival
STD	Scheduled time of departure
TSA	Transport Security Administration
ULD	Unit load device
US CBP	United States Customs and Border Protection
VLSI	Very large scale integration
WB	Wide-body aircraft

Table of Contents

Chapter 1

Introduction

This chapter provides an introduction to this thesis. First, a general introduction is provided in Paragraph 1.1. Here, the basic knowledge of baggage handling systems (BHS) will be given which is needed for the rest of this document. Thereafter, in Paragraph 1.2, NACO will be introduced. NACO is the company that provided the opportunity for this thesis. The paragraph will also provide their design process for BHS. Next, Paragraph 1.3 will discuss the motivation behind this thesis. The link between this thesis and a previous Msc thesis at NACO will also be explained in this paragraph. In Paragraph 1.4 the aim of the thesis, main research question and the sub research question will be given. The scope of the research will be discussed in Paragraph 1.5. At last, Paragraph 1.6 will discuss the research methodology used for this research and how this is implemented into the reports structure.

1.1 General introduction

With the expected global growth in air traffic (Airbus, 2018; Boeing, 2018; Embraer, 2018), current airports will have to expand and new airports should be developed. The airports should not only be able to cope with the increase in aircraft, but also the increase in passengers and their baggage. Stated by Edwards (2005):

"Baggage handling is one of the most complex and, in terms of passenger perception, most critical factors in the success of a terminal".

In the future, BHS should operate much more efficient and with greater flexibility (Bradley, 2010). Therefore, key aspects of airports are their BHS. These often complex systems handle all the hold baggage of arriving, departing and transfer passengers. The importance of these systems can be illustrated with two examples. The first example is that of Denver International Airport (de Neufville, 1994), which is a common example of BHS failure. When opened in May 1994, the fully automated BHS caused massive problems and delayed the opening of the airport. After 16 months of delay, the engineers were able to resolve the problems and the airport reopened. However, it is estimated that the delays costs the airport around $500 million. A more recent example is that of Gatwick Airport (Swartjes, van Beek, Fokkink, & van Eekelen, 2017), the second airport of London. Here, a failure of the BHS caused thousands of travelers to fly without their bags. From these two examples it becomes clear that the BHS are a crucial part of the airport. This makes the design process of these systems complex and of importance to the performance of the airport.

At an airport three different types of baggage flows can be distinguished. These flows are the departing, arriving and transfer flows. In Figure 1.1 these flows are illustrated together with the BHS boundaries. The flows can be described as following:

- **Departing flow** - The departure flow handles the baggage of departing passengers. The flow starts at the check-in, where the bags enter the BHS. The bags are transported to the hold baggage screening (HBS) area where the baggage is screened for explosives. When screening is done, the bags are transported to the sorting area. Here the bags are either send to early baggage storage (EBS) or send to the right make-up position. The EBS is optional and is only needed if the airport provides early check-in or long transfer times for passengers between flights. At the make-up, the bags are loaded onto unit load devices (ULDs) or carts. The usage of ULDs or carts depends on the aircraft type and the airline which the bags are destined for. Hereafter, the bags leave the BHS and are transported to the aircraft. The departure flow is indicated with the blue arrows in Figure 1.1.

- **Arriving flow** - The arriving flow handles the baggage of the arriving passengers. These bags enter the BHS via the offloading area. Here the bags arrive in an ULD or cart and are offloaded on the reclaim belt. This belt transports the bags to the reclaim area where the passengers can pick up their bags. The arriving flow is indicated with the green arrows in Figure 1.1.
- **Transfer flow** - The transfer flow handles the bags of transfer passengers. The bags enter the BHS via a separate offloading area. From here they are transported to the screening area where they follow the departure flow. In the USA, if the transfer is between domestic flights (DOM), bags can skip the screening process by going directly to the make-up area. Tail-to-tail transport is also possible for bags, this means that the bags are transported directly between aircraft and bypass the BHS. This however is not common practice due to security issues. The transfer flow connection to the departure flow is indicated by the red arrows in Figure 1.1.

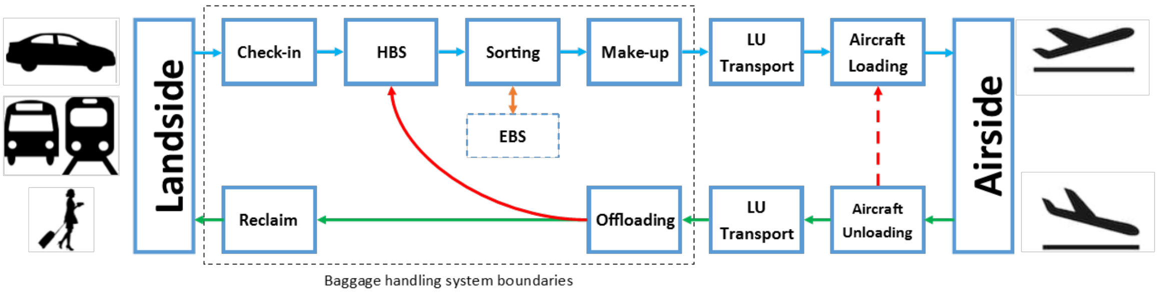


Figure 1.1: The baggage flow at an airport, the blue arrows represents the departing flow, the green arrows the arriving flow and the red arrows represent the possible transfer baggage connections.

The boundaries of a BHS in this research are defined by the boundaries provided in Figure 1.1. This means that two types of baggage are excluded, the odd-size baggage and baggage which is checked-in at the aircraft. The latter is usually only done on narrow body aircraft where their is not enough space to store all hand luggage in the aircraft cabin. Also, tail-to-tail transport of baggage is not included into this report.

To handle the baggage flow, a BHS consists of 7 subsystems: check-in, screening, sorting, make-up, offloading, reclaim and EBS. In the explanation of the flows the functions of the systems are already explained. An eight subsystems can be distinguished, the transportation system. This system is needed whenever two subsequent subsystems are not placed directly after each other and need to be linked.

1.2 NACO

NACO (Netherlands Airport Consultants), is a world-leading independent airport consultancy and engineering firm. For 65 years the company has been working on projects within the aviation industry, from major intercontinental hubs to small domestic airports. NACO has served 600 airports in more than 100 countries. Amsterdam Airport Schiphol (AAS) has worked together with NACO since the 1950's. In every single terminal expansion of AAS, NACO was involved. As a company of

Royal HaskoningDHV, a network of 5,000 professionals in 35 countries is available (NACO, 2017).

Within NACO, the Special Airport Systems (SAS) department has a team dedicated to the design of BHS. They specialize in optimizing baggage handling facilities to create a safe, compliant and seamless operation. Some of the projects the SAS team has worked for include AAS and the development of the New Mexico City International Airport (NAICM). This thesis is performed in collaboration with the BHS section of the SAS department.

The design process for BHS at NACO can be split into 4 phases. The first phase is the master planning. During this phase, the requirements of the BHS are defined based on passenger data and baggage process equipment. With this data, the basic size of all facilities and amount of check-in desks are decided. This stage is performed by master planners, so not by the SAS team.

The second phase is where the work of the SAS team starts. In the second phase the conceptual design is created. Besides the data of the master planners, the design is also based on a questionnaire with the stakeholders. With this data, the rough size of each BHS subsystem is given in a functional design layout.

When the conceptual design is finished the third phase is started. In this phase, a scheme design is created. This scheme is shown as a material flow diagram in which the flow of baggage and the amount of equipment is given. The rough size of the BHS subsystems can now be converted into a more complete 3D drawing during the last phase, known as the detailed design phase. When the design of the BHS is finished, a final 3D model is made which will be used for simulation.

1.3 Research motivation

Described by Pahl, Wallace, and Blessing (2007), 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. The conceptual design stage is a crucial process within engineering design. As stated by Hsu and Liu (2000), decisions made during the conceptual design have significant influence on the cost, performance, reliability, safety and environmental impact of a product. The decisions made during this stage can account for more than 75% of the final product costs. Even though the impact of decisions are high during the conceptual design phase, tools are lacking (L. Wang et al., 2002). This is made visible in Figure 1.2 where it can be seen that as decision impact decreases over time, the availability of tools rises.

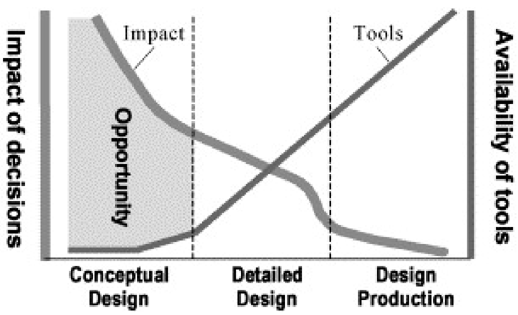


Figure 1.2: The impact of design decision against the availability of tools during the design process (L. Wang et al., 2002)

At the moment, the conceptual design phase of a BHS is done manually by the engineers which rely on their knowledge. As stated by a BHS designer from NACO: *"The outcome of a concept design depends on the moment. If it was done another time with the same engineers, the outcome could* *yield a completely different design"*. Both design will perform as desired, however, an aiding tool could bring structure in the conceptual design of BHS. This is again highlighted by de Neufville and Odoni (2013) as they say: *"This variety of systems for screening and moving bags means that there are few rules about planning baggage handling systems at the conceptual stage"* . At last, the time it takes to make a conceptual design can be reduced by means of automating the concept generation.

In literature, proposals for conceptual design tools can be found (Antoine & kroo, 2005; Fitzgerald, Herrmann, & Schmidt, 2010; de Aguiar et al., 2017). However, when it comes to BHS, only the work by Van Noort (2018) focuses on a possible aiding tool in the conceptual design phase. This tool by Van Noort, developed for the NACO SAS team, provides a generative model for the design of BHS. A process which normally takes weeks is reduced to only a few minutes. The tool, however, is still in the early design stage and has to be improved. That is why this thesis aims at improving the current model and convert it to a more realistic and user-friendly tool.

Besides the motivation to create an aiding tool for the conceptual design of BHS, the goal is also to extend the current research into BHS concept design. Research into this field is lacking and most research is aimed at the control systems (Saygin & Natarajan, 2010; Black & Vyatkin, 2010). Some university research can be found on BHS design. The work by Lemain (2002) is focused on the sales phase of BHS design. Pielage (2005) describes a design approach for automated freight transport systems, which BHS are part of. Research done by Grigoraş and Hoede (2007) does focus on the design of BHS, however, the focus is mainly on the routing aspect of BHS and not the generating of concept designs. More recent work include that of Van Enter (2018), which studies the impact of design decisions on the energy consumption of BHS.

The earlier mentioned work by Van Noort (2018) is the only research which provides a model for the automation of BHS concept design. However, this research mainly focuses on defining the criteria for generating BHS concept design in an automated fashion. The following four criteria are given:

- A set of design rules are required in the form of constraints and system requirements considering; demand, in-system-time, area, combinatory rules, overlapping rules and adjacency.
- A standard equipment library, that contains information regarding the equipment for the different sub-systems is required.
- There needs to be a means of search method to search through the solution space, while evaluating the encountered solutions by minimizing CAPEX and system area.
- The identified desirable solutions need to be visualized by means of a graph or 3D drawing.

With these criteria a model is proposed by Van Noort (2018). This models takes a flight schedule and an Excel file with the BHS equipment parameters. The output is given as a trade-off curve between capital expenditure (CAPEX) and system area. Also, a 3D model containing the blocks of each subsystem by area is created. These blocks are then manually placed in the right configuration. However, the airport specific data still has to be put in manually in the code and the model needs improvements to yield a better outcome.

1.4 Research questions

The aim of this research is to improve the current design model of Van Noort (2018) for the automated generation of BHS design. This model works by finding the optimal solution. However, the term optimal is relative since every airport is different and each stakeholder has different trade-offs for the BHS. That is why the current model has to be improved to become more realistic and incorporate more stakeholder desires. To define what should be improved, the following research question is developed:

How can the development of concept designs for greenfield baggage handling systems be automated using a predefined set of input parameters?

From the research question, several sub questions arise. These sub questions are as following:

1. *Are there any models in literature for the generation of concept design for material handling systems and which can be used for BHS applications?*
2. *How can the different possibilities in design be visualized for the stakeholders?*
3. *Which input parameters are needed to develop a BHS concept design?*
4. *How can the conceptual design stage of BHS be automated using a model?*
5. *How does the outcome of the model compare to the manually developed conceptual BHS design of different airports?*
6. *To which extend can the concept behind the model be applied to other material handling systems?*

The research questions have been arranged in the order in which the model will be designed. First, transport design generating will be discussed in general. Some design models will be discussed and one is chosen to develop BHS concept designs. Next, the desired output of the model is discussed which is followed by the input needed to develop a concept design. All the gathered data is then used to develop a design model. To validate the model, it is tested against existing airports. At last, the possibilities of the model are explored for other types of material handling systems.

1.5 Research scope

This research focuses on the automated generation of BHS concept design. To do this it is important to define the borders of a BHS concept design. As stated in Paragraph 1.2, the input data for the concept design consists of a flights schedule, based on one day, and a questionnaire with the stakeholders. From the questionnaire, the airport policies can be determined. However, if the stakeholder cannot provide some data, like the opening time of the make-up, assumptions have to be made. Another important input data is the terminal layout plan for the BHS. This can be either a fully defined area, or a first concept design. At last, a given set of equipment with their parameters is needed. For this research, generalized parameters are assumed for the equipment. This means that the difference between manufacturer is not taken into account. The left side of Table 1.1 shows the important input data for the concept design.

The output of the conceptual design stage can be split into four parts. First a 3D model containing the rough size of each subsystem is made. This model shows the layout of the BHS facility. Second, the output consists of the maximum capacity the BHS can handle. The capacity is retrieved from the flight schedule and consist of the peak hour at the airport. This peak hour is specified for each baggage flow and is given in bags per hour. At NACO, the peak hour is calculated by determining the peak 15-minutes and multiplying this by four. The third set of output data is what equipment is used and how many of each is needed. At last, the CAPEX is also retrieved from the concept design. In the right side of Table 1.1, the output data of a concept design is given.

Table 1.1: The input and output data of the conceptual design stage.

Input	Output
Flight schedule	Operational capacity
Equipment parameters	Equipment types and amount
Terminal layout plan	3D model containing rough sizes
Stakeholder questionnaire	CAPEX

At the check-in and reclaim area, passengers come in touch with the BHS. Because the main focus is on the BHS system, the research starts one meter before the check-in desks. This means that the space for a queue in front of the check-in desks is seen as the work of the terminal master planners and not the BHS engineer. The master planners define the amount of check-in desks and reclaim carousels. For check-in, calculations and requirements will be made in this research since multiple types of equipment can be used. For reclaim the exact scope will be discussed in Paragraph 4.7.

As stated in the research question, the research will focus on the BHS generation of greenfield BHS. A greenfield BHS is a project which is build up from nothing. This means that no existing structures or equipment is installed in the designated BHS area. Therefore, if an existing airport needs to expend their BHS, the model can be used if the plan is to completely replace the current BHS or a new BHS section is added to the airport. For the latter, the model can be used to define a BHS for the new building.

At last it is important to mention that the aim of the developed model is not to replace the engineers in the design process, but provide them with a tool to speed up the process. It will also provide more insight into the impact of design decisions made as early as possible. The creativity and experience of the engineers is still needed to developed a working design for BHS and to finalize the conceptual design.

1.6 Research methodology and report structure

For this research, a design science methodology is used for information research which has been used for software development (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). Since the aim of this research is to develop a design tool, the link to software development can be made. The methodology consist of the of six steps which are defined as following:

1. **Problem identification and motivation** - Define the specific research problem and justify why this problem is relevant to solve.
2. **Define the objectives for a solution** - In this step the requirements of the solution need to be defined. The goal is to find out what the solution could be and what is possible with the current knowledge.
3. **Design and development** - In this step, the "artifact" is created and explained. The artifact is seen as whatever creates the solution, for example a program or a model.
4. **Demonstration** - This step is used to demonstrate the use of the artifact and how it operates.
5. **Evaluation** - In the evaluation, it is observed and measured how well the created solution supports the problem.
6. **Communication** - The last step focuses on spreading the knowledge of the research.

The structure of the report is based on the six steps of the methodology. The first step of the methodology has been completed in this chapter. The research problem can be described as the need for a structured way of BHS designing and the solution, in this case the model, could bring this structure into the design process. A secondary problem can be the lack of research into BHS design. The solution brought forward by this research will broaden the knowledge into BHS design.

Chapter 2 till 4 provide a literature study into BHS design and automation of design. The chapters are ordered to go from a large perspective, material handling systems in general, to a smaller perspective by zooming in to a detailed look into BHS design. With this knowledge the objectives and possibilities of the solution can then be defined which applies to the second step of the methodology. The design and development step of the "artifact" is given in Chapter 5 and 6. Here, the design model will be developed which will generate the conceptual designs.

The demonstration step is performed in Chapter 7. This chapter consists of case studies on three different airports by applying the model to these airports. The model is used to determine the required space and equipment for the BHS and is compared to the conceptual design engineers developed for the airports. This chapter will then validate the model, and demonstrate how the model works. The evaluation step is performed in Chapter 8. Here, it will be evaluated how well the model provides a solution to the problem. The last step is that of communication. This step is aimed at spreading the knowledge of the research which can be done by a research paper. In Appendix A, a research paper of this thesis is therefore provided.

Figure 1.3 shows how the report is structured. A summary is given of which chapter is included in each step of the methodology. It is also stated where in the report each sub question is answered.

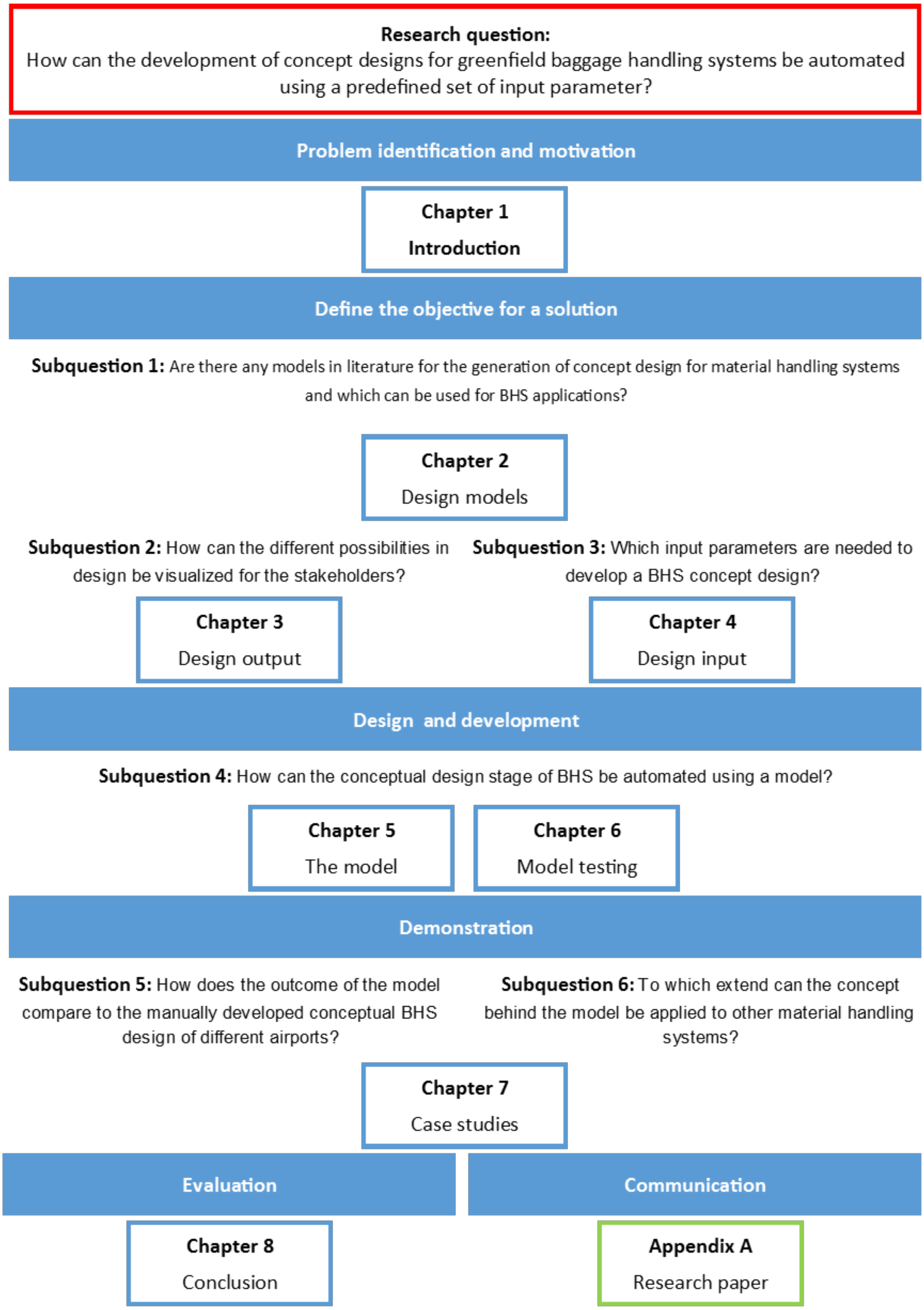


Figure 1.3: The structure of the report, beneath each subquestion it is indicated in which chapters the question is answered

Chapter 2

Automation of design

Before developing any model, a research is done to find out what is already written about design automation regarding the conceptual design phase of material handling systems. As part of her research, Van Noort (2018) already gave an insight into generative design. It is therefore not chosen to repeat this research, but to find different models which can be used for automated design generating. In Paragraph 2.1, different design generating models for material handling system will be discussed. This will give a generalized design framework for material handling systems. As part of this framework needs further research, Paragraph 2.2 and 2.3 aim to gain more insight into this. In the end this Chapter will answer the research question: *"Are there any models in literature for the generation of concept design for material handling systems in general and which can be used for BHS applications?"*. Paragraph 2.4 will conclude this chapter by giving an answer to the research question. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

2.1 Automated design

Multiple design models exists which can automatically generate designs for different applications. This paragraph will highlight some of these models which can be used for material handling systems. As stated before, this research is based on the work of Van Noort (2018). Her model will therefore be introduced first. As this model is already designed for BHS applications, this model will be the basis of this research. Thereafter, a few other design automation models will be discussed which contain elements that are not found in the model by Van Noort. Next, the information of all models is combined to develop a general design framework for material handling systems. In the end, the improvements which need to be made to the current model by Van Noort will be discussed.

2.1.1 BHS design model

The model by Van Noort consist of multiple steps. First, using a flight schedule and some system requirements, the demand values for the BHS are defined using Pyhton as a programming language. This is done by extracting information from the flight schedule regarding the arrival/departure time, aircraft type, airline or destination, amount of O&D PAX and amount of transfer PAX in combination with the system requirements. The flight schedule is presented as an Excel file while the system requirements are implemented into the Python script.

The second step in the model is done in Dynamo, which is a visual programming language for Autodesk Revit. From this step on, all of the following steps will be performed in Dynamo and Autodesk Revit. The step starts by manually inserting the demand values determined in the previous step. Next, a Python code is used in Dynamo to convert the demand data into equipment data. This equipment data consists of the amount of units needed to handle the demand, the CAPEX, the area and the IST for each possible equipment type.

The third step is a binary integer programming (BIP) model to make equipment choices using the data from step two. This model is based on research by Ölvander, Lundén, and Gavel (2009) and the theory of Hillier and Lieberman (2015). The BIP consists of three parts: the decision variables, objective function and the constraints. Each are describes as following:

- **Decision variables** - The decision variables represent the use of a certain equipment type for a certain subsystem. The representation of the decision variables is given in Equation 2.1.

$$x_{ij} = \begin{cases} 1 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is yes} \\ 0 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is no} \end{cases} \tag{2.1}$$

- **Objective function** - The objective function of this BIP model is to minimize a trade-off between CAPEX, c, and system area, A. Here α is introduced, which represents the trade-off between the two values. The objective function give in Equation 2.2:

$$min \left(\alpha * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} c_{ij} * x_{ij}}{\text{optimal value } CAPEX} + (1-\alpha) * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} A_{ij} * x_{ij}}{\text{optimal value } area} \right) \tag{2.2}$$

- **Constraints** - In total, four constraints are given to the BIP model. The constraints and their mathematical representation are as following:

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

$$\sum_{j=1}^{m} x_{ij} = 1 \quad \forall i \tag{2.3}$$

  2. The IST cannot be exceeded.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} t_{ij} * x_{ij} \leq \text{IST} \tag{2.4}$$

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

$$\sum_{i=1}^{n} \sum_{j=1}^{m} A_{ij} * x_{ij} \leq \text{max area} \tag{2.5}$$

  4. Some equipment types cannot be combined.

$$2 * x_{ef} - x_{gh} - x_{ij} \leq 0 \tag{2.6}$$

Using this model, the optimal solution regarding the equipment choice and amount of equipment needed can be retrieved.

The fourth step consists of an integer linear program (ILP) model which is used to create a system layout. The model is based on a method described by Drira, Pierreval, and Hajri-Gabouj (2007). Using the equipment amount and some sizing assumptions, the area of each subsystem can be determined. The ILP model is built up from the same parts as the BIP model. The parts are described as following:

- **Decision variables** - For the ILP model the decision variables are the x and y coordinates of each subsystem center. The coordinates can be in the range described in Equations 2.7 and

2.8, in which i indicates the subsystem and l_i and w_i are that subsystems length and width respectively:

$$x_i \in \left(\frac{1}{2}l_i, l_{area} - \frac{1}{2}l_i\right) \tag{2.7}$$

$$y_i \in \left(\frac{1}{2}w_i, w_{area} - \frac{1}{2}w_i\right) \tag{2.8}$$

- **Objective functions -** The goal of the ILP model is to minimize the distance between two sequential subsystems. To do this, an adjacency factor a_{ij} is introduced. The higher factor, the more important the adjacency relation is. The objective function is given in Equation 2.9

$$min \sum_{1 \leq i < j \leq N} a_{ij}(|x_i - x_j| + |y_i - y_j|) \tag{2.9}$$

- Only one constraint is introduced which is the constraint that the subsystems cannot overlap with each other. The constraint consist of two parts of which only one has to be true. The constraint is given as following:

$$|x_i - x_j| \geq \frac{1}{2}(l_i + l_j) \tag{2.10}$$

or

$$|y_i - y_j| \geq \frac{1}{2}(w_i + w_j) \tag{2.11}$$

This model will provide the coordinates for each subsystem.

The last step of the model is to visualize the data with a 3D model. This is done by using the width, length, and center points per subsystem retrieved from the BIP and ILP model. Although both optimization problems are done in 2D, assuming a height value gives a 3D model. Each system has a different color so they are distinct from each other. The designer is able to drag the blocks to another place. Also, a trade-off curve is given in which the effect of different α values is shown.

2.1.2 Other design models

Nazzal and Bodner (2003) developed an automated design model for the generation of material handling systems for wafer fabrications facilities. Their model includes an import factor into the system: the level of automation (LoA). The level of automation looks at how much human involvement is present with a certain type of equipment. They highlight the importance of increased automation in the future. The higher the LoA of the system, the higher the investment costs. It is therefore of importance to keep the interest of the clients in mind when it comes to the LoA.

The model consists of seven stages. The first stage is to define the processing characteristics desired by the fabricator. This is done by simulating the wafer fabrications process and generate a report on the process. Stage two is to retrieve all the important data from this simulation which will give the requirements for the material handling system. In stage three, the system requirements are used to make the first architectural design. This design is primarily focused on the physical part of the system and not on the behavioural side of the design. This can be seen as the ground equipment in the layout, so the equipment which is always in the same position. Next, stage four aims at optimizing the physical components. This is for example the amount of vehicles needed together with their transport speed. Stage five is mainly focused on the behavioural side of the design. Here, all the rules and policies of the model are defined. In the sixth stage the system is developed. This gives multiple design alternatives. For each alternative a simulation model is developed to be able to show the difference of each alternative. In the seventh and final stage, the simulation models of stage six are connected to the simulation model of stage 1. The end results still need fine tuning when finished. In the field of automated material handling systems, more literature can be found with similar models (Montoya-Torres, 2006; Cardarelli & Pelaggage, 1995). However, similar to the model described here, they mainly focus on the simulation side of the systems, not the layout.

Duchateau (2016) describes a generic interactive concept exploration approach for preliminary ship design. Although ship design is different to material handling system design, the concept exploration approach can be useful to develop a design framework. This approach consists of six steps. The first step is to gather all required input. The next step is to define the problem goal using a set of initial preferences. This can be done by answering the question: "What are we looking for?". Next, a search algorithm is used to provide a set of solution fitting the initial preferences. The fourth step is to analyze and explore the different solutions. In the fifth step, based on the different solutions the initial preferences can be changed. If these are changed, the approach goes back to the third step. If the preferences remain unchanged the final step can be performed which is choosing a solution.

In a similar research, Rose (2017) developed an algorithm for the automatic production planning for the construction of ships. After collecting all the input data, a three step algorithm is followed. The algorithm starts with the erection planning method. This is a plan which defines the erection time of each ship section. Thereafter, in the second step, a section building plan is developed. This plan tells the builders how long each section will take to assembly and what sections should be outsourced. In the last step of the algorithm the outfitting plan is developed. This will tell the builders how much time it takes to finish each section.

2.1.3 Design framework

Based on the models described in the previous sections, a generalized design framework for material handling system can be developed. The framework developed consists of four stages and can be seen in Figure 2.1. The first stage is to define the system capacity needed. To do this, usually the supply data of the system is needed together with the systems requirements. The latter is usually defined by the way the system will be operated. The supply data consist of information for both the inbound and outbound flows of the system. This data is then used to define the system requirements needed for the design.

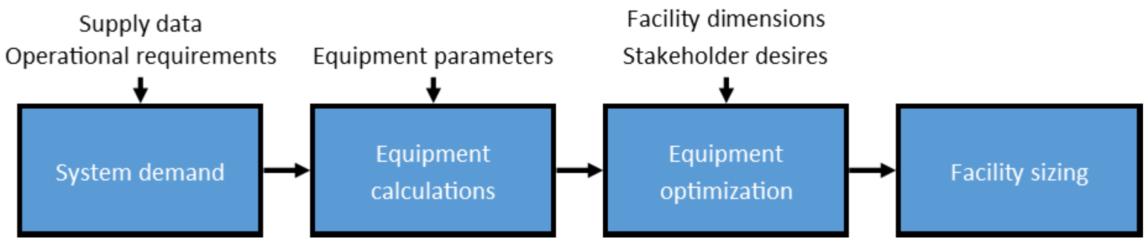


Figure 2.1: The general design process for material handling systems with the required input on top

The second stage of the model is to define the equipment data. This data is the amount of equipment needed for each possible equipment type that can be used for the system. For this, the equipment parameters are needed. This is a list of all the possible equipment that can be used for each of the subsystems. For the BHS, this would be a list of all equipment parameters from the suppliers.

In the third stage the equipment is chosen and a first indication can be given on the size and design of the system. The equipment choice is based on the desires of the stakeholders, the system requirements and the facility layout. These data sets are used to define the systems boundaries. The facility layout defines the available area and height. The system requirements are used to rule out certain equipment types. If for example a process unit cannot spend more than a certain time in the system, some transport equipment is not suitable. At last, the desires of the stakeholders are used to develop a definition for the optimal solution.

With the equipment chosen, the facility sizing can be done. In this stage all the equipment chosen in the previous stage is placed inside the facility. The model defines the location of each equipment unit and makes sure that it is placed inside of the facilities border. For facility sizing, the capacity of each connection is the driving force of the placement. This will mean that the larger the capacity is of a line, the shorter the connection should be.

2.1.4 Improvement of the model

The model by Van Noort will be used as a basis of the model developed in this research. This model, however, needs further developments. First of all, not all trade-offs can be found in the model. As stated previously in the research by Nazzal and Bodner (2003), the LoA is important to the stakeholders. The basis model only uses the CAPEX and system area as trade-offs. To improve the model, a research will be done in Chapter 3 to find the important trade-offs. Here, it is also researched how the data can be visualized by the model. Also, to further imporve the outcome of the model, a new research is performed to find the input parameters needed to develop a BHS concept design. This research will be done in Chapter 4.

At last, it is recommended by Van Noort to further research the block layout design aspect of routing. In the model, blocks are placed according to adjacency rules. Converting this to the placement based on reducing the routing between subsystems will provide a more detailed concept design. This will reduce the need to relocate a subsystem after the model is done. One type of algorithm which take into account routing are very large scale integration (VLSI) algorithms. In the next paragraph, VLSI algorithms will be discussed. Thereafter, a self-designed placement model named the droplet search will be discussed.

2.2 VLSI

A similar process to the subsystem placement in BHS is the component placement on circuit boards. These circuits consist of multiple components which have to be placed on a board in an efficient manner. In the early 1970, circuit board only consisted of a few components. Over time, the amount of components grew to billions. As distributing billions of components by hand would take a lot of time, the distribution became automated (Das, 2015). The models designed for this process are known as VLSI models.

Lim (2008) provides an overview of different VLSI problem types. The placement problem relates to the distribution of BHS subsystems. The placement algorithms aim at distributing different components while reducing the wire length needed between them. Placement is usually performed in two steps. First, global placement is performed. This process gives the global locations of the blocks. The blocks are distributed as points, so the optimal routing between the points is determined during global placement. This can result in the overlapping of the blocks. The next step removes the overlapping were needed which is known as the detailed placement.

Markov, Hu, and Kim (2015) provide a clear overview of the development of VLSI placement and state the important placement algorithms. The modern algorithms like MAPLE (M.-C. Kim, Viswanathan, Alpert, Markov, & Ramji, 2012) and Kraftwerk (Spindler, Schlichtmann, & Johannes, 2008) aim at processing billions of components in a short amount of time. However, the BHS only consists of a few systems. The early generation algorithms will therefore be sufficient. Lim (2008) provides a description of three placement algorithms which will be discussed separately.

2.2.1 Mincut placement

This algorithm developed by Breuer (1977) and later improved by Dunlop and Kernighan (1985), performs the global placement of blocks. Stated by Markov et al. (2015) as one of the first developed placement algorithms, the intial algorithm by Breuer worked by dissecting the area. First, the relationship between each block is used to develop a graph model in which each block relationship is expressed in connection lines. The lines are not allowed to cross each other. Then, bipartioning is used to divide the area in two. The blocks are distributed over these areas. The bipartioning of areas and distribution of the blocks is repeated until each block has their own area. Then, the minimum wire length can be determined. The conversion from graph model to a fully divided area is visible in Figure 2.2

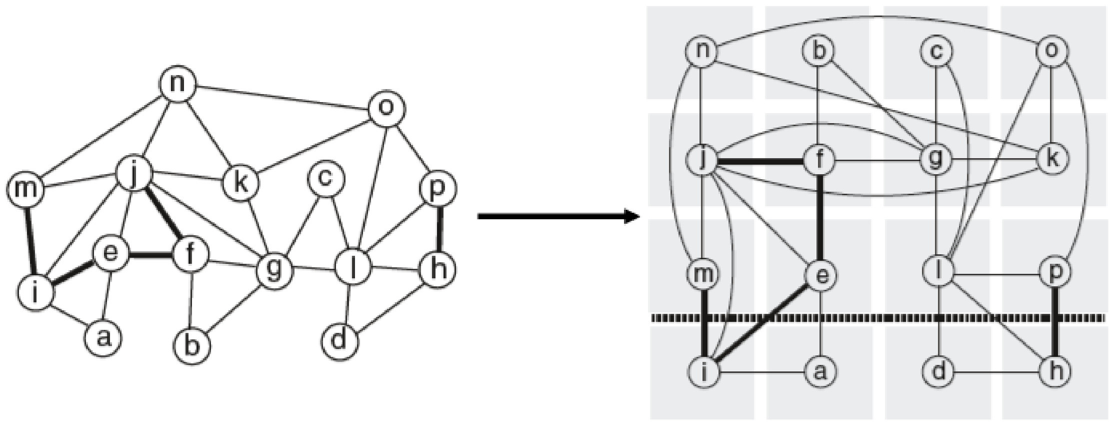


Figure 2.2: The conversion from graph model to completely divided area (Lim, 2008)

Dunlop and Kernighan (1985) improved this algorithm by adding terminal propagation. This method checks at every bipartioning if the blocks which need to be distributed are also related to blocks in areas which are not dissected at that step. If that is the case, these blocks are then distributed in the area as close as possible to their other connections. This reduces the minimal wire length in the end. Figure 2.3 shows the result of the mincut placement of Figure 2.2 when terminal propagation is used.

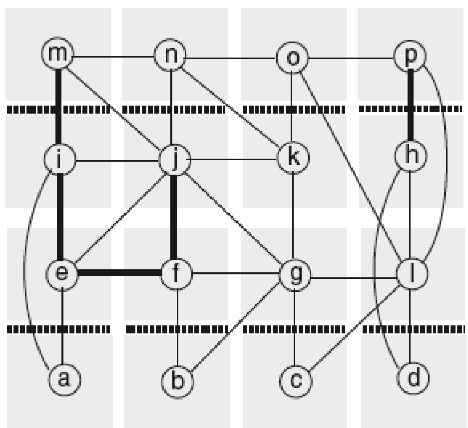


Figure 2.3: The same divided area as in Figure 2.2 but with terminal propagation introduced (Lim, 2008)

When the bipartioning is finished, each block is assigned to an area and is is assumed that each block is centered in that area. If the dimensions of the block exceeds the size of the area, overlapping can occur. The mincut placement therefore only provides a global placement and needs further processing to get a detailed placement.

2.2.2 Gordian placement

The Gordian placement, developed by Kleinhans, Sigl, Johannes, and Antreich (1991), adopts quadratic programming for the placement problem. Quadratic programming (QP) is used in several modern placement models (Markov et al., 2015) and was one of the first methods using QP. The method starts by constructing a clique-based undirected graph model. Cliques, first described by Luce and Perry (1949), are a set of nodes which are all connected to each other. Each edge in the graph gets a weight of $2/k$, were k is the amount of nodes in a clique. Custom weights can be applied to an edge. To prevent the model to place all nodes in the center, some nodes have to be fixed along the border. The fixed nodes will be referred to as pins. The graph is then converted into a matrix C and two vectors d_x and d_y. The matrix C is called the Laplacian matrix and shows the connectivity between nodes. d_x and d_y represent the connectivity between the pins and nodes.

C can be determined by first computing the adjacency matrix. In this square matrix the rows and columns represent the nodes. It depicts the weight between each node if they are connected. Next, the pin connection matrix p is made. In this matrix the rows represent the nodes and the columns the pins. The weight between the connections determines the value in the matrix. Thereafter, the degree matrix is build. This diagonal matrix is the summation of the rows of both the adjacency and pin connection matrices. At last, C is determined by the degree matrix minus the adjacency matrix.

The d_x and d_y vectors are determined based on the pin connection matrix and the location of the pins. Each row in d_x is computed by taking the summation of each corresponding column in the pin connection multiplied by the x-coordinate of that pin. Equation 2.12 shows the mathematical representation to determine d_x. For d_y the same equation is used only $x(p_j)$ is replaced by $y(p_j)$.

$$d_x = -\sum_i \sum_j p_{ij} * x(p_j) \tag{2.12}$$

With the important values defined, an iterative process starts defined by the optimization level l. At level $l = 0$, the QP is solved for both the x and y-coordinates using the objective function defined in Equation 2.13. The QP can also be solved by two QPs, one for the x-coordinates and one for the y- coordinates.

$$min\left(\frac{1}{2}x^T Cx + d_x^T x + \frac{1}{2}y^T Cy + d_y^T y\right) \tag{2.13}$$

After the coordinates are computed the next level, $l = 1$, is solved. This level starts by dissecting the area using a horizontal or vertical line into two parts. Where the line is placed depends on the amount of nodes per area. If the nodes cannot be split equally, the area will not have a similar size. For both partitions, the center points are stored as an u_x and u_y value. The nodes are distributed over the partitions and a matrix A is introduced. This matrix shows which node each partition has and the ratio of the node area to the partition area. At last, a linear constrained QP is solved using the same objective function as in Equation 2.13 but subject to the constraints shown in Equation 2.14.

$$Ax = u_x \quad \text{and} \quad Ay = u_y \tag{2.14}$$

The dissecting and resolving of the linear constrained QP is repeated until the size of the partitions are small enough. The end result provides a distribution of points for the area, as is visible in Figure 2.4. These points are optimal for routing though, so when converting the points into blocks overlapping might occur. The Gordian placement therefore only applies for global placement.

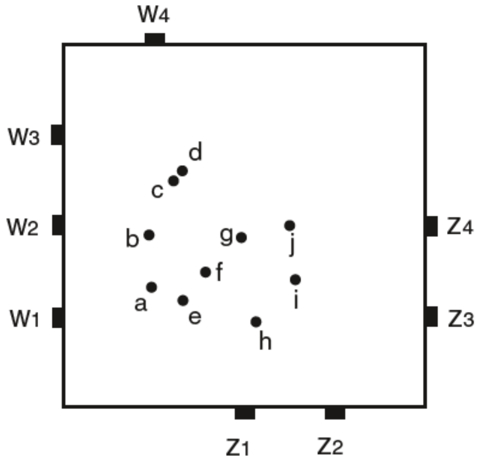


Figure 2.4: An example of Gordian placement after level $l = 0$ (Lim, 2008)

2.2.3 TimberWolf placement

The TimberWolf algorithm was first develop by Sechen and Sangiovanni-Vincentelli (1985). It bases placement on simulated annealing and is able to perform both global and detailed placement. The version described in this section is that of Sun and Sechen (1995). With simulated annealing, the solution space is explored randomly. It starts the algorithm with a high temperature and calculates the energy state for a certain configuration. Next, a new configuration is randomly chosen in what is called a move. The energy states of the configurations are then compared and if the second state is "better" the move is good and the second configuration is chosen as the new standard state. If the second state is "worse", the move is ranked bad. After a move is ranked bad, based on a probability, the move might be accepted as a good move. At high temperatures, the probability that a bad move is accepted is high. This process is repeated in an iterative way and with every move, the temperature is lowered. This lowers the chance that a bad move gets accepted. By accepting bad moves in the beginning, the solution space is explored and local maximums will be mapped. As the temperature of the model goes down, it will slowly converge to the global maximum, or in this case the optimal solution.

The TimberWolf algorithm starts with two data sets, a gate-level netlist, which describes all the routing lines, and a standard cell placement where the cells are already to dimension. It is important that cells are orientated in rows. The wirelength is computed and is set as the standard value C. Next, two cells are assigned for swapping. Because the cells will have different lengths and widths, the can overlap other cells after swapping. The row which will get the cell with the largest dimension, will be shifted. The gap which appears in the row with the smaller cell will not be adjusted. This is because it is likely to be removed during a next cell swapping. The change in C is determined using Equation 2.15. Here ΔW is the change in wirelength due to swapping and ΔW_S the change in wirelength due to the shifting. This process will be repeated and is the iterative process of the simulated annealing method.

$$\Delta C = \Delta W + \Delta W_S \tag{2.15}$$

Where ΔW is determined accurately, ΔW_S is estimated. This is because the time it takes to determine ΔW_S can be significant when a lot of cells are shifted. One way to estimate ΔW_S is to first define the gradient of a shifted cell z using Equation 2.16. Here, N_z are the nets the cell is involved in and $D_i(0)$ the rate of wirelength change of net i measured at origin. If the cell is at the left boundary of the bounding box of the net, $D_i(0) = -1$. If it is at the right boundary, $D_i(0) = 1$.

Otherwise $D_i(0) = 0$

$$gradient(z) = \sum_{i \in N_z} D_i(0) \tag{2.16}$$

With the gradient defined, ΔW_S can be determined using Equation 2.17

$$\Delta W_s = \sum_{j \in shifted_{cell}} gradient(j) * shift_{amount}(j) \tag{2.17}$$

2.2.4 Model choice

One of the VLSI placement methods will be chosen to adjust to BHS. To make a decision on this, the advantages and disadvantages when applying each method will be discussed from which one method will be chosen.

The main advantage of the mincut placement is the simplicity and reliability of the model. The partitioning of the area and the distribution of the nodes is a simple and quick process. As stated by Markov et al. (2015), before 2005 most placement methods did not outperform mincut placement. Also, for all possible equipment configurations, the point distribution remains the same. This means that the placement can be performed once and is then applicable to all possible trade-off configurations. However, a downside of this method is that no weights can be applied to connections and nodes cannot be fixed to a certain space. As some BHS systems like the check-in, have a fixed place, the mincut placement will be hard to adjust to this. Since mincut placement performs global placement, a secondary detailed placement model is required. This secondary placement does need to be run separately for every trade-off configuration.

Gordian placement is able to handle the fixed positions of some nodes and weights can be assigned to the connections. This does come with more complexity and longer computational time. Due to the small amount of nodes in a BHS, the complexity is limited. Like mincut placement, Gordian placement only has to be performed once and needs a secondary detailed placement model.

The TimberWolf algorithm has been used in the industry for design flow (Markov et al., 2015). The main advantage of TimberWolf is that no secondary placement model is required. Also, the model explores the solution space so a the global maximum is likely to be found. However, BHS system are not placed in rows but scattered over the area. Another disadvantage is that the model has to be run for every possible trade-off configuration.

It is chosen to use the Gordian placement method due to the ability to fix certain nodes. Also, because it only has to be run once it becomes more attractive. However, a secondary detailed placement model should be introduced. How the Gordian placement model is adjusted to handle BHS and the definition of the detailed placement model will be described in Chapter 5.

A downside to VLSI models is that they mainly focus on system placement not facility sizing. VLSI system placement aims at reducing routing distances between connected subsystems based on the amount of connections. However, in facility sizing, the capacity of a connection is more important then the amount of connections of each system. Also, for material handling systems the placement order is of importance which is not included in VLSI placement. It is therefore thought that VLSI placement models might not be sufficient for material handling systems. This is why a second placement model will be introduced in the next chapter. This model is based on VLSI placement, but adjusted to facility sizing.

2.3 Droplet search

The droplet search method is a self-made model for the facility sizing of material handling systems. This model is based on keeping the different subsystems as close to each other as possible and therefore keep the transport distance as low as possible. This is done by defining were the desired location of each subsystem is. This desired location can be a single point like the check-in hall, or the center between multiple points like between the HBS and make-up. Next, using a droplet based search method, the closest possible location for the equipment is defined. Here the equipment is placed and this sequence is repeated until all equipment of the subsystem is placed.

The first step is to define the starting point. This location is the desired location of the system to be placed. The location can either be the midpoint of a previous subsystem or the midpoint between two subsystems. When the starting point is defined, the equipment of the system can be placed. This placement is inspired by a droplet falling into a liquid surface. This action will cause a wave to travel in all directions at equal speed. The model will work with the same principle. It will start at the starting point and check if there is enough space at that coordinate to plot a piece of equipment. If there is no space, the model will expand the search in all directions until a coordinate is found where there is enough space.

Figure 2.5 shows a schematic example on how the search is performed. Different to a wave created by a droplet, the search method is an expanding square and not a circle. This means that the distance between the points in the square and the starting point is not equal. The model therefore defines the sequence in which it will check the points in the square based on the distance to the starting point. In Figure 2.5, this sequence is indicated for each square. To prevent unnecessary calculations, if more than one equipment unit has to be placed for a subsystem, the model will remember the last square it searched at and continue from there.

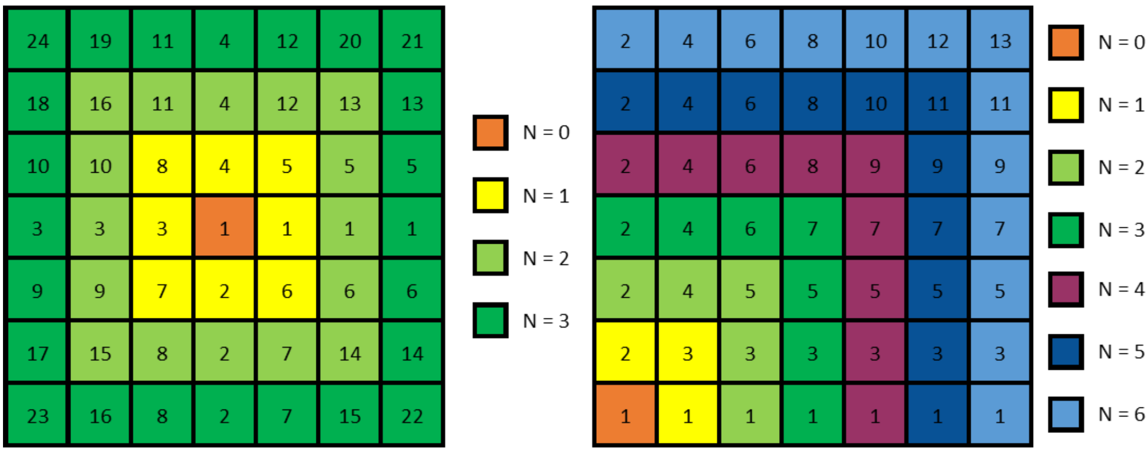


Figure 2.5: Two examples of the droplet search, were the color of the tiles represents the steps N and the search sequence of each ring is indicated in the tile

The process of defining the starting point and place the equipment using the droplet method is repeated for each subsystem until all places are filled. Chapter 5 will discuss how the droplet search will be applied for BHS.

2.4 Summary

This chapter answers the question *"Are there any models in literature for the generation of concept design for material handling systems in general and which can be used for BHS applications?"*.

Multiple models have been found in literature (Van Noort, 2018; Nazzal & Bodner, 2003). Based on these models, a design framework for material handling systems is made. This framework is applicable for material handling systems in general and can be seen in Figure 2.1. It consists of four stages. In the first stage, the systems requirements are determined. This will define the capacity needed for the system. Thereafter, in stage two, for each possible equipment type, the important data is needed. With this data, in stage three an equipment choice is made. This choice depends on multiple factors regarding stakeholders interests, operational requirements and the facility layout. In the last stage, the chosen equipment is placed within the facilities borders during the facility sizing. This will result in a conceptual design.

As the model of Van Noort is already developed for BHS applications, it is used as a basis for the model developed in this research. As the model of Van Noort is a proof of concept, it still needs improvements. These improvements mainly focus on making the model more applicable to the stakeholders desires (Chapter 3) and further defining the desired input parameters (Chapter 4). Also, a new placement model will be developed for the subsystem placement. For this, VLSI placement models are researched. These models aim at placing the subsystems while reducing the distances between connected subsystems. This is done by looking at the amount of connections between subsystems. The Gordian placement model is seen as the most suitable for material handling system applications. For facility sizing, the routing should be capacity driven and not be driven by the amount of connections. The Gordian placement is therefore thought to be insufficient for material handling systems. A self-made placement model is developed which is more suitable for material handling systems. This model, called the droplet search, defines the desired placement point and searches for the closest possible location to this point to place each individual equipment unit.

Chapter 3

Visualization of a concept design

With the basis of the model defined, the desired output can be developed. To determine the output, first the stakeholders should be defined together with their interests. As for each material handling system the stakeholders involved is different, only the stakeholders for BHS are highlighted. The stakeholders will be discussed in Paragraph 3.1. Next, the important BHS aspects for stakeholders should be defined. These trade-offs will be discussed in Paragraph 3.2. As stated in Section 1.5, the output of a concept design consists of a 3D model, the operational capacity, the equipment specification and the CAPEX of the system. How this output can be visualized will be given in Paragraph 3.3. This chapter will answer the research question: *"How can the different possibilities in design be visualized for the stakeholders?"*. In Paragraph 3.4 the chapter is concluded by providing the answer to this question. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

3.1 Stakeholders

To be able to define the stakeholders involved with a BHS, the definition of the term stakeholder must be provided. Freeman (1984) gives the following definition of a stakeholder:

"Any group or individual who can affect or are affected by the achievement of an organization's purpose"

With this definition, the different stakeholders at an airport can be distinguished. Schaar and Sherry (2010) defined all the stakeholders at an airport. They distinguish 15 different stakeholders. Five of these stakeholders are of importance to the BHS which are as following:

- **Airport organizations** - Those responsible for building and operating the airport.
- **Service providers** - Providers of services to the air carriers, in this case the baggage handlers.
- **Air carriers** - All passenger carriers.
- **Federal government and customs** - The operator and legislative entity of the security section of the airport.
- **Passengers** - The O&D and transfer passengers.

One entity can function as multiple stakeholders. At AAS, for example, KLM is both an air carrier and one of the service providers for baggage handling. It is also possible that a government owns part of the airport. Then, the government can become multiple stakeholders.

For all five stakeholders, Schaar and Sherry (2010) provide their important goals for the airport. Adjusted to the BHS, similar goals remain. Passengers want a quick and convenient experience, on-time performance and low fares. Air carriers want on-time performance, low cost of operations, ensure safety of operations and provide access to high yield. The airport organization wants high safety and security, grow revenue and manage cost, drive economic growth and ensure sufficient infrastructure capacity. The service providers want to maximize traffic volumes and minimize fees paid. Finally, the federal government wants to ensure safety, security and efficient operations.

When designing the conceptual BHS, the design request is usually from the airport organization or service provider. They are therefore seen as the main stakeholders in the BHS design process. During this stage, passengers have no role in the decision making. Their goals are therefore seen as secondary goals and are not the main drivers for the design.

3.2 Trade-offs

For each stakeholder and airport, different BHS characteristics are of importance. Therefore, trade-offs have to be made when choosing a BHS concept design. This is an iterative process in which the designers provide a concept design and the stakeholders comment on it. To reduce the number of iterations, visualizing the different trade-off effects beforehand can help the stakeholders. Before visualizing, the different trade-offs have to be defined. This is done by first providing a short literature review which is followed by all the important trade-offs for to the stakeholders. The latter is based on the literature research and the experience of NACO engineers.

3.2.1 Literature on BHS trade-offs

Van Noort (2018) states in one of the criteria for the automation of BHS design that both CAPEX and system area are important trade-offs. An airport wants to minimize both values. However, reducing the CAPEX of the BHS will result in an increase in area. This negative feedback results in a model in which both CAPEX and area get a weighted value. The model then uses these values to determine a concept design.

Abdelghany, Abdelghany, and Narasimhan (2006) provide operational requirements, given in Section 4.5.1, and assigning make-up positions (MUP) to flights as the main trade-offs. Lin, Shih, Huang, and Chiu (2015) use two system performances as trade-offs. They simulate a BHS which has a buffer system within the sorting loop. If the buffer is full, bags are manually sorted. They use the amount of manually sorted bags and the average number of bags which loop around as trade-off values. However, these models are aimed at the simulation part of the BHS, not the conceptual design. As simulation is done after the detailed design is developed, these trade-offs are already too detailed for the conceptual design phase.

Rezaei, Kothadiya, Tavasszy, and Kroesen (2018) provide five service quality dimensions as criteria for BHS assessment. These five criteria are: tangibles, reliability, responsiveness, assurance and empathy. From their research it is concluded that reliability is the most important criteria for BHS. In a similar research by Chou, Liu, Huang, Yih, and Han (2011) regarding airline services, reliability is also seen as the most important criteria. However, using a different research method, (Tsaur, Chang, & Yen, 2002) find tangibles as the most important criteria.

Le, Creighton, and Nahavandi (2007) state that a BHS is a fragile system. Any equipment failure can have large impact on the system performance of either the subsystem or the entire system. Maintainability and availability of equipment are therefore important trade-offs. By having equipment for which maintenance requirements are low and the availability is high, the chance of a breakdown decreases. Maintainability and availability relate to the earlier mentioned reliability.

Research done by Van Enter (2018) shows the importance of operational expenditure (OPEX) on the conceptual design. The research provides a simulation model which can define the energy consumption of different conveyor types for BHS. He concludes that with increasing bag demand, the energy consumption between conveyor belt and DCV-systems become almost equal. Also, the effect of different aircraft and passenger arrival distributions and different conveyor speeds are shown in this research.

3.2.2 BHS trade-offs

Combining the literature and experience of NACO, seven trade-offs can be distinguished. The values of these trade-offs will be part of the output parameters of the concept design. Each trade-off will be discussed separately.

Capital expenditure
The CAPEX is stated as the most important trade-off for stakeholders. The value indicates the investment costs for the BHS. Based on the CAPEX of different BHS configurations, the stakeholders can get a clear image of what they get in return for their investment. The CAPEX is also understandable to both engineers and non-engineers. The value is given in the local currency.

The system area can be included into the CAPEX. As the floor space of a building has a monetary value, the system area can be implemented into the CAPEX calculations. Instead of system area, a more complete value would be to use the system volume. This value can be provided by the terminal designers as they can get a rough estimate of the building costs.

Operational expenditure
Already stated in literature, the OPEX is an important trade-off which is usually not included. This is due to the fact that it can be hard to give a definitive value on the power consumption. However, doing simplified calculations can provide some estimates on the OPEX. The OPEX can be expressed in two forms: in the energy consumption (kW h) or in costs per hour (€ /h). An advantage of the latter representation is that the costs of the human operators can be included. However, as electricity prices and energy consumption fluctuate during the day, providing a monetary value for this can be complicated. It is therefore chosen to use two output values for this trade-off: the energy consumption if all equipment runs on full power in kW h and the number of human operators needed. If the average income of an operator is known, the latter can also be expressed in (€ /year). These OPEX values can then be used by the stakeholders to get an insight into the OPEX.

In-system-time
The in-system-time (IST) refers to the time a bag spends in the BHS. Related to the IST is the minimum connection time (MCT) which is in a BHS perspective: the minimum time it takes for a transfer bag to move between two aircraft. This value is important to hub airports which want to provide short transfer times. As this research does not include the transport from and to the aircraft, the IST is used and not the MCT. As the IST differs per bag, determining a value for this can be difficult. It is therefore chosen to look at the minimum IST possible for transfer bags. The minimum IST will be referred to as just the IST from this point on.

Flexibility
Flexibility is the opportunity for the BHS to accommodate future growth. This implies that within the BHS, room is reserved for possible extensions and is partially empty. As part of master planning, usually multiple scenarios are developed for the airport. This includes a future perspective of the airport requirements. The flexibility can therefore be included by simply using this data. This means that the flexibility is given as an input parameters and can show the effect of growth on the BHS to the stakeholders.

Redundancy
Redundancy refers to the ability of the system to handle equipment malfunctions. The value is given as a percentage and represents the amount of bags the system has to be able to process even if one piece of equipment breaks down. Usually the design is made keeping a fixed redundancy in mind. Therefore, showing the effects of certain redundancy percentages on the system helps the

stakeholders. The concept of redundancy will be looked at in more detail in Chapter 4.

Level of automation
The LoA of the system refers to amount of automation which is applied to the BHS. The higher the level, the lower the human intervention will be in the process. For the LoA, seven levels are distinguished. Chapter 4 will give a more in dept descriptions of these levels, however, insight into the effects of automation should be shown to the stakeholders.

3.3 Visualization

Now that the trade-offs are defined, they need to be visualized for the stakeholders. The process of data visualization is described by Ware (2013) with four stages. The first stage is the collection and storage of data. The second stage is the data transformation. In this stage, the data is transformed to something that is easier to manipulate. The third stage is the mapping of the data into a visual representation. The fourth and last stage is the human perceptual and cognitive system. From the fourth stage, a human can provide feedback to one of the other three stages. The process is made visible in Figure 3.1.

The four stages relate to the conceptual design process of a BHS. First, the input parameters are gathered which equals the first stage. This data is then used to determine the required equipment type and amount needed. This can be seen as the data transformation stage. At last, the equipment data is translated in a 3D model and additional data described in Section 1.5. This maps the data into a visual representation. The engineers and stakeholders provide the human perception. The feedback they give can then alter one of the other three stages.

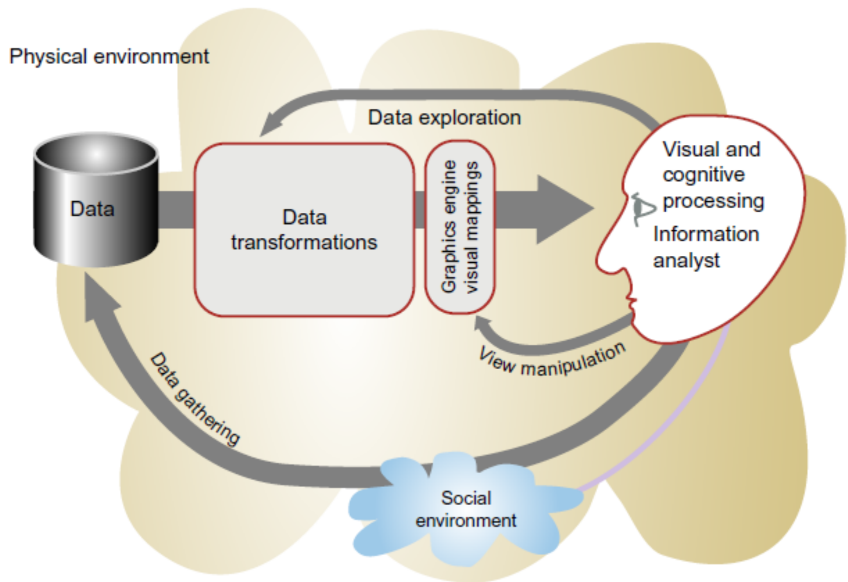


Figure 3.1: The visualization process (Ware, 2013)

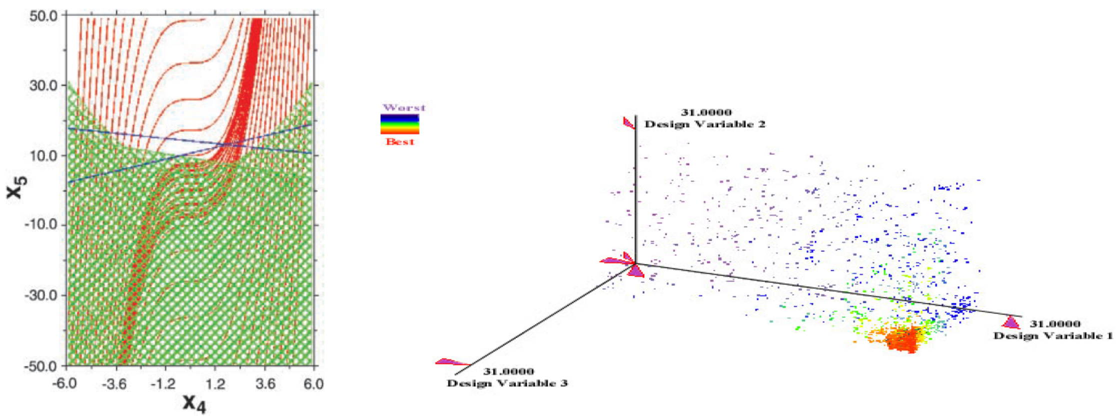
The main focus of this paragraph is on the mapping the data into a visual representation to present to the clients. With this representation, the designers and stakeholders can then explore the solution space together and make design choices for the eventual BHS. One of the criteria by Van Noort (2018) states that the identified solution should be visualized by means of a graph or 3D drawing. Messac and Chen (2000) states a third way of data visualization, namely tables. All visualizations will be discussed separately.

3.3.1 Graph representation

Van Noort (2018) proposes a 2D graph for the graphical representation of BHS trade-offs. As the model only has two trade-offs, this representation type is sufficient. When more then two trade-offs are used, a 2D graph cannot show all data. The 2D representation can be used to show the relationship between two trade-offs. Doing this for all trade-off relations will take a lot of time as every relationship has to be calculated separately.

Kanukolanu, Lewis, and Winer (2006) describe four visualizations methods for optimization problems with more then two trade-offs. The first method by Winer and Bloebaum (2002b) is called graph morphing. With graph morphing the designer is able to show a n-dimensional optimization problem in a two or three dimensional graph. The axis of the graph represent variables and the remaining variables can be adjusted. Adjusting the variables will result in the "morphing" of the graph, hence the name. The designer is then able to view the effects of each variable and find the optimal solution. An example of graph morphing for a 6-dimensional optimization problem is visible in Figure 3.2a.

The second method described is cloud visualization, which can be used for both single and multidimensional optimization problems. This method is described by Eddy and Lewis (2002) as a means by which a designer can view all previously generated design information in both the design and performance space simultaneously. The design space correlates to the design variables and the performance space to the performance objectives. The information is displayed as points in a two or three dimensional graph. Figure 3.2b shows an example of a three dimensional cloud visualization.

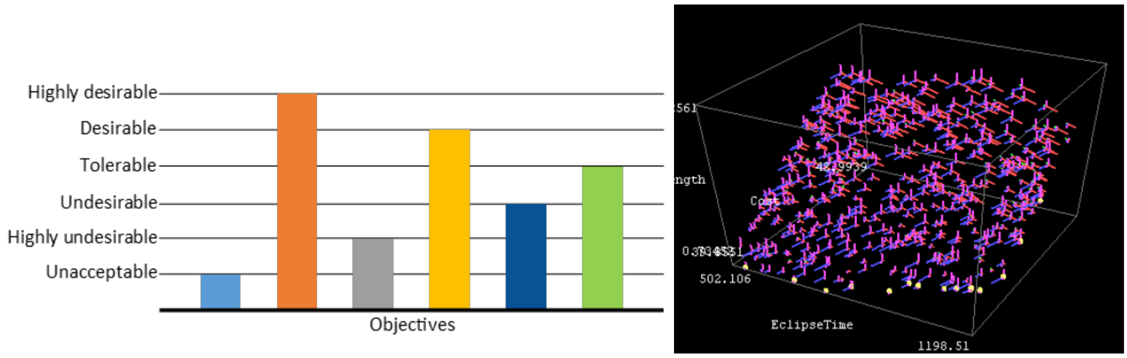


(a) (b)

Figure 3.2: Examples of graphs developed using graph morphing (a) and cloud visualization (b) (Winer & Bloebaum, 2002a; Eddy & Lewis, 2002)

The third method described is physical programming visualization (PPV). Messac and Chen (2000) provide a description for this method. The first goal in PPV is to define 6 degrees of preferences, form high desirable to unacceptable. When a solution is defined, for each trade-off it is defined in which range this lies. This is then presented in the form of a graph to the designer. In one instance, the designer can see how the solution ranks without retrieving data. An example of how the graph can be presented is visible in Figure 3.3a.

The last method described is the multidimensional visualization interface. This interface developed by Stump et al. (2002) combines glyph plots, brushing and scatter matrices as an interface. A glyph plot is a graph in which each possible solution is described as a shape. With brushing, boundaries can be applied to the graph. The scatter matrix plots each performance variables against each other in a grid pattern. An example of a multidimensional visualization is visible in Figure 3.3b.



(a) (b)

Figure 3.3: Examples of graphs developed by physical programming visualization (a) and multidimensional visualization (b) (Stump et al., 2002)

For the exploration of the solution space, both designers and stakeholders should be able to understand the graph. Although the graph morphing, cloud visualization and multidimensional visualization might be understandable to the designer, for the stakeholder the graph will look very complicated and can be hard to understand. Therefore, these three visualizations methods are excluded. This leaves the 2D graphs and PPV as possible options. Each trade-off will have a different weight per stakeholder. A downside of the PPV method is that no weight can be applied to the different trade-offs, since the eventual representation is similar to the weight scale. It is therefore chosen to use the 2D representation.

Already stated as a downside of the 2D graphs is that for every possible solution the model has to be run. To reduce the amount runs, the graphs will only show the effect of the trade-offs on the CAPEX, as this is the most important trade-off to the stakeholders. The designer can then show the graphs to the stakeholders which will visualize the relations between the CAPEX and the other trade-offs. The stakeholder can use these graphs to define the weight they want to apply to each of the trade-offs.

3.3.2 3D drawing

In the conceptual design phase, a 3D model is developed. Visualization of this model can happen in different ways. Virtual reality, for example, can be used to help with design review (Wolfartsberger, Zenisek, & Sievi, 2018). However since the model developed for the concept design consist of square blocks. Implications like virtual reality are to detailed for these purposes so a 3D drawing or a top view of each terminal floor is sufficient.

It is important to define which data is shown with the 3D model. Like the graphs, individually providing the model for each possible solution would cost a lot of time and work. Therefore it is chosen to provide only the 3D models of the extremes of the trade-offs. For the LoA, this will for example result in two 3D models. One for the minimum possible LoA and one for the maximum possible LoA. For the CAPEX only the minimum possible value is of interest.

3.3.3 Table representation

At last, a table representation of the data can also be useful to the stakeholders. The table can be showed together with the 3D models and show the numeric values of each trade-off and some additional data per subsystem. An example table is presented in Table 3.1. A table can be made for each scenario and can be shown to the stakeholders.

Table 3.1: An example for the table representation for BHS, the figures in this table are fictional

	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 [€]	150,000	600,000	22,000	772,000
Energy consumption [kW h]	45	40	44	129
Operators	10	0	0	10
LoA	3	7	6	5.33
IST [min]	2	0.85	0.02	2.87

3.4 Summary

This chapter answered the question *"How can the different possibilities in design be visualized for the stakeholders?"*. This is done by first defining the stakeholders regarding BHS which are the airport organizations, service providers, air carriers, federal government and customs and the passengers. Next, the design aspects of BHS which are important to the stakeholders are defined. These are the CAPEX, OPEX, IST, flexibility, redundancy and LoA. At last, it is researched how the output can be visualized for the stakeholders.

Three different visualizations methods are developed. First, a 2D graph showing the influence between two trade-offs can be made to highlight the effect of them. Next, a 3D model can be made to show the space reservation needed and will give an insight on the appearance of the final design. At last, a table can be made which shows for each sub systems individually the values of each trade-off.

Although this chapter is focused on BHS design, the same trade-offs can be found for other material handling systems. In a container terminal for example, similar types of stakeholders can be found. The operator of the material handling is always the service provider for example. The same trade-offs can be applied but the importance of each of them can be different. In airports IST are more important then in container terminals for example. The data visualization also applies to other material handling systems.

Chapter 4

Parameters for BHS design

With the framework and output of the model developed, the input of the model can be defined. In this chapter the focus is completely on BHS design since a BHS will need a different set of input parameters as other material handling systems. The research starts by breaking down each subsystem of the BHS first in Paragraph 4.1 till 4.8. Each paragraph starts with defining the equipment types for each system and then provide the input parameters needed. All these paragraphs end with a table that contains all input parameters discussed in that paragraph. Next, Paragraph 4.9 will provide general input data which influences all systems and not one in particular. It is important to state that the focus of the research is on conceptual design. This means that not all input parameters for a detailed BHS design are given in this chapter, only for a conceptual design. This chapter will answer the question: *"Which input parameters are needed to develop a BHS concept design?"*. Paragraph 4.10 will provide a summary in which the question will be answered. This paragraph also contains input parameters found in literature which will not be used in the model. That is why a table is added in Paragraph 4.10 which contains all input parameters used for the model. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

4.1 Check-in

The Check-in system is where the bags of arriving passengers are loaded into the BHS. Four types of equipment can be chosen (Van Noort, 2018):

- **Staffed counter** - This is the conventional way of check-in. Passenger check their bags in at a counter which is manned by one operator.
- **One-step-drop-off** - This is a self service check-in machine. The passenger checks-in, tag and drops off their bags them self. Per 6 machines, one operator has to be available.
- **Two-step-drop-off** - Same principle as the one-stop-drop-off. However, check-in is done on a separate machine. With the growth of online check-in (Sabatová, Galanda, Adamĉík, & Šulej, 2016), this option can be interesting for airlines which offer online check-in.
- **Curbside** - Curbside check-in is not located in the main check-in hall. The equipment is, usually, located close to land side entrance point, like car parks and train stations, and operates similar to the staffed counter.

In the US, curbside check-in can be found in a few airports. However, outside of the US it is rarely used. That is why for the designed tool, curbside check-in is not included. However, if a curbside system is available, the ratio between passengers using the curbside and terminal facilities needs to be taken into account when designing the check-in system (Appelt, Batta, Lin, & Drury, 2007).

The International Air Transport Association (IATA) distinguished two types of desk configurations (IATA, 2004): the island and linear configuration. Behind the check-in equipment, a collector belt is present. This belt brings the bags to the next system. The difference in layout is determined on which sides of the conveyor belt desks are present. If only one side of the conveyor is utilized it is a linear layout. If both sides are utilized it is an island configuration. Also, were island configurations are scattered over the arrival hall, linear configurations are usually placed close to or against the wall. Figure 4.1 shows an example of an island layout. For some airports, the collector belt is replaced by human operators. This means that after bags are checked in, an operator takes the bag and moves it to the BHS. The amount of desks per island side is recommended by IATA to be between 10 and 20 desks. Also, they recommend to use between 24 and 26 meters between islands.

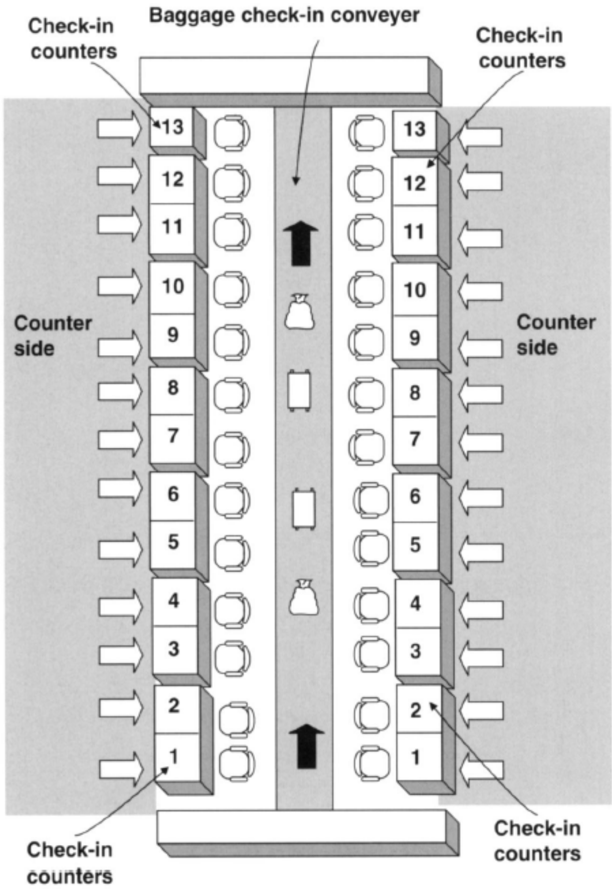


Figure 4.1: An island configuration for the check-in desks (Tang, 2010).

According to Jenks et al. (2010), the requirements for the check-in system can be determined with the following information:

- Number of peak hour enplaning origin and destination (O&D) passengers
- Number of airlines
- Time distribution of passengers arriving at the terminal
- Average service times and maximum waiting time targets
- Percentage of passengers using each type of facility in the ticket lobby vs. other locations or going directly to the gate
- Use of curbside bag check-in or fully remote bag check-in

- Level of service (LoS) of the airport

Appelt et al. (2007) states that the arrival pattern for curbside check-in differs to that of the arrival distribution in the check-in area. So this should be taken into account. In a study on the effect of multiple airlines sharing a check-in area (G. Kim, Kim, & Chae, 2017), it is stated that due to queue imbalances, the sharing of check-in area creates lower service levels.

The percentage of passengers which use the check-in facilities can be defined in two ways. The first representation is the one given by Jenks et al. (2010), which takes the percentage of people which use the check-in machines. At NACO this value is further defined as the percentage of: passengers bypassing check-in, passengers collecting boarding pass but have no checked baggage, passengers undertaking check-in and dropping checked baggage and passengers already checked in but have to drop their checked bag. Another way to define this value is to use the amount of bags per passenger per airline. This is a more general parameter which takes into account passengers bypassing check-in and the airlines regulation towards the allowed number of checked baggage. In the US for example the average value is 0.67 (Schaal, 2014), while for Qatar airways this value can be 1.3 (Van Noort, 2018). However, it does not specify which services passengers need.

LoS refers to the quality of which the services take place at an airport (de Neufville & Odoni, 2013). Traditionally, six LoS are defined, from A (best) to F (worst). For passenger buildings, the LoS is defined by the amount of space available per passenger in a peak hour. Since passengers are present in the check-in area, the LoS influences the size of the area. However, for check-in the only LoS specification is for the queuing area. As stated in the scope of this research, this is not of importance for the BHS design. So for the check-in systems, the LoS is not included. The same accounts for the maximum waiting time targets.

In a research by Barret (2004) which compares low-cost carriers to full-service carriers, it becomes clear that the type of airlines at an airport also influences the check-in system. Low-cost carriers tend to use less check-in desks. This is due to the fact that hold baggage usually requires an extra fee for low-cost carriers. Due to that, most passengers only carry cabin baggage. Also, the check-in procedure of full-service carriers tends to take longer because of the extra services provided. For example, Ryanair, a low-cost carrier, is able to handle 110,000 passengers per desk at Dublin airport in a year, while other airlines only reach 48,000 passengers per desk.

Koshravi, Nahavandi, and Creighton (2009) developed a simulation model for an entire BHS. For the check-in systems, or BHS in general, the flight type is also of importance. The flight type is related to the tickets sold for a flight, economy and business class tickets. It is highlighted that the arrival distribution of economy and business travellers is different. Airlines also tend to have check-in desks dedicated towards business travellers.

In literature, other simulation models can be found for check-in systems. Joustra and van Dijk (2001) propose a model in which they determine the average queuing time based on a set of input parameters. They conclude that peaks in the arrival distribution of passengers calls for the need of simulation to evaluate check-in systems. However, their model does not determine how many check-in desks are needed but works for predefined check-in systems. Chun and Tak (1999) propose a model which determines per flight how many check-in desks need to be allocated. As input values they use data involving the arrival pattern, the check-in process and which queuing principle is used. They highlight that the arrival pattern varies during the day. Other models like those of (Van Dijk & van der Sluis, 2006) and (Bruno & Genovese, 2010) determine the number of check-in desks needed to satisfy a certain level of service or try to find the number of desks needed by balancing the waiting time against the cost of the desks. These models, however, are too detailed for the concept design, which only provides a basic number of check-in desks. Factors like queuing time and the amount of check-in desks are not yet accounted for in the concept design. For the concept design, the amount of check-in desks is based on the capacity of the equipment and the peak demand for the O&D

departure passengers expressed in bags per hour.

In Table 4.1, a summary of all input parameters for the check-in system are given.

Table 4.1: The input parameters to design a check-in system

Input parameters	Unit	Source
Check-in equipment	-	NACO
Desk configuration	-	(IATA, 2004)
Desks per island side	-	(IATA, 2004)
O&D departure Peak	PAX/h	(Jenks et al., 2010)
Number of airlines	-	(Jenks et al., 2010)
Arrival distribution passengers	PAX/h	(Jenks et al., 2010)
Arrival distribution curbside	PAX/h	(Appelt et al., 2007)
Average service time	h	(Jenks et al., 2010)
Percentage of passengers using check-in	%	(Jenks et al., 2010)
Bags per passenger per airline	bags/PAX	NACO
Low-cost vs. full-service carriers	-	(Barret, 2004)
Flight type (economy and business)	-	(Koshravi et al., 2009)

4.2 Hold baggage screening

The security system for hold baggage of an airport consists of two processes: the screening of bags and baggage reconciliation (de Neufville & Odoni, 2013). In a BHS screening system, also referred to as hold baggage screening (HBS), the first process after the bag is loaded into the BHS is performed. The International Civil Aviation Organization (ICAO) provides the following description for the screening process (Shanks & Bradley, 2004):

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

According to Bradley (2010) two international legislative requirements can be found for HBS: a document by the European Civil Aviation Conference (ECAC) and ICAO Annex 17, of which the latter is the globally targeted document. ECAC (2010) states that on of the following four types of equipment have to be used for screening:

- **Hand search** - This method involves manually checking each bag
- **X-ray equipment** - These automated systems check for irregularities via x-ray and have to separate suspected baggage.
- **Explosive detection system (EDS)** - These automated systems check for irregularities by measuring for explosive substances and have to separate suspected baggage.
- **Explosive trace detection (ETD)** - With this method a sample is taken of the baggage and it is checked for explosives.

ECAC recognizes a fifth equipment type, the explosive detection dogs (EDD). Unlike the other four equipment types however, EDD can only be used as a supplementary means of screening.

As of 2012, the global standard in HBS is to screen 100% of the bags (de Neufville & Odoni, 2013). In the US, this standard was already set by the Transport Security Administration (TSA) in 2002 (Leone & Liu, 2005). The TSA then introduced four ways to perform HBS. Of these four, one is nowadays used for all airports, the in-line EDS process. This process, seen in Figure 4.2, consists of multiple levels (TSA, 2017). All baggage arriving from check-in has to flow through an automated

EDS machine. This machine either marks the baggage as clear, which goes on to sorting, or is marked non-clear at which point is needs to be send to the level 2 security. At level 2 on-screen resolution (OSR) machines are used by operators to check the bags within 45 seconds of leaving the level 1 EDS. If the operator also marks the baggage as non-clear, it is send to the level 3 area. At this level, known as the checked baggage resolution area (CBRA), bags are checked manually using ETD equipment mainly. Hereafter, clear bags can carry on with their journey while non-clear bags are removed from the BHS.

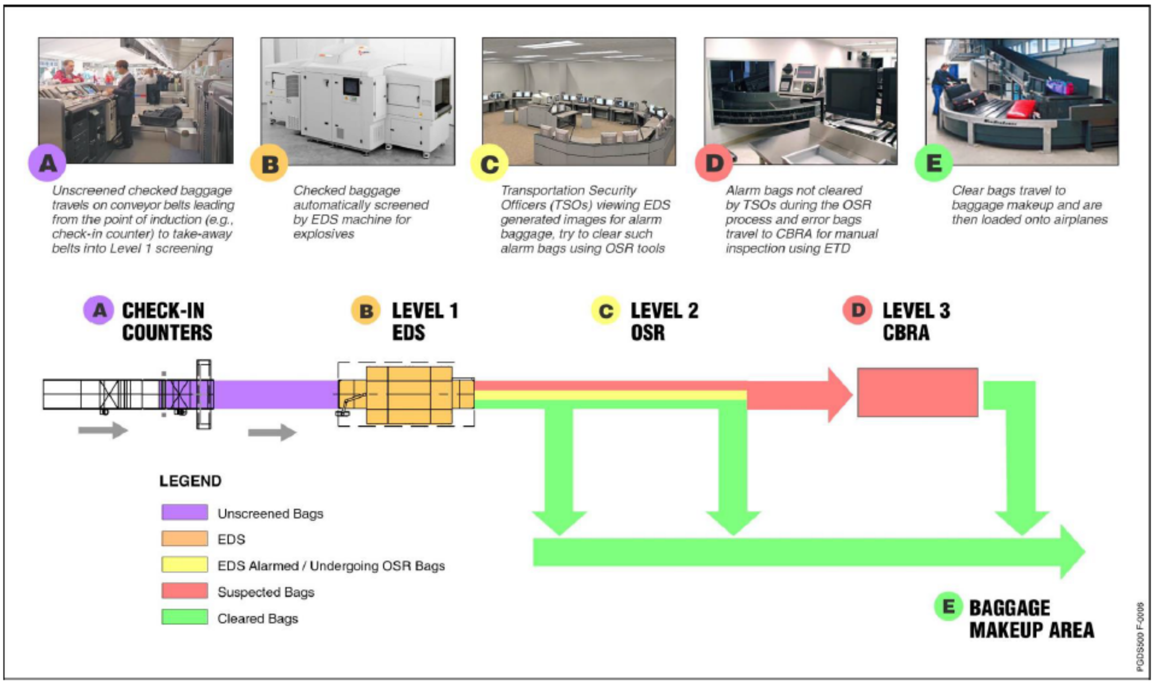


Figure 4.2: The TSA screening process (TSA, 2017)

The previous mentioned HBS equipment from ECAC can be related to the three security levels by the TSA. At level 1 the automated EDS machines are used. At OSR, digital images of the EDS machines are reviewed by operations and at the CBRA ETD equipment and hand searches are applied. So, even though ECAC requires a different standard, they do yield similar designs compared to the TSA standard. Local and national authorities can also legislate their own security requirements (de Neufville & Odoni, 2013). However, as with the ECAC standard, they are similar to the TSA standard. For the concept design the TSA standard is therefore used.

For each of the HBS levels different machines can be used (Van Noort, 2018). The EDS machines are categorized by their capacity. This results in the following EDS types from highest to lowest capacity: high speed, medium speed and stand alone EDS. The OSR equipment is all categorized in one equipment type. At the CBRA, the ETD can either be used for a normal check or full search. This leads to the two ETD equipment types of ETD normal check and ETD full search.

With the TSA standard as basic design, the input parameters can be determined. Leone and Liu (2005) provide an equation to determine the amount of EDS stations needed. The equation is shown in Equation 4.1. They use the following parameter: planning hour passenger volume (P), percentage of passengers passengers that do not have baggage (T), percentage of passengers which bags have to go to level 2 screening (K), the demand scale factor (r), the amount of checked bags per passenger (B), service rate of the EDS (S) and the utilization factor (f). The demand scale factor accounts for the variability of the passenger arrival rate and the utilization factor is introduced to prevent that operators and equipment operate at maximum capacity during peak times.

$$N_{EDS} = \frac{P(1-T)(1+K)r \times B}{S \cdot f} \tag{4.1}$$

The planning hour passenger volume, percentage of passengers who do not have bags and the amount of checked bags per passenger are used to determine the screening demand peak. This demand consists of peak value of the O&D departure and transfer arrival streams combined. In the article they do not take into account both streams. However, since this research is on the entire BHS system, these values should be used. That is why the above mentioned parameter can be replaced by the O&D departure demand and transfer arrival demand.

For the level 2 and 3 equipment, the percentage of non-clear bags at the previous level should be known. The capacity required for these levels can then be determined by taken the percentage rejected bags in the previous level multiplied with the demand peak at the previous level. Also, as stated before, the search method for the ETD needs to be known.

Some models for HBS can be found in literature. Work by Feng (2007) provides a model taking both costs and risk into account. They also experiment with the amount of security levels. Sahin and Feng (2009) also include risk and cost-effectiveness. Their model helps with choosing the right equipment types based on their costs and accuracy. Skorupski and Uchroński (2015) provides a model which includes human factors, for example the tendency to make mistakes. The model can be used to indicate the right control process organization option.

Table 4.2 provides a summary of the input parameters for HBS design.

Table 4.2: The input parameters to design the HBS system

Input parameters	Unit	Source
Screening equipment	-	NACO
Local security standards	-	(de Neufville & Odoni, 2013)
O&D departure demand	bags/h	NACO
Transfer arrival demand	bags/h	NACO
Demand scale factor	-	(Leone & Liu, 2005)
Utilization factor	-	(Leone & Liu, 2005)
Level 1 rejection rate	%	(Leone & Liu, 2005)
Level 2 rejection rate	%	(TSA, 2017)
ETD normal vs full search	-	NACO

4.3 Transportation

After the screening process, baggage is usually transported towards the sorting area. This transportation can be just a few meters at small airports, to kilometers at large airports. Throughout the BHS, transportation is needed and can be done using different types of transport equipment in the same BHS. However, for this research, it is assumed that only one type of transport equipment is used throughout the system. In general, the following four types of transport equipment can be used:

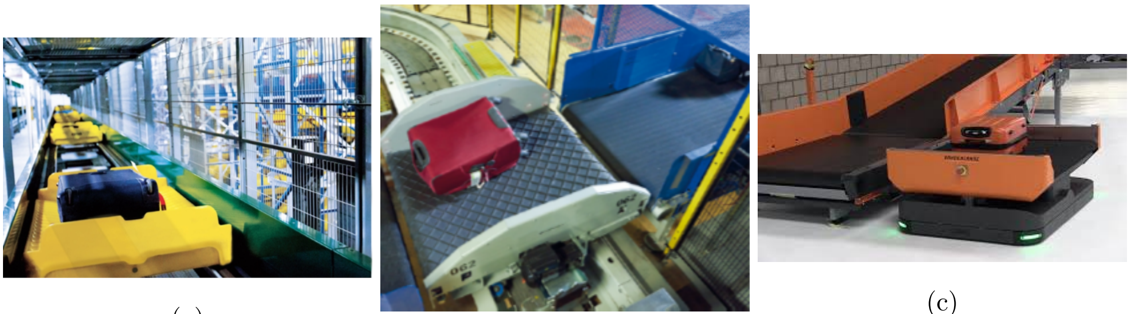
- **Belt conveyor** - With this option, bags are loaded onto a conveyor belt and are transported over the belt.
- **Destination coded tray (DCT)** - With a DCT conveyor, bags are loaded into trays. These trays are then transported throughout the system via a conveyor system. An example is shown in Figure 4.3a.

- **Destination coded vehicle (DCV) type 1 -** A DCV conveyors uses individually powered carts instead of trays. In a type 1 DCV system, the carts are equipped with a conveyor belt. This means that the trays can load and unload themselves. An example is shown in Figure 4.3b.

- **DCV type 2 -** In a type 2 DCV system, the carts are automated guided vehicles (AGV). This means that no additional track is needed for the carts and they find their own route through the system. An example is shown in Figure 4.3c.

If a DCT or DCV system is used, the individual trays have to be loaded. As stated before, the DCV type 1 systems can load them self. DCT and DCV type 2 equipment need additional loading equipment. The loading can either be done by a top loader or a side loader. The bags need to be unloaded from the system. However, this happens at the sorting system which will be discussed in Paragraph 4.4.

The DCT and DCV type 1 need more track then a conveyor belt. This is because empty units need to return to the loading section of the system. Therefore, additional track is needed to return the units to the infeed or storage areas. Outside of the peak hours, trays and carts need to be stored. Trays can be easily stacked using special tray stackers, DCV systems need special storage lanes. Conveyor belts do not need any additional track or storage space.



(a) (b) (c)

Figure 4.3: Examples of a DCT (a), DCV type 1 (b) and DCV type 2 (c) conveyor system (Vanderlande, 2018b; BEUMER group, 2018; Vanderlande, 2019)

Which equipment type is chosen is based on several system requirements. IATA (2004) categorizes the airports by peak baggage flow and provides recommendations for each of these categories. For airports with a peak below 1000 bags/hour, category A airports, a manual or conveyor belt is recommended. For airports up to 5000 bags/hour, category B, a DCV type 1 system is recommended. Airports with more then 5000 bags/hour, category C, are recommended to use DCV type 2 systems. The DCV type 2 system they mention, however, is a different type of systems which is not used anymore. Because the transportation follows after each subsystem, the same demand values can be used of the subsystem it started.

Besides the capacity requirements, some design requirements effect the transport system. First of all, the length of the transport section is of importance. For longer distances, faster equipment can become more attractive. Also, the speed at which the transport needs to be performed effect the equipment choice.

At last, the bags handled by the system influence the transport system. If, for example, odd-size baggage is transported over the same conveyor, the conveyor should be adapted to these bags. This could result in the use of special trays for example. However, as stated in the scope, these types of bags are excluded from the research.

Table 4.3 provides a summary of the input parameters for the transportation system.

Table 4.3: The input parameters to design the transport system

Input parameters	Unit	Source
Transport equipment	-	NACO
O&D departure demand	bags/h	NACO
Transfer arrival peak	bags/h	NACO
Transport distance	m	NACO
Desired transport speed	m/s	NACO
Bag sizes	m	NACO

4.4 Sorting

In the sorting process, bags are send to the right MUP or EBS, if available. In general, sorting can happen in two ways. Most airports make use of sorting loops. The loops consist of the transportation equipment described in Paragraph 4.3 and are located above the make-up area, the latter will be described in Paragraph 4.5. At each of the make-up entry, sorting equipment is used to transfer the bags to the make-up. Figure 4.4 shows a schematic representation of a sorting loop. Due to redundancy, usually multiple loops are present in a BHS. For smaller airports, manual sorting at the MUP is also possible.

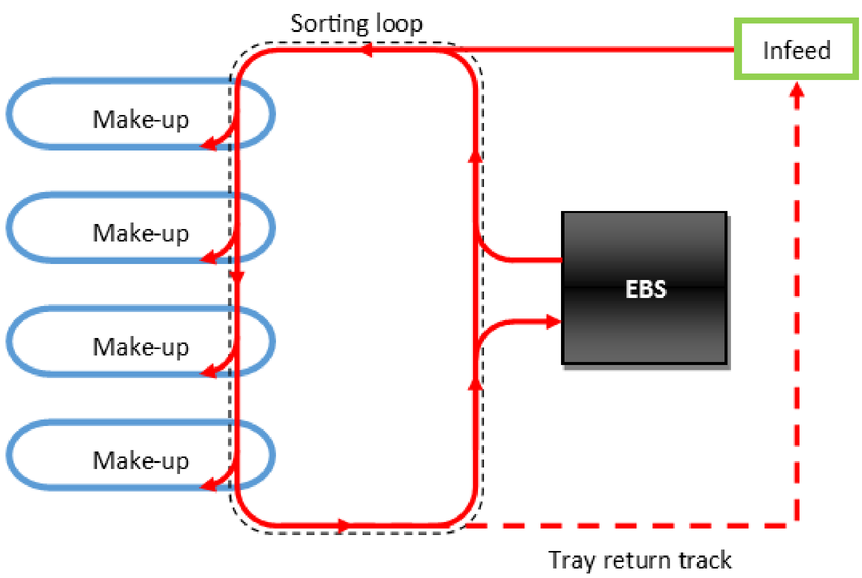


Figure 4.4: An schematic example of a sorting loop

The four types of transportation equipment given in Paragraph 4.3, can be combined with different sorting equipment (Van Noort, 2018). The following transport and sorting equipment combinations are possible for conveyor belts:

- **Cross belt** - Cross belt conveyor consist of individual carriages linked together to form a loop. Each carriages has a smaller belt conveyor perpendicular to the travel direction.

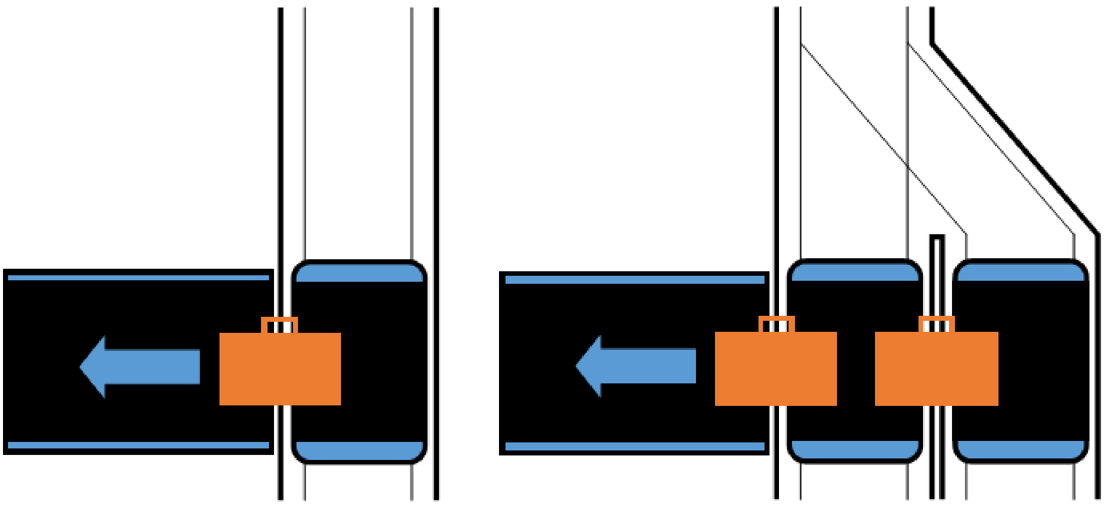
- **Push tray** - The conveyor consist of an ongoing chain of trays were bags are pushed off by a sliders, this system is similar to the DCT transport system.
- **Tilt tray** - The conveyor consist of an ongoing chain of trays. The bags are removed by tilting the tray towards the desired output.
- **Pusher low speed** - Low speed pusher can extend an arm which then redirects a bag to the right direction.
- **Pusher high speed** - High speed pusher push the bags into the right direction.

The main difference between the equipment is that the pusher are additional equipment for the conveyor belts while the other three equipment types are complete conveyor types. For DCT and DCV type 2 conveyors the following sorting equipment can be used:

- **Static discharge** - With static discharge, the tray or cart comes to a complete stop before discharging the bag.
- **Dynamic discharge** - with dynamic discharge, the bag is discharged while the tray or cart is still travelling. As a rule of thumb, dynamic discharge has twice the capacity of a static discharge sorter and requires more space.

Because DCV type 1 conveyor can load and unload automatically, no additional sorting equipment is needed. However, how the unloading configuration can be as following:

- **Chute** - The bags are unloaded onto a chute while the cart is still moving.
- **Parallel** - The bags are loaded onto a parallel conveyor belt while the cart is still moving.
- **Single** - The bags are unloaded individually while the carts stands still, see Figure 4.5a.
- **Double** - The bags are unloaded two carts at a time into the same conveyor. The carts, parallel to each other, stand still during the unloading, see Figure 4.5b.
- **Single 2x** - Two single unloading stations after each other.
- **Double 2x** - Two double unloading stations after each other.



(a) (b)

Figure 4.5: Single unloading (a) versus double unloading (b)

Besides the transport equipment and the use of loops or manual sorting, other factors influence the sorting system of an airport. First of all, since the sorting process is linked to the make-up, they use the same demand profiles: the O&D departure and transfer arrival demand.

As was already visible in Figure 4.4, the transportation, sorting and make-up systems of a BHS are connected to each other. The input parameters for these individual systems therefore effect all three systems. This means that the input parameter given in Paragraph 4.3, also influence the sorting system. Because of the similarities in the systems, research into the sorting systems of BHS is usually combined with the make-up systems. The researches assume a certain equipment type and use this for an allocation problem related to the make-up. Johnstone, Creighton, and Nahavandi (2010), for example, assume the sorting to be done using a high-speed tilt tray loop system. With this assumption, two algorithms are presented which reduce the state space for diverters. Ascó, Atkin, and Burke (2011) state that the make-up configuration influences the sorting system. The article states more parameters, however, these are related to the make-up. These parameters will be discussed in Paragraph 4.5

Table 4.4 provides a summary of the input parameters for the sorting system.

Table 4.4: The input parameters to design the sorting system

Input parameters	Unit	Source
Loop or manual sorting	-	NACO
Sorting equipment	-	NACO
Transportation equipment	-	NACO
O&D departure demand	bags/h	NACO
Transfer departure demand	bags/h	NACO
Make-up configuration	-	(Ascó et al., 2011)

4.5 Make-up

The make-up is one of two output points of the BHS. Here, the outgoing baggage is loaded into load units before send to an aircraft by vehicles. This means that the make-up can be combined into two parts, the loading part and the outlet part. The outlet implies the process of bringing the loading units to the vehicles which take them to the aircraft. This paragraph is therefore separated into two sub paragraphs, one for loading and one for the outlet.

4.5.1 Make-up loading

Depending on the airline and aircraft, at the make-up, bags are either loaded into containers which can be loaded into the aircraft, or carts which are unloaded at the aircraft. Containers, or ULDs, are usually used for WB aircraft and carts for NB aircraft. Figure 4.6 shows an example of both the ULD and cart.

The capacity of the make-up is defined by the amount of make-up points (MUPs) needed. A MUP is a point in the make-up area, were bags of a certain flight can be found for loading. Depending on the aircraft type and the airports policies, a flight can use one or multiple make-up points. The loading of the bags can happen manual or automated. The following equipment types can be used (Van Noort, 2018):

- **Chute** - A chute is the most basic equipment type available for make-up. 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. Here multiple bags can accumulate and operators take the bags off the belt. One lateral equals 4 MUPs and can have up to two operators.

(a)

(b)

Figure 4.6: Examples of a baggage ULD (a) and baggage container (b) (VRR, 2018; AERO Specialities, 2018)

- **Carousel** - A carousel works with the same principle as a lateral. However, instead of a straight line, it is looped. One carousel equals around 13 MUPs and can have up to four operators

- **Robot** - A robot can also be used instead of an operator. These robots get their bags from a conveyor belt. The robots currently can only handle ULDs and work in fenced off areas. One robot equals 4 MUP and one operators is used per robot to help if a robot cannot load a bag.

Currently, robots for make-up operate slower then humans, have high CAPEX and need larger areas then the other equipment. Only if a constant supply of bags is assured, the robot outperforms a human since it takes no breaks. Therefore, only a few airports globally utilize these robots. With the current development in robotics it can be assumed that these robots will become faster and cheaper. Therefore, adding these equipment types into the model makes sure that the model is also applicable in the future.

Abdelghany et al. (2006) describe a model for a make-up configurations with piers. These piers, or laterals, are placed perpendicular to the sorting loop. Their model assigns baggage to available laterals of an air-carrier. The article states that the following input parameters are needed: the bag demand, MUP buffer time and the amount of airlines. The MUP buffer time is the time a MUP stays closed after the flight is scheduled to depart. This buffer time is introduced to prevent baggage mix up between different flights when a flight is delayed. Other parameters are stated in the article, however, these consist of rules for lateral assignment which are not important for the concept design. Ascó et al. (2011) include the buffer time into the service time of the baggage. Their model, also related to the MUP allocation, goes into more detail regarding the in-system-time of the bags.

To determine the capacity requirements of the make-up, the O&D departure demand and transfer departure demand should be known. However, the transfer departure demand is hard to require for greenfield BHS since the flight schedule does not always contain the information needed for this. One way to avoid this problem is to use the MUP demand instead of the bag demand. This demand is based on the amount of MUP needed per aircraft type. This value is not constant but changes over time. Three aircraft types are distinguished from large to small: wide-body (WB), narrow-body (NB) and regional jets (RJ). Every airport applies their own rules for the amount of MUPs open per aircraft type. An example of the MUP distribution is given in Figure 4.7. By using the MUP demand instead of the bag demand, the service time related parameters are not necessary. The MUP demand also includes the rule that each MUP can only handle one flight at a time, calculating from the bag demand does not include this.

When the information about transfer arrival passengers is available, the transfer arrival distribution can be used. This distribution is similar to the arrival distribution of the check-in passengers, but usually starts earlier. If no information about the distribution is given, assumptions have to be made for this.

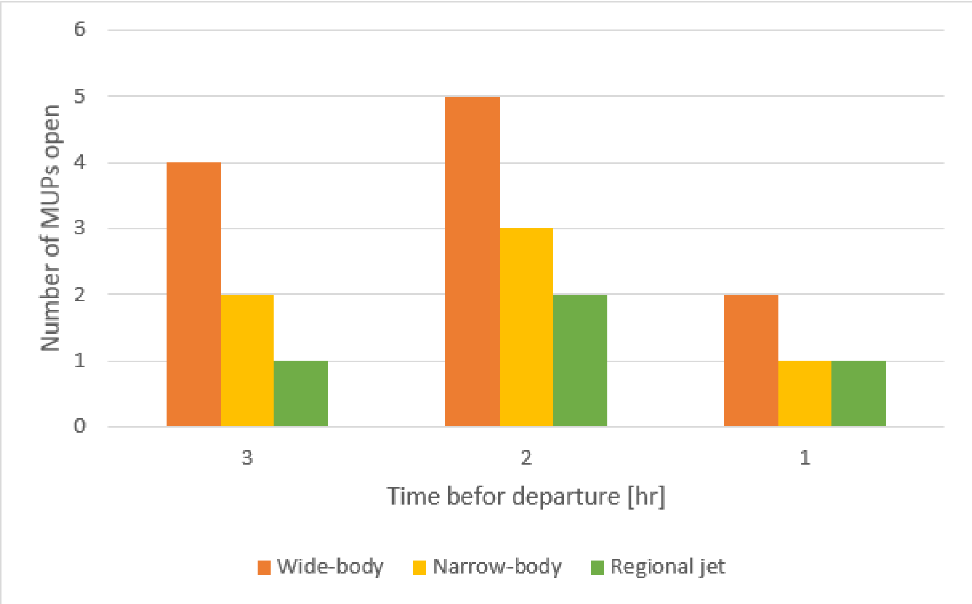


Figure 4.7: The amount of MUPs open per aircraft type over time

When airports increase in size, the transportation time from make-up to the aircraft can become very high. That is why at large airports, the make-up area can be decentralized. This implies that there is not a single make-up area but multiple. These make-up areas all take a certain part of the demand and combined equal the entire MUP demand. Therefore, the part of the MUP demand which they process should be provided as an input.

4.5.2 Make-up outlet

As stated in the beginning of the paragraph, at the outlet the ULDs are transported to vehicles which take them to the aircraft. The transport can happen in two ways: directly at the MUP or by automated load unit transportation (ALT). With a direct system the ULDs are already connected to the vehicle when they are loaded at the MUP. This means that the operators fill the ULDs and the vehicle drives away when the operators are finished. This method requires the make-up area to be big enough for the vehicles to drive and turn. With an ALT system, the ULDs are positioned on a roller conveyor, as can be seen in Figure 4.8. 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. A new ULD is then transported to the operator. Because the vehicles do not need to enter the make-up area, less space is required. Also, buffers can be added to store ULDs. However, the CAPEX of an ALT system is high compared to a direct system. Three types of ALT systems can be distinguished:

- **Non driven** - The operators push the ULDs over the roller deck.
- **Driven** - The rollers are driven and transport the ULDs.

- **Transfer vehicles** - Transfer vehicles individually transport ULDs through the system, like AGVs.

Figure 4.8: A non-driven ALT system at Paris-Charles de Gaulle airport (Aircargonews, 2015)

Tractors, or tugs, are used for the transport of the baggage load units. The tractors perform two kinds of movements: in-terminal movements and apron movements. In-terminal movements are performed within the make-up area and bring fully loaded ULDs to a buffer. Airport restrict the amount of carts that can be moved at once within the terminal. Whenever an operator has reached this limitation, the carts will be send to the buffer. The apron movements are the movements made by the tractors outside of the terminal. Like the in-terminal movements, restrictions are made for the amount of carts that can be towed on the apron. If enough ULD are present at the buffer to match this restriction, a tractor brings the ULDs to the aircraft stand. When direct loading is used, roads are needed around the make-up equipment. The road width is therefore required to dimension the area.

If an ALT system is used, no more in-terminal movements have to be made by trains and the roads can be removed from the make-up area. ALT systems will therefore require less trains and take up less space. To determine the amount of trains needed, different input parameters are needed. First for both the WB ULD and NB carts, the average amount of bags is needed. In addition to this, the maximum of ULDs per train for both the in-terminal and apron movements should be defined. At last, for the arrival flights, the time a tractor is reserved to bring the ULDs from the aircraft to the offloading points should be defined. This will be referred to as the train occupancy time.

Table 4.5 provides a summary of the input parameters for the make-up system.

4.6 Early baggage storage

If an airport chooses to use EBS, bags which arrive at the sorting system before any MUPs are assigned to their flight, are send to the EBS. IATA (2004) states that baggage which dwells within the system for longer then two hours can be routed to an EBS. It is important to state that storage can also be done by keeping bags within the sorting loop. However, for this research loop storage is excluded. The following three equipment types for EBS can be used:

- **Lane** - With lane storage, lanes of conveyor belts are assigned to flights were early baggage can accumulate. As soon as the make-up opens, the lane is unloaded back into the sorting system. Lane storage works with the first in first out (FIFO) principle, see Figure 4.9a.

Table 4.5: The input parameters to design the make-up system

Input parameters	Output	Source
Make-up equipment	-	NACO
MUP demand	MUP/h	(Abdelghany et al., 2006)
Aircraft to MUP distribution	-	NACO
Transfer arrival distribution	PAX/h	NACO
Centralized or decentralized	-	NACO
Demand division per area	-	NACO
Direct or ALT	-	NACO
Average of bags in a WB ULD	bags	NACO
Average of bags in a NB cart	bags	NACO
Maximum of carts\ULDs for in-terminal movements	carts	NACO
Maximum of carts\ULDs for apron movements	carts	NACO
Road width	m	NACO
Train occupancy time	min	NACO

- **Individual** - With individual storage, the bags are loaded onto individual storage units which have a conveyor belt. Each unit needs a driver to power the belts, see Figure 4.9b.
- **Rack** - In a rack storage, bags are loaded onto trays. These trays are then loaded into a rack. This loading can either happen with a shuttle, which can only move vertically along the rack, or with a crane which can go both vertical and horizontal, see Figure 4.9c.

(a) (b) (c)

Figure 4.9: Examples of Lane (a), individual (b) and rack storage (c) (Vanderlande, 2018a; Alstef, 2018)

The transportation equipment used can have effect on the decision which EBS equipment to utilize. If a conveyor belt is used, lane storage becomes a better option. If a DCT system is used, the rack system becomes more suitable. If a DCV systems is used, the individual storage can become more suitable. It is important to state that the individual storage is not a common used storage type due to the fact that it has a high CAPEX and large system area. Also, the transportation with EBS equipment combinations are not fixed. Some airport for example have DCT systems but store the trays in a lane configuration. Other airport only load bags onto trays when they need to be stored in an EBS rack system.

The storage size of the EBS is defined by the amount of bags which arrive before any MUP is appointed to their flight. For the O&D arrival passengers this value can be easily defined by using the passenger arrival distribution and the time before departure when MUPs are assigned. For transfer passengers the transfer arrival distribution, defined in Paragraph 4.5, can be used. Adding the O&D arrival demand and the transfer arrival demand related to EBS, the storage demand can be determined.

Some airports or services require single bag access for their EBS. This means, that a bag can be withdrawn from the EBS at any moment. When this service is needed, lane storage cannot be used.

Due to the FIFO nature of the storage, this would imply that if a bag is needed, the entire lane has to be emptied into the system. An example of a service for which single bag access is needed is the US border preclearance (CBP, 2014). With this service, passengers can already clear the US customs and have a quicker transfer time at their destination. Stated by the U.S. Customs and Border Protection (CBP), checked bags should be made available for secondary inspection at the request of a CBP officer. Therefore, single bag access should be available.

Hallenborg (2007) provides a model which includes the EBS into a BHS which utilizes a DCT system. The EBS is included by making the EBS a MUP with infinite capacity. Bags which arrive 3 hours before departure will then enter the imaginary MUP and leave when an actual MUPs is assigned to their flight. The article also states that empty trays could also be stored in the EBS to prevent cluttering of trays during peak hour.

Table 4.6 provides a summary of the input parameters for the EBS system.

Table 4.6: The input parameters to design the EBS

Input parameters	Unit	Source
EBS equipment	-	NACO
Transport equipment	-	NACO
Transfer arrival demand	bags/h	NACO
O&D arrival demand	bags/h	(Hallenborg, 2007)
Opening time check-in	h	(Hallenborg, 2007)
Opening time make-up	h	(Hallenborg, 2007)
Single bag access	-	(CBP, 2014)

4.7 Reclaim

The second output point of the BHS is the reclaim system. Here, O&D arrival passengers retrieve their bags from a reclaim unit. Not much variation can be found in the reclaim equipment. IATA (2004) provides two reclaim equipment types: a reclaim carousel or a free roller conveyor. The carousel is the exact same principle as the make-up carousel, only now passenger retrieve bags from the belt and not operators. Free roller conveyors can be used at small airports but they are not preferred by both airports and passengers. Therefore, free roller conveyors are excluded form this research.

Reclaim carousels have two different ways of stacking baggage: flat or tilted. A flat belt can only hold one bag along the width of the belt, tilted belts two. To determine the amount of reclaim belts some values are needed. These are: the division between DOM and international flights (INT), the passenger bag ratios for both DOM and INT and the length of the reclaim carousels. Table 4.7 shows the typical bag to passengers ratios provided by IATA. They do mention that these values differ for each airport. For reclaim belt length they advice to have a belt length for WB between 70 and 90 meters, and for NB between 40 and 70 meters.

Table 4.7: Typical bag to passenger ratios (IATA, 2004)

Type of PAX traffic	Europe	Asia/Africa	USA	Other
International	1.0-1.5	2.0	2.0	1.5
Domestic	0.0-1.0	1.0-2.0	1.0	1.0

For the concept design of BHS, the amount of reclaim belts has already been defined by the architects. It is therefore chosen not to include the reclaim system into the model. The amount of reclaim belt

is required as an input parameter since this will be used for the offloading systems.
Table 4.8 provides a summary of the input parameters for the reclaim system.

Table 4.8: The input parameters to design the reclaim system

Input parameter	unit	source
Reclaim equipment	-	NACO
O&D arrival demand	PAX/h	(IATA, 2004)
Division of DOM and INT	-	(IATA, 2004)
Passenger bag ratio	bags/PAX	(IATA, 2004)
Carousel length	m	NACO
Amount of carousels	-	NACO

4.8 Offloading

For baggage from arriving passengers, the offloading system is the entrance to the BHS. The bags arrive in ULDs and are unloaded on a belt conveyor. This conveyor takes the bags further into the system. Other then a conveyor belt, no other equipment can be used in the offloading system. The offloading process can be automated by using a bag tipper. These devices shake and tilt the ULDs so the bags slide out and land on the belt conveyor. Two offloading point are present in the system: the O&D and transfer points. Both points will be discussed separately.

The O&D point consists of offloading quays. These quays are connected to one of the reclaim carousel. The amount of quays correlates to the length of the carousel. As a rule of thumb, per 60 meters of reclaim carousel, one offload quay is needed. This rule follows from the fact that reclaim belt longer then 60 meter usually handle bags of WBs or multiple flights at once. Due to the larger amount of bags multiple quays is preferred.

The transfer point also consist of quays. However, these quays are all connected to the screening system. The amount of quays needed here depends on the transfer arrival demand. Barth, Timler Holm, and Lindorff Larsen (2013) provide a model for transfer baggage. They state that offloading can be decentralized. Their model for decentralized transfer offloading aims at minimizing missed connections, minimize transport time, maximize the capacity buffer and balance the use of different infeeds. Their model, however, goes into too much detail for the concept design.

Table 4.9 provides a summary of the input parameters for the offload system.

Table 4.9: The input parameters to design the offloading system

Input parameter	unit	source
O&D arrival demand	bags/h	NACO
Transfer arrival demand	bags/h	NACO
Reclaim equipment	-	NACO
Manual or automated unloading	-	NACO
Amount of reclaim carousels	-	NACO
Carousel length	m	NACO
Centralized or decentralized	-	(Barth et al., 2013)

Now that all subsystems are defined, a schematic overview of a BHS can be made. This overview can be found in Appendix B.

4.9 General data

Now that every BHS subsystem is researched, parameters which influence the entire BHS can be discussed. Each sub paragraph defines a certain set of input parameter.

4.9.1 Peak demand

Each of the subsystem depends on different baggage flows. On which flows they depend and how they are determined have already been discussed in the previous paragraphs. This section will elaborates on how these peak values are defined. Table 4.10 shows which flows influence the subsystems. It can be seen that the transfer departure stream is not used. This is because determining this from a flight schedule is not possible without additional transfer data.

Table 4.10: The demand values needed to determine the peak values for each system

	Departure		Arrival		Other
Systems	O&D	Transfer	O&D	Transfer	Make-up positions
Check-in	x				
HBS	x			x	
Transportation	x			x	
Sorting	x			x	
Make-up					x
EBS	x			x	
Reclaim			x		
Offloading O&D			x		
Offloading transfer				x	

Stated by Suryani, Chou, and Chen (2010), analyzing air travel demand is an important factor when dealing with capacity utilization. They state that the following factors influence the demand: airfare impact, LoS impact, GDP, population, number of flights per day and dwell time. For the peak demand value, using the highest hourly demand of the year is not sensible (P. T. Wang & Pitfield, 1999). Doing this would be uneconomical and a wasteful investment. Therefore, the peak demand of the 30st busiest day of the year is usually used. To determine the peak hour, NACO determines the peak 15 minutes and multiplies this value by four. Combining the data for passenger arrival distribution, flight schedule PAX data and airline bag ratios are then used to determine the peak values.

For hub airport considering multiple days can be useful. If the 30st busy day, for example, is of a day with a lot of transfer PAX, the O&D part of the BHS might not be well designed. In the research by Van Noort (2018), it is shown that within a span of 3 days, transfer and O&D demand can be completely different due to national holidays.

With greenfield airports, knowing the peak demand value is enough. However, if a BHS is extended, the existing system capacity should be taken into account. This is to prevent the new BHS section to be designed for a higher capacity then required.

4.9.2 System redundancy

Section 3.2.2 already gave a brief introduction on redundancy. This section will go into more detail on this subject. During operation, machines can break down. To prevent the entire BHS from failure when one machine breaks down, redundancy is introduced. A 100% redundant system is a system which is still able to handle all bags when a machine breaks down during the peak hour. However, a 100% redundant system would mean over engineering of the system and a waste of resources. In literature, different approach to redundancy can be found. Bradley (2010) provides different redundancy values for airports. Airports with a peak demand value up to 999 bags per hour, should have a redundancy of 50%. When an airport has a peak value above 999 bags per hour, 75% redundancy should be used. IATA (2004) provides another view on redundancy. They state the following rules regarding redundancy:

- The probability that the system will be available to handle 100% design capacity at any instant during the operating duty cycle should be typically greater than 99%.
- The probability that the system will be available to handle ≥75% design capacity at any instant during the operating duty cycle shall be typically greater than 99.9%.
- The probability that the system will survive an operational year, at the stated usage, without inducing a critical failure, shall be greater than 99.99%.

For this research, the definition of redundancy by Bradley is used which is sufficient for the concept design.

4.9.3 Terminal layout

Airports terminals come in many different shapes and sizes. As the BHS is included into the terminal, the layout is effected by the BHS design. Cited by Edwards (2005): *"The terminal layout and the needs of baggage handling should be integrated at the design concept stage."*. Adding the terminal layout to the model is therefore of importance to the concept design. Two important features of the layout effect the BHS: the shape of the terminal and the amount of levels present. The shape of the terminal will be discussed first.

Described by de Neufville and Odoni (2013), five basic terminal configurations can be distinguished:

- **Finger piers** - These are terminals which extend from a central passenger facility and have gates present on both sides. AAS is an example were this principle is used.
- **Satellites** - Similar to fingers piers, however, all gates are concentrated at the end of the finger. The connection to the passenger building can be above or underground. Tampa International Airport is an example for a satellite configuration.
- **Midfield** - Midfield concourses are linear of X-shaped gate facilities which are placed far from the central passenger building, typically between parallel runways. Hartsfield-Jackson Atlanta International Airport utilizes a midfield configuration.
- **Linear** - Linear terminals are long terminals which have the aircraft on one side, and the landside entrance, usually at a parking area, on the other. Linear terminals can be straight or curved. Kansas City Airport consist of multiple curved linear terminals.
- **Transporters** - At transporters, or apron terminals, passenger are brought to the aircraft by rubber-tired vehicles. It is the only configuration which does not include boarding gates and therefore is the most basic of all five configurations. Rotterdam The Hague Airport operates with a transporter terminal.

When airports are first developed, usually only one terminal configuration is used. However, as airports grow in size over the years, space can become limited. This can cause airports to utilize multiple terminal configurations. Paris Charles de Gaulle Airport for example, utilizes all five terminal configurations, as can be seen in Figure 4.10. Modern terminals differ from older airports. Where older terminals are build up of basic shapes, new terminals include more complex shapes. This effects the BHS since it should fit within the shape of the terminal. The growth of an airport also effects the BHS. Most airport start with a fully centralized BHS. When terminals are added, the BHS needs to be expended. This can favour decentralizing the BHS systems, like the make-up and offloading, to reduce travel times. The effect of growth on the demand of the BHS will be further discussed later in this paragraph.

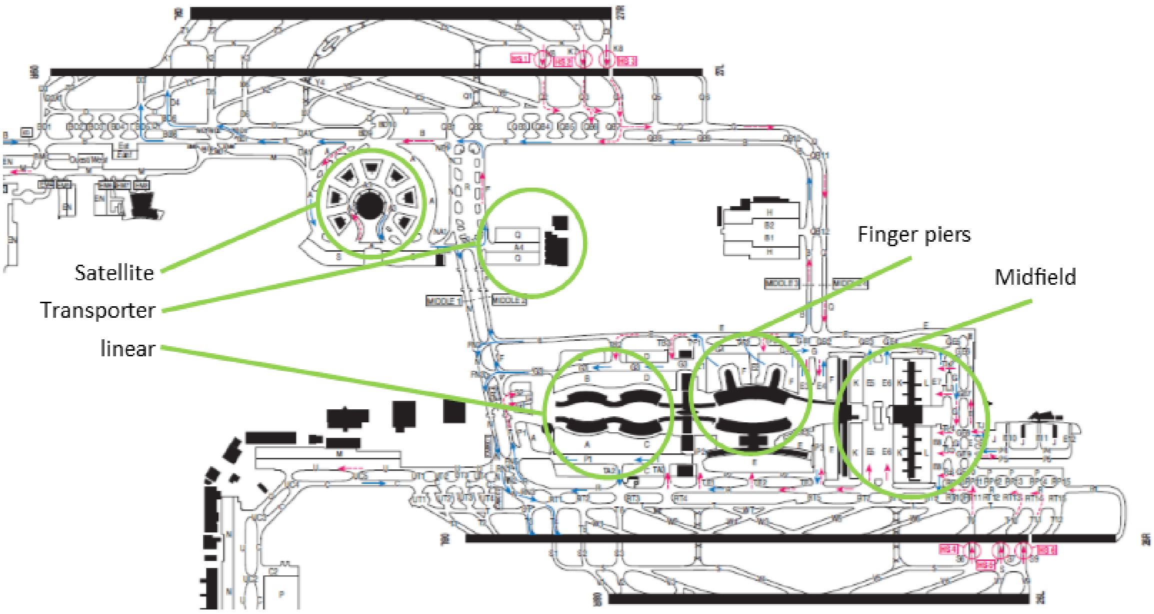


Figure 4.10: The different terminal configurations at Paris Charles de Gaulle Airport (VATFrance, 2018)

One of the reasons that terminals can be multilevel, is the complexity of the baggage movements (Edwards, 2005). The more complex a BHS is, the more levels it requires. Typical airports have between one and three levels (Kazda & Caves, 2015). For small airport which use no gates, an one level system can be used. All system of the BHS are then located on the apron level. When gates are used, two level configurations can be used for the passenger flow. To a certain extend, the BHS can then still be installed on an apron-level basis together with part of the the passenger facilities. However, at large airports, this would require too much area. When this happens passenger and baggage flows are split and a third level can be introduced. One of the levels can then act as a BHS level where no passenger facilities are present. Figure 4.11 shows some examples of how the passenger en baggage flow can be organized with different for different amount of levels.

With the introduction of levels, equipment is needed to transfer baggage between the levels. These lifting equipment can be used for both upwards and downwards movements. The following lifting equipment can be distinguished:

- **Inclined conveyor** - The transport equipment described in Paragraph 4.3 can operate under an angle. Due to angle limitations, this solution can take up a lot of area.
- **Continues lift** - Continues lifts are similar to escalators as they operate in one direction. Platforms are connected to a chain which forms a loop. Bags are picked up at the loading point and discharged on the offloading point which is located on the desired level.
- **Discontinues lift** - Discontinues lifts operate like elevators as they are able to handle both upwards and downwards movement. At the loading point, bags are picked up individually. The lift is then able to discharge the bag at one of multiple offloading points.

The maximum angle of the inclined conveyors depend on several factors. These factors are the transport equipment, vertical movement and baggage type. Although the maximum angle is manufacturer dependant, the following assumptions can be made. For upwards movements, a maximum angle of 15° can be achieved(Edwards, 2005). If a DCT system is used, this angle can get up to 20°. For downwards move, a maximum angle of 20° can be used. If baggage needs to be tracked, the maximum angle is set at 12°. An example for tracking baggage is in the HBS. If a bag leaves

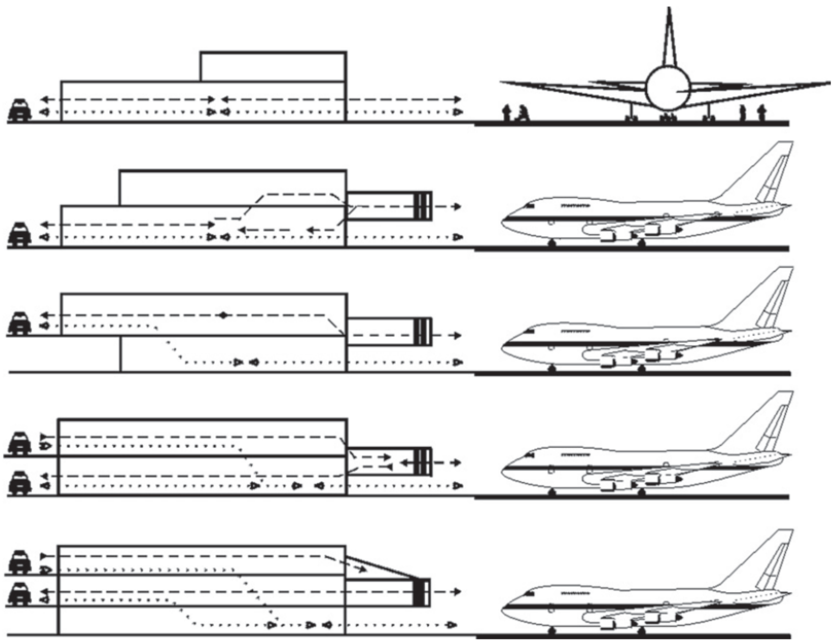


Figure 4.11: Typical airport terminal layout for different amount of levels. The dotted lines indicate the baggage flow (Kazda & Caves, 2015)

the EDS, within a certain time frame it is decided if in needs to enter the next level. During this time frame, the position of the bag needs to be known exactly so that it can be diverted if needed. Above an inclination of 12°, the bags could slip over the track which makes the position unreliable. Trays are easily traceable so DCT systems are excluded from this rule.

Edwards (2005) provides some guiding principles when designing BHS. One related to the terminal layout is to avoid turns and level changes to keep the BHS as simple as possible. However, in practice having a straight BHS can be hard to reach due to space limitations. It also states that the baggage sorting-area should be adjacent to the apron. This area consist of the sorting and make-up systems. From Kazda and Caves (2015) it can be retrieved that check-in is usually at the level which passengers arrive and reclaim at the level where passenger leave. This could mean that in a multilevel terminal, some bags have to go down one or more levels to reach the next subsystem. As the check-in hall and reclaim area have already been predefined by the master planners, their location is fixed. The positions of these areas should also be considered when designing a concept design.

At last, as already stated in Section 3.2.2, the volume reservation of each equipment unit will be included in the model. This will mean that a volume price is needed which represents the monetary value of 1 m^3 of BHS space. based on the data provided by the terminal planners at NACO, the average value for this is € 160 € /m^3. This value will mean that even if an equipment type is cheaper, due to the space it will occupy a smaller more expensive option might be chosen.

4.9.4 Level of automation

In Section 3.2.2 the LoA has already been discussed briefly. The LoA desired by an airport depends on multiple factors. In countries with low labour costs, doing everything manual can be a good solution. Opposite, if labour costs are high or health and safety regulations strict, a fully automated BHS can be the solution. So the average income of a BHS operator should be included. Also, for each subsystem, the equivalent manual solution should be added.

Fasth, Stahre, and Dencker (2008) describe seven LoA for both mechanized and computerized manufacturing processes. With each higher level, more control is laid into the hands of the machines. Where the last level are fully autonomous machines which need no human interaction. Because the LoA are designed for assembly system and not BHS, the levels have been adapted to BHS equipment. Based on the article, the following seven levels of automation are developed:

1. **Totally manual** - No equipment is used in the process and all work is performed manually. An example of this is the manual sorting of bags.

2. **Human driven** - An operator does most of the work and the equipment is used an aid. The equipment has no ability to receive or process information. An example of this are the make-up chutes.

3. **Human dependant** - The equipment is able to process information but cannot sense disruptions in the process. The equipment gives an instruction to the operator how to operate it and provide the information. An example of this is the ETD screening systems.

4. **Cooperative** - The equipment is semi-automated because it still needs an human to provide input. It can process information and sense disturbances in the process. The operator is warned if a mistakes is made. Examples of this are the self-service check-in desks which need bags and passenger information as input and can sense if the check-in process is not performed correctly.

5. **Static** - The equipment is completely automated, however, it cannot process information. It is programmed to perform one movement repeatedly and do this whenever it is called on. Operators are present to supervise and adjust the process when needed. An example of this are the sorting pushers.

6. **Equipment driven** - The equipment is completely automated as it can process and receive information. It can perform different tasks and defines what movement is should make. However, an operator is still needed to adjust the equipment if it made a mistake. An example of this are the make-up robots.

7. **Fully automated** - No human interaction needed for the equipment as it can perform everything independently. An example of this are the EDS machines.

In Paragraph 4.10, a table is given for all the available BHS equipment. Here it is indicated in which level each equipment type can be placed.

4.9.5 Airport growth

Between 1990 and 2010, passenger traffic increased at an average of 4% per year (de Neufville & Odoni, 2013). This implies that every 15 to 20 years, air traffic doubled in size. One of the main drivers of the traffic growth is the liberalization of the international aviation market (Fu, Oum, & Zhang, 2010). Table 4.11 shows the expected annual growth for both traffic and fleet sizes in different global regions for the next 20 years. Here it can be seen that traffic grows with a higher percentage then the fleet size. This implies the increase in larger aircraft.

The increase in traffic will push airport to enhance their capacities which includes their BHS (Francis, 2012). However, their is a capacity limit which can be reached. When airports get close to this limit, it becomes capacity critical. Examples of current capacity critical airports are London Heathrow Airport, New York LaGuardia Airport and the current Mexico City International Airport. As they are surrounded by urban areas, expanding the airport is not an option. According to Gelhausen, Berster, and Wilken (2013), the amount of capacity critical airports will grow in the next years. It is therefore of importance to design a BHS keeping future growth in mind to prevent this from happening to new airports.

Table 4.11: The annual traffic and fleet growth for different global regions (Boeing, 2018)

Region	Traffic growth [%]	Fleet growth [%]
North America	3.1	1.8
Europe	3.8	3.0
Latin America	5.9	4.2
Middle East	5.2	4.9
Russia & Central Asia	3.9	2.6
Africa	6.0	4.4
China	6.2	4.5
Southeast Asia	5.9	5.5
South Asia	7.8	7.4
Northeast Asia	2.0	1.7
Oceania	4.0	2.8

There are two ways growth can be included into the concept design. The first one to use a future flight schedule developed by the master planners. These flight schedules include both the traffic and fleet growth as both the PAX and aircraft are given in these schedules. If the flight schedule is not available, the traffic and fleet growth can be included separately. Providing a future vision of the BHS can help the airport in the equipment choice. They can then choose to use a certain equipment type which might be idle most of the time now, but in the future would benefit the system. For example, at a small airport using a medium speed EDS might be too much capacity in the beginning, however in the long term it can be beneficial.

4.9.6 Equipment parameters

For all the possible equipment types, parameter are needed. The following parameters are needed for the concept design:

- **Equipment dimensions** - For each equipment type the length, width and height is needed. All equipment is assumed to be rectangular. If equipment is placed on top of other equipment, like pushers, the dimensions are not needed.
- **Capacity** - The capacity values for all equipment types need to be known. All capacity values are given in bags/h and for the make-up load equipment, the values are given in the amount of MUPs it has.
- **Number of operators** - For equipment which requires operators, the amount of operators needs to be added.
- **CAPEX** - The purchase costs of equipment needs to be provided. This value is given in € /unit, or in € /meter, depending on the equipment type.
- **Energy consumption** - The energy consumption of the equipment needs to be added for equipment. These values are given in kW/h per unit.
- **LoA** - This has already been discussed in Section 4.9.4
- **Compatibility** - Some types of equipment cannot be paired with other types of equipment. It is important that the equipment is chosen with this in mind.

Table 4.12 provides a summary of the general input parameters.

Table 4.12: The general input parameter influencing all BHS subsystems

Input parameter	unit	source
Current system capacity	bags/h	NACO
Redundancy	%	(Bradley, 2010)
Terminal size	m^2	(de Neufville & Odoni, 2013)
Terminal shape	-	(de Neufville & Odoni, 2013)
Terminal levels	-	(Edwards, 2005)
Volume price	e /m^3	NACO
Lifting equipment	-	NACO
Maximum inclination rules	°	NACO
Check-in and reclaim positions	-	(Kazda & Caves, 2015)
Average income operator	€	NACO
Level of automation	-	(Fasth et al., 2008)
Traffic growth	%	(de Neufville & Odoni, 2013)
Fleet growth	%	(de Neufville & Odoni, 2013)
Equipment parameters	-	NACO

4.10 Summary

The sub question *"Which BHS parameters are needed to develop a concept design?"* can now be answered. As stated in Paragraph 1.1, four input sets are provided when designing a BHS: a flight schedule, stakeholder questionnaire, terminal layout plan and the equipment parameters. These four sets can be converted into three parameter sets. First, the flight schedule and airport specific policies are used to calculate the demand flows given in Table 4.10. Second, the available BHS equipment should be defined with the equipment parameters. Table 4.13 summarizes all BHS equipment defined for this research and which parameters are needed for each type. Manual processes are excluded from this table. At last, all other input parameters needed to develop a concept design are given in Table 4.14. Here it is also indicated if the parameter is present in the model by Van Noort (2018), if not it will be added in the newly developed model. With these three parameters sets, a BHS concept design can be developed.

Table 4.13: All the equipment available for the BHS, the LoA is indicated together with which equipment parameters are needed

Equipment type	LoA	Dimension	Capacity	Operators	CAPEX	OPEX
			Check-in			
Staffed counter	3	x	x	x	x	x
One-step-drop-off	4	x	x	x	x	x
Two-step-drop-off	4	x	x	x	x	x
			HBS			
High speed EDS	7	x	x		x	x
Medium speed EDS	7	x	x		x	x
Stand alone EDS	7	x	x		x	x
OSR	4	x	x	x	x	x
ETD	3	x	x	x	x	x
ETD full search	3	x	x	x	x	x
			Transportation			
Belt conveyor	5	x	x	x	x	x
DCT	6	x	x		x	x
DCV type 1	7	x	x		x	x
DCV type 2	7	x	x		x	x
			Sorting - conveyor belt			
Cross belt	7		x		x	x

Equipment type	LoA	Dimension	Capacity	Operators	CAPEX	OPEX
Push tray	6	x	x		x	x
Tilt tray	6		x		x	x
Pusher low speed	5		x		x	x
Pusher high speed	5		x		x	x
			Sorting - DCT & DCV type 2			
Static discharge	5	x	x		x	x
Dynamic discharge	5	x	x		x	x
			Sorting - DCV type 1			
Chute	5	x	x		x	x
Parallel	5	x	x		x	x
Single	6		x		x	x
Double	6		x		x	x
			Make-up			
Chute	2	x	x	x	x	x
Lateral	4	x	x	x	x	x
Carousel	4	x	x	x	x	x
Robot	6	x	x	x	x	x
			EBS			
Lane	5	x	x	x	x	x
Individual	7	x	x	x	x	x
Rack	7	x	x	x	x	x
			Reclaim			
Flat belt	4	x	x	x	x	x
Tilted belt	4	x	x	x	x	x
			Offloading			
Belt	4	x	x	x	x	x
Bagtipper	5	x	x	x	x	x
			Lifting			
Inclined conveyor	5	x	x	x	x	x
Continues lift	6	x	x	x	x	x
Discontinues lift	7	x	x	x	x	x

Table 4.14: The input parameters needed to develop a BHS concept design together with the presence of the parameter in the model by Van Noort (2018)

Input parameter	Unit	In model by Van Noort
Check-in		
Desk configuration	-	yes
Desks per island side	-	yes
Arrival distribution O&D passengers	PAX/h	yes
Transfer distribution O&D passengers	PAX/h	no
Bags per passenger per airline	bags/PAX	yes
Hold baggage screening		
Local security standards	-	no
HBS level 1 rejection rate	%	yes
HBS level 2 rejection rate	%	yes
ETD normal vs full search	-	yes
Transportation		
Transport distance	m	yes
Maximum IST	min	yes
Make-up and sorting		
Loop or manual sorting	-	yes

Input parameter	Unit	In model by Van Noort
Aircraft to MUP distribution	-	yes
Average of bags in a WB ULD	bags	no
Average of bags in a NB cart	bags	no
Maximum of carts\ULDs for in-terminal movements	carts	no
Maximum of carts\ULDs for apron movements	carts	no
Road width	m	no
Direct or ALT make-up outlet	-	yes
Opening time check-in before departure	h	yes
Opening time MUP before departure	h	yes
Train occupancy time	h	no
EBS		
Single bag access	-	yes
Storage height	m	no
Reclaim		
Amount of reclaim carousels	-	yes
Length of a reclaim carousel	m	yes
General input		
Current system capacity	bags/h	no
Redundancy	%	yes
Terminal size	m^2	yes
Terminal shape	-	no
Terminal levels	-	no
Cubic room price	€/m^3	no
Maximum inclination rules	°	no
Check-in and reclaim positions	-	no
Average income operator	€	no
Level of automation	-	no
Annual traffic growth	%	no
Annual fleet growth	%	no

For other material handling systems these input parameters do not apply. However, if similar research is done, the input parameters for these systems can be determined. This could then be used to develop a design model focused on that specific type of material handling system.

Chapter 5

Model development

Now that the input, output and functionality of the model are defined, the model can be developed. Two models will be created, one using the Gordian placement and one using the droplet search. As both models start with the conversion of the flight schedule, this will be discussed first in Paragraph 5.1. Thereafter, the Gordian model will be discussed in Paragraph 5.2 and the droplet model in Paragraph 5.3. Both models end up with the same result. How this result is visualized will be discussed in Paragraph 5.4. This chapter is concluded with a summary in Paragraph 5.5. After this chapter, a start is made on answering the question: *"How can the generation of BHS concept design be automated?"*. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

5.1 Flight schedule conversion

The flight schedule conversion is the first step of both models. Here the flight schedule and additional input parameters are used to determine the daily demand figures for the airport. Van Noort (2018) proposed an approach for this conversion which is used as the basis for this part of the model. Before defining the model however, first the flight schedule has to be generalized. This is needed because there is no standard template for flight schedules. In order for a generalized model to work, the flight schedule has to be generalized to.

5.1.1 Generalizing the flight schedule

Although different templates are available for flight schedules, the same data has to be extracted in order to determine the demand data. 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.
- **Airline** - In order to make the link between the bags per airline per passenger, the airline is needed.
- **Flight direction** - The direction of the flight is needed to determine which demand is influence by the flight. The direction can either be inbound or outbound and also 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.
- **Transfer PAX** - The amount of PAX on the flight which transfer are transfer passengers.
- **Local PAX** - The amount of PAX on the flight which are O&D passengers.

In order for the model to recognize the important data in the flight schedule, the data should be organized in a standard format. As most flight schedules are made in Microsoft Excel, it is chosen to use an Excel-file as the input source of the flight schedule. However, as stated before, different templates can be used for flight schedules. It is therefore required to convert the data from the original flight schedule, to a standardized format.

Table 5.1 shows an example flight schedule which can be used by the model. As is visible, each of the six data sets needed is represented in a separate column. The title of the column should always be the same as this is used to recognize the data. The model is designed in such a way that it can both handle 24-hour clock notation and minutes. The latter describes the amount of minutes from the start of the day, so 600 correspondents to 10:00.

As shown by Van Noort (2018), it is important to choose the right flight schedule. A 6 day difference can already have a big impact on the BHS, as the difference in O&D and transfer passengers changes per day. It is therefore advised to provide multiple flight schedules to ensure the BHS is capable of both handling the O&D and transfer flows at the airport. Also, the time span of the flight schedule should be adapted to the airport operational hours. For example, if an airport has a midnight peak in flights, starting the flight schedule at 00:00 would not be a good representation of an operational day. The flight schedule used should therefore be chosen wisely.

Table 5.1: An example of a generalized flight schedule

STA/STD	AIRLINE NAME	INBOUND/OUTBOUND	AIRCRAFT TYPE	TRANSFER PAX	LOACAL PAX
600	Royal NACO	I	A380	378	139
660	NACO Airways	I	B738	47	122
720	AeroNACO	I	E120	0	102
15:00:00	Royal NACO	O	A380	89	428
16:00:00	NACO Airways	O	B738	169	0
17:00:00	AeroNACO	O	E120	50	52

5.1.2 Data conversion

With the data retrieved form the flight schedule, it can be converted into the important peak data. This is done by combining the input data together with the flight schedule data. The model simulates an entire day at the airport in 15-minute sections and and generates graphs from this data. Besides the O&D and transfer flows, three other graphs are made: the MUP demand, the EBS demand and the train demand. The EBS demand shows the amount of bags present in the EBS over the day. The train demand shows the amount of trains needed during the day for both inside and outside terminal movements.

Next, the important 15-minute peak values for each subsystem are determined. These either correlate directly to one of the graphs or combine multiple graphs. Table 5.2 shows which peak values are needed by the model and which demand they combine. It is visible that the O&D arrival demand is not used. This is due to the fact that it is only needed for the arrival offload quays and the reclaim area. However, as the reclaim belts are predefined and the offloading area is linked to this, the O&D arrival demand is not of importance.

5.2 The Gordian model

The Gordian model consists of three parts. The first part is the global placement, based on the model described in Section 2.2.2. After the global placement, the equipment choices can be made. This will result in the sizes of the subsystem. At last, the detailed placement is performed. Each part will be discussed separately.

Table 5.2: The demand data used to determine the peak values for the BHS

Peak value	Demand needed	unit
Check-in	O&D departure	BAX/h
Screening	O&D departure + Transfer arrival	BAX/h
Sorting	O&D departure + Transfer departure	BAX/h
Make-up	MUP demand	MUP
Transfer arrival	Transfer arrival	BAX/h
In-terminal trains	Train demand	Trains
Apron rains	Train demand	Trains

5.2.1 Global placement

As stated in Section 2.2.2, first a clique-based undirected graph model must be made. To make this graph, the pins must be defined. In the terminal layout plan, the check-in and reclaim area are already defined. These are represented as pins in the system. It is also known where the aircraft are parked. Depending on the terminal layout, each aircraft parking stand can be given as a pin or multiple can be represented by one. The same can be done for the reclaim and check-in. Each check-in island or reclaim belt can be individually inserted as a pin or clustered into one pin. In Figure 5.1 an example of a clique graph is given. Here, the entire BHS is centralized and the gates are combined by one node. It can be seen that two cliques exist.

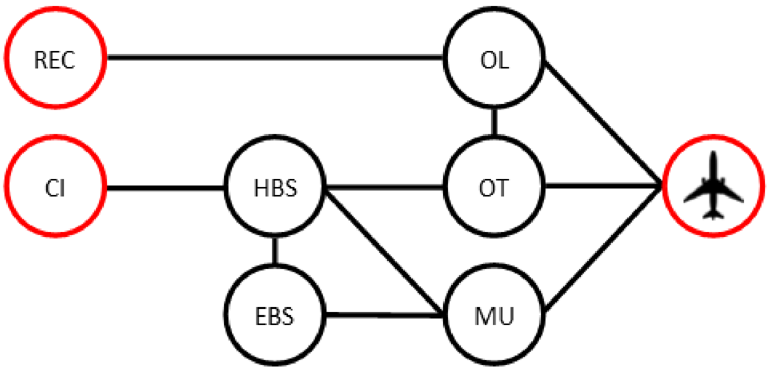


Figure 5.1: A clique-based undirected graph model for a basic BHS. The pins are indicated by the red outline. (REC = reclaim, OL = Offloading O&D, OT = Offloading transfer)

Because of the lack of cliques in a BHS, a different approach will be used to weight the routes. It is chosen to use the amount of bags which the route handles in its peak as the weight value. As the Gordian model will minimize the routing length needed, routes with a higher weight will be closer to each other. The weight definition is the only adjustment made to the Gordian placement model, so the definition of the optimization model is the same as given in Section 2.2.2. The optimization model will be done using integer values to speed up the model. Also, area is seen as a rectangle made of 1x1 meter squares. This will be used for the placement

After the global placement is finished, the coordinates of each subsystem are known. For the next step, the amount of transport distance should be known. This distance is the total amount of conveyor length needed in the BHS. By using the Pythagoras theorem, a value can be retrieved for this. Also, the transport distance for transfer baggage should be calculated. The importance for this value will be explained in the next section.

5.2.2 Equipment choice

The equipment choice model will be based on the trade-offs given in Section 3.2 and the BIP model proposed by Van Noort. What remains unchanged to the model are the decision variables given in Equation 5.1. This means that without single bag access in the EBS, 47 decision variables are divided over 13 subsystems.

$$x_{ij} = \begin{cases} 1 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is yes} \\ 0 & \text{for subsystem } i \text{ if the decision for machine } j \text{ is no} \end{cases} \tag{5.1}$$

The objective function is changed to include all trade-offs given in Section 3.2. This results in the objective function given in Equation 5.2. Where E_{ij} represents the energy consumption, Op_{ij} the amount of operators and LoA_{ij} the LoA per decision variable. The weight of each trade-off are given by α, β, γand δand are subject to Equation 5.3. The amount of operators and the LoA are linked to each other. If the operators should be minimized, the LoA should be maximized and the other way around. This link is made by subtracting the LoA section instead of added and by introducing μ. μ is used to change the operators for both parts if the LoA should be minimized and is subject to Equation 5.4.

$$min \left(\alpha * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} c_{ij} * x_{ij}}{\text{minimum value } CAPEX} + \beta * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} E_{ij} * x_{ij}}{\text{minimum value } Energy} + \mu * \gamma * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} Op_{ij} * x_{ij}}{\text{minimum value } Operators} - \mu * \delta * \frac{\sum_{i=1}^{n} \sum_{j=1}^{k} LoA_{ij} * x_{ij}}{\text{minimum value } Automation} \right) \tag{5.2}$$

$$\alpha + \beta + \gamma + \delta = 1 \tag{5.3}$$

$$\mu = \begin{cases} -1 & \text{If the amount of operators should be maximized and the LoA minimized} \\ 1 & \text{If the amount of operators should be minimized and the LoA maximized} \end{cases} \tag{5.4}$$

Looking at the important trade-offs, one i not included the objective function: the IST. The IST is included in the constraint of the model. This is because stakeholders usually provide a maximum IST and not try to minimize the value. The IST constraint uses the transfer transport distance given by the Gordian placement. The constraints of the model are as following:

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

$$\sum_{j=1}^{m} x_{ij} = 1 \quad \forall i \tag{5.5}$$

2. The IST boundary cannot be exceeded.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} t_{ij} * x_{ij} \leq max_{IST} \tag{5.6}$$

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

$$\sum_{i=1}^{n} \sum_{j=1}^{m} A_{ij} * x_{ij} \leq max_{area} \tag{5.7}$$

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

$$\sum_{j=1}^{m} h_{ij} * x_{ij} < max_{height} \tag{5.8}$$

Different to the model of Van Noort is that the fourth constraint regarding the invalid combination between certain equipment types. These combinations regard the equipment used for the make-up offloading, make-up outlet, sorting , transportation and loading/offloading for the transport. The model is adjusted that when converting the equipment parameters, all possible combinations between these subsystems are already defined. This makes the model shorter, but increases the amount of decision variables to 432.

5.2.3 Detailed placement

After the equipment choice is made, the detailed placement model should be performed. The Gordian placement is done on a rectangular shaped area. Already discussed in Section 4.9.3, terminals come in different shapes, sizes and can consist of multiple leveled. The detailed placement should therefore take these factors into account. This can be done by introducing fixed blocks, referred to as shape blocks. These blocks represent the space in the area in which nothing can be placed. An example of this can be seen in Figure 5.2. If a subsystem then overlaps with the shape block, the detailed placement should change the position of the block. If no space is left over on the desired floor, the model should search on the next floor for available space. Whenever a new floor is used, lifting equipment should be placed first. As a rule of thumb, if there is enough space for an inclined conveyor this type of equipment is used. If there is not enough space for the conveyors, lifts are used.

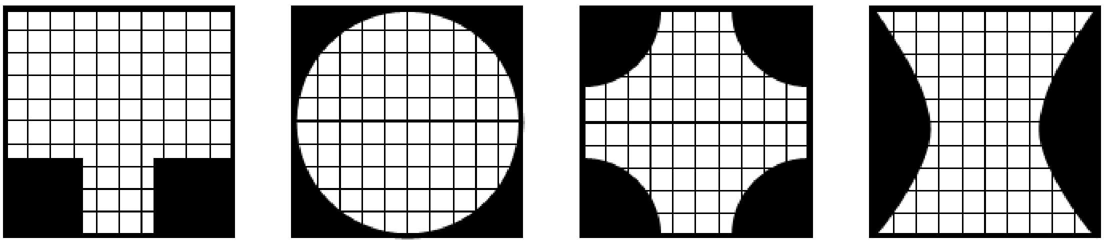


Figure 5.2: Examples of how different terminal shapes can be expressed using shape blocks

The sequence in which the subsystems are placed depends on how important they are for the airport. The make-up area is usually bound to the apron since trains enter from this level. It is therefore of importance to place this first on the same floor as the apron. The first screening level (EDS machines) should be as close to the check-in at O&D airports. However, if the airport has a large percentage of transfer passengers, the EDS machines should be closer to the transfer offload points. A placement sequence could be as following:

1. Make-up area
2. HBS level 1
3. EBS
4. Transfer offload quays
5. HBS level 2
6. HBS level 3
7. O&D offload quays

5.3 The droplet model

For the droplet model, first the terminal area is divided into 1x1 meter squares for each floor. Each square is numbered with the bottom left square being Tile 1. Thereafter, the shape blocks are placed with is done similar to the process described in the Gordian placement. This can then be used to determine the available floor space which will be used later. Next, the model will follow three steps. First, based on the available floor space, the ground equipment is chosen. The ground equipment is all equipment which is placed on the floor with the exception of the transport equipment. Thereafter, the droplet search is used to place each machine within the terminal. At last, based on the placement of the ground equipment, the last equipment types can be chosen. Each step will be discussed separately.

5.3.1 System sizing

As stated before, with the system sizing, the ground equipment is placed based on the available floor space. Table 5.3 shows which equipment is chosen during this phase and which is chosen in the last phase of the model. The optimization model used for this part is the same as the model described in Section 5.2.2. However, instead of the 432 decision variables, this step has 32 decision variables.

Table 5.3: The phase of the droplet model in which each equipment type is chosen

System sizing	Droplet search	Routing optimization
All HBS levels		Transportation
Make-up outlet		Sorting
Make-up offloading		
EBS		
Transfer offload		
O&D offload		

5.3.2 Droplet search

With the amount and type of equipment known, the equipment can be placed. Similar to the detailed placement of the Gordian model, the placement should be performed in a sequence. When this sequence is defined, the droplet search can be applied for each subsystem. The starting point for each subsystem is different. The model can handle two types of starting point: either as close as possible to one point, or in the middle of two points. Similar to the sequence, the starting point of each subsystem depends on the airport type. For airport with a large number of O&D passengers, the HBS level 1 machines should be close to the check-in area. With an large share of transfer passengers the HBS level 1 machines should be closer to the transfer offloading point. Table 5.4 shows an example of how each starting point can be defined.

Table 5.4: The starting points for the droplet search method for each subsystem

Subsystem	Close to	Between
HBS level 1	Check-in	-
Make-up	Aircraft	-
EBS	-	HBS level 1 & Make-up
HBS level 2	HBS level 1	-
HBS level 3	HBS level 2	-
Transfer offload	-	HBS level 1& Aircraft
O&D offload	Reclaim	-

Although the transportation equipment is not chosen at this point, space should be reserved for this. The model is therefore extended with a routing definition. This routing process creates a lane with the width of two conveyors between two points. This is done by taking the middle point of the two subsystems and then connect the two point by first moving horizontally and next vertically.

Figure 5.3 shows a schematic overview of the droplet placement for the HBS level 1, make-up and EBS equipment. First, the HBS machines are placed as close as possible to the check-in. Next, the make-up equipment is placed as close as possible to the aircraft. When this is done, a route is made between the HBS and make-up equipment. At last, between the HBS and make-up two EBS areas are reserved. Because the EBS is located around the transport equipment, no routing has to be made between the EBS and the other subsystems.

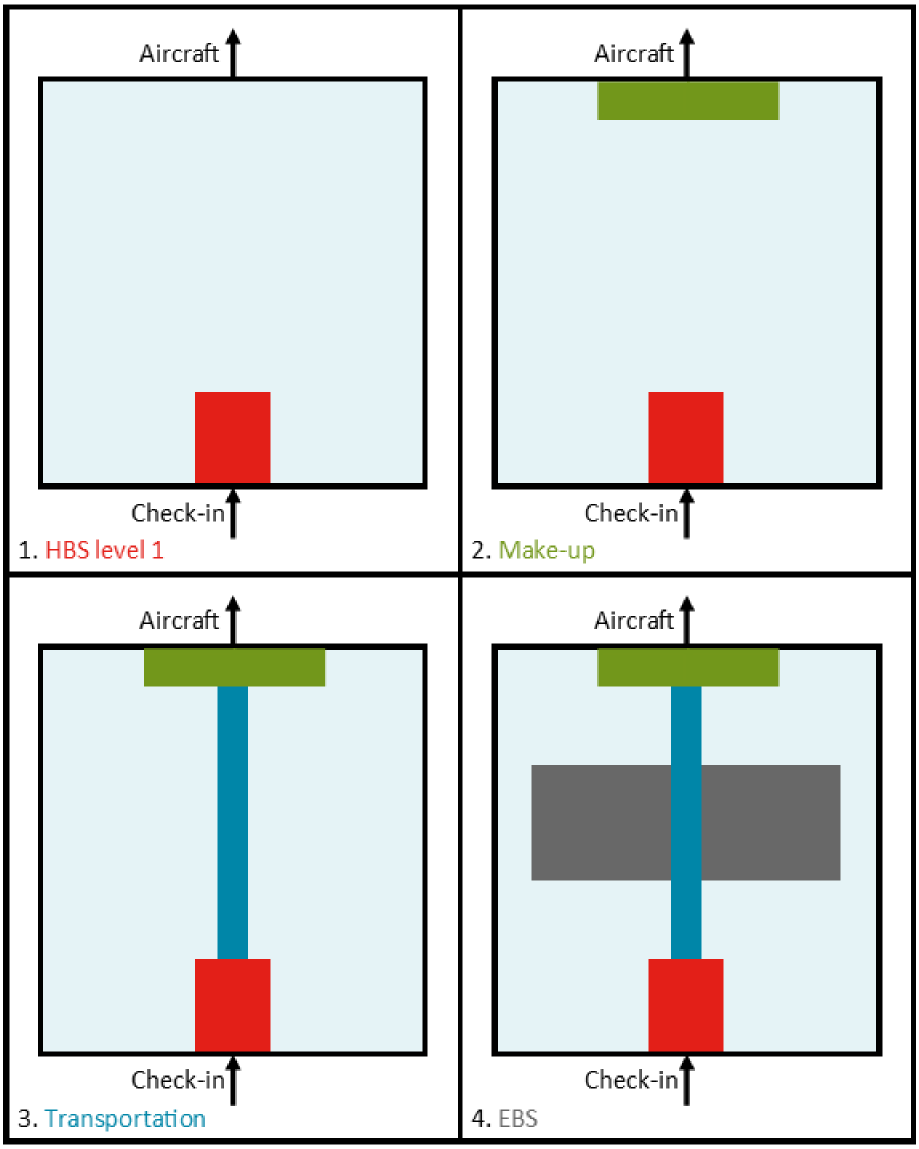


Figure 5.3: A schematic overview of the placement of three subsystems with routing

When the placement is finished, a first estimate of the total conveying length can be made. The model determines this based on the transport lines it calculated, the size of the make-up and the amount of transport lines needed. Besides this figure, the transfer transport length can also be determined. This value is used in the next step for the IST of each transport equipment.

5.3.3 Routing optimization

With the transport and transfer distances known, the last part of the droplet model can be performed. As is visible in Table 5.3, in this part the transportation and sorting equipment are chosen. If a DCT or DCV system is used, special loading equipment is also added in this part of the model. The same optimization model is used as described in Section 5.2.2. Each possible transport and sorting equipment is given as a decision variable. This results in 27 different decision variables of which one is chosen.

5.4 Data visualization

The end result of the model has to be visualized. How the visualization will be done is already discussed in Chapter 3. In total three visualization methods will be made: a graph representation, a 3D model and a table representation. How each visualization will be presented by the model will be discussed separately.

To show the link between different trade-offs, graphs will be made. The model can do only one trade-off combination at a time. So in order to make the graphs, multiple runs have to be made. The graphs are made by running the model for 2 trade-off combinations at a time. For example, if the CAPEX and energy consumption are chosen, the α and β variables are changed between 0 and 1.0. This will give a graph with 11 measurement points. The graphs will be made using Microsoft Excel. As this is a time consuming process, only the graphs regarding the CAPEX and each of the three other trade-offs will be developed, resulting in three graphs in total.

As the model is made in Autodesk Revit, a 3D model is the direct output given by the program. Before making a model, a standard color coding should be applied to the subsystems. Which colors are applied to each subsystem are given in Table 5.5.

Table 5.5: The colors used in the 3D model for each subsystem

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	

After the model is run, Revit presents a 3D model consisting of blocks which are color correctly and a table in Microsoft Excel. The blocks will represent the space reservation of each equipment unit. This means that the entire block is not only the equipment unit, but also any additions which are needed. Two examples of the blocks are given in Figure 5.4. It can be seen that the block used for HBS level 1 also includes additional transport equipment which is needed to process the information gather inside the equipment and maintenance and service area. For the make-up chutes, roads are located on two sides of the chute together with a loading area for the carts. If ALT is used, the roads are not includes in the blocks. The example table given in Table 3.1 will be developed by the model in Excel. Information on each subsystem will be given together with a summary of the entire BHS.

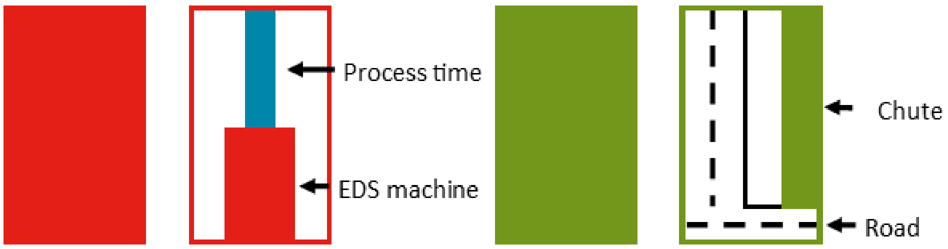


Figure 5.4: A graphical representation of what is inside the 3D space reservation blocks

5.5 Summary

In this chapter a start is made to answer the question *"How can the conceptual design stage of BHS be automated using a model?"*. By combining the information from Chapter 2, 3 and 4, two design models are developed. The first model is made using the Gordian placement model. This model starts by placing each subsystem as a coordinate, then choose equipment for it and finally perform a detailed placement which introduces the size of each subsystem and the shape of the terminal. The second model is based on the droplet search and starts by introducing the shape of the terminal. Thereafter, the ground equipment is chosen, followed by placing each piece of equipment in the terminal using the droplet search. Finally, the transportation and sorting equipment are chosen.

Both models are based on the model of Van Noort (2018) but are adjusted to gain a more accurate result. The models are different to the model by Van Noort (2018) in three ways. First, the equipment choice is no longer based on a trade-off between CAPEX and system area, but between CAPEX, energy consumption, number of operators and LoA. The system area is included into the CAPEX trade-off. Second, the model by Van Noort only works for rectangular shapes and plots rectangular boxes for the sub systems. Both new models can handle complex shapes and the shape of the sub systems is also no longer rectangular. The availability of multiple levels has been introduced by the new models and the placement now not only includes adjacency rules, but also keeps in mind routing.

Both models have been developed keeping the design framework defined in Chapter 2 in mind. However, both models add an extra step to the framework. This is caused by the relation a BHS development has between the equipment calculations and the facility sizing. The transport equipment connects each subsystem to the next. However, when choosing the equipment types, the placement of the equipment has not been performed. The transport equipment can therefore not be chosen before all other sub systems are chosen. This causes both proposed models to add an extra step. The Gordian model adds an extra step before making the equipment calculations and the droplet model adds a secondary equipment calculations and optimization step at the end. It is expected that this will have impact on the final outcome, but this will become clear after the model has been devloped.

Chapter 6

Model testing

With the models defined and developed, they have to be tested to determine if the models behave as expected. In this chapter and Chapter 7, three airports will be used to apply the model to: New Mexico City International Airport (NAICM), Hamad International Airport (DOH) and Queen Beatrix International Airport (AUA). These three airports will be first introduced in Paragraph 6.1. Thereafter, the Gordian placement and droplet placement are tested in Paragraph 6.2 and 6.3 respectively. Based on these two paragraphs a placement model for BHS applications is chosen and the entire model can be tested. This testing will be done in Paragraph 6.4 and will tell if the model behaves as expected. This chapter will answer the question: *How can the conceptual design stage of BHS be automated using a model?*. Paragraph 6.5 will provide the answer to this question. Unless stated otherwise, the data in this chapter is retrieved from documents and engineers of NACO.

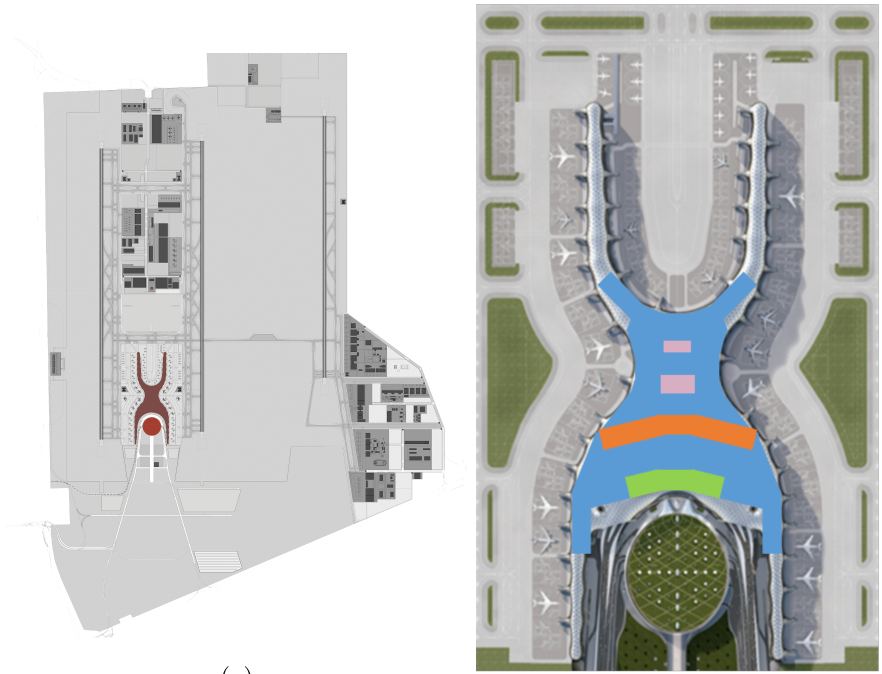
6.1 Airports

To validate the model, data from three different airports will be used. Each airport is different in size and serves different purposes. First, the largest of the three airports is discussed, NAICM. When constructed, this airport will be one of the largest airports globally. Next, DOH is discussed which is about half the passenger size of NAICM. At last, AUA is discussed, which is small compared to the other two airports. However, due to the high amount of O&D passengers this is an interesting case.

6.1.1 New Mexico City International Airport

NAICM is planned to be the new airport serving Mexico's capital city and replace the current airport Benito Juárez International Airport (Grupo Aeroportuario de la Ciudad de México, 2018). Currently under construction, NAICM is planned to have a capacity of 70.000.000 passengers annually when operation starts in October 2020. The airport has space reserved to eventually handle a capacity of 125 million passenger annually. When operational it will be the busiest airport in Latin America, taking this status from the current Mexico City Airport. Figure 6.1a shows the airport layout of NAICM. The rounded X-shaped terminal consists of 5 levels and has 96 gates. Around 60% of the flights are done by NB aircraft, 35% by RJ and the remaining 5% by WB aircraft. Around 80% of the bags in the peak hour are from O&D passengers and 20% from transfer passengers.

Figure 6.1b shows the area were the BHS can be installed. This area has a width of 500 meter and a length of 800 meter and follows the curves of the terminal. The airside apron and reclaim arrival hall is located on the first level. The check-in hall is located on the fourth level. International transfer passengers have to collect their bag at a reclaim belt and check it in before heading to their next flight. This adds an extra input and output point for the BHS. The transfer check-in area is located on the first floor and the transfer reclaim area on the second floor.



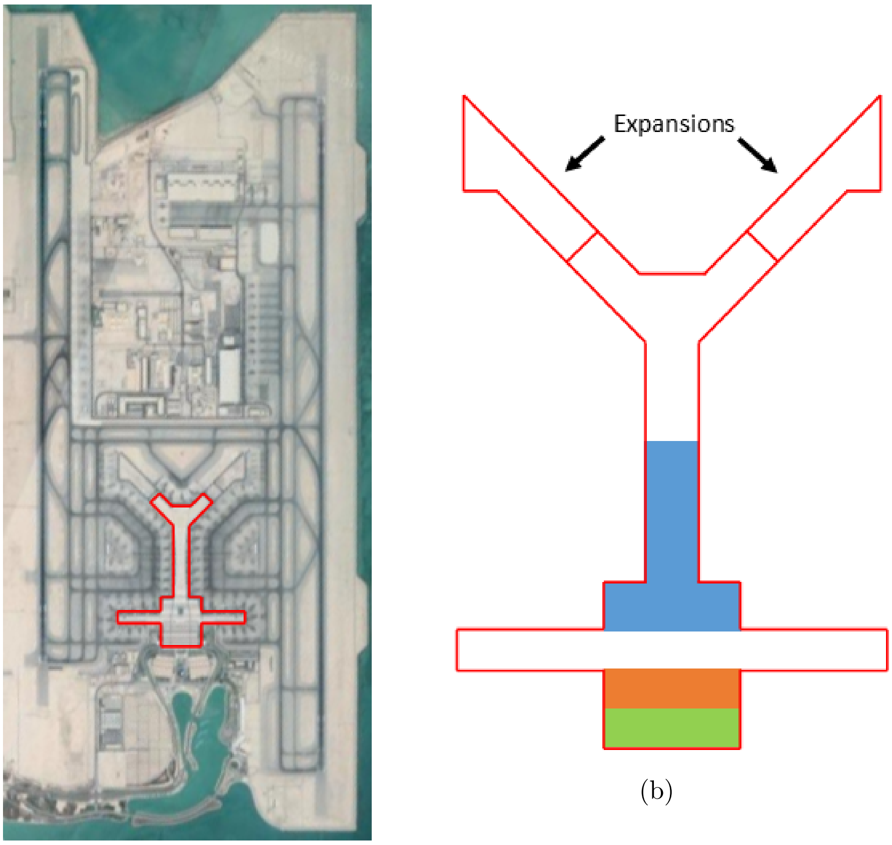
(a) (b)

Figure 6.1: The airport layout of NAICM (a) and the areas dedicated for the BHS (b) were blue is the available space and the green, orange and represent the check-in ,reclaim and transfer areas respectively (Grupo Aeroportuario de la Ciudad de México, 2018)

6.1.2 Hamad International Airport

DOH is the main airport of Doha, Qatar's capital, since 2014 (HIA, 2018). The airport is located on the edge of the city and partially on reclaimed land. Currently the airport sees around 35 million passengers annually and plans to host 50 million passengers in 2022 when the FIFA World Cup is in Qatar. To reach this capacity the terminal will be expanded. Figure 6.2a shows the airport layout of DOH. The terminal is Y-shaped with 5 levels and has 41 gates, of which 6 are specially made for the Airbus A380. Except for the connecting route between the check-in and the BHS system, all sub systems are placed on two floors. Due to the location of Doha, the airport is mainly used as a hub airport between the continents. That is why almost 80% of the passengers at DOH are transfer passenger. Due to the airport functioning as intercontinental hub, the percentage of WB aircraft is high compared to NAICM. 50% of the flights is handled by WB aircraft and the remaining 50% by NB aircraft, so no RJ.

Figure 6.2b shows the area designated for the BHS. The area consist of 2 rectangles. The top rectangular has a width of 60 meters and a length of 300 meters. The bottom rectangular has a width of 200 meters and a length of 100 meters. The first level is home to the airside apron and hosts the arrival reclaim area. The check-in hall is located on the fourth level. Although check-in and reclaim are on separate levels, all BHS equipment is located on the first floor. Only the transport equipment which connects the reclaim belt and check-in desks to the BHS are not located on this floor. It is therefore chosen to only include two floors in the placement model. The baggage of transfer passengers is loaded directly into the BHS so no additional input and output points are present.



(a) (b)

Figure 6.2: The airport layout of DOH (a) and the areas dedicated for the BHS (b) were blue is the available space, green the check-in hall and orange the reclaim area (Google, 2018; HIA, 2018)

6.1.3 Queen Beatrix International Airport

AUA is the main and only airport on the Caribbean island of Aruba (Aruba Airport Authority N.V., 2018). As part of a terminal expansion, a new BHS is installed. This is therefore a greenfield project where a complete new BHS building is designed. This new building is highlighted in Figure 6.3. Currently, AUA seen around 2.5 million passengers annually of which around 70% arrives from the USA and 15% from Latin America. The airport has 8 gates, 10 after the expansion, in a linear layout. As AUA is a holiday destination, the amount of transfer passengers is low and no information is given on how large this number is. Around 75% of all aircraft landing at the airport are NB and around 22% RJ. The remaining 3% are WB which are mostly the flights to Europe.

In the new BHS building all BHS processes will take place with exception of the offloading of the O&D baggage. The area is 90 by 45 meters and consists of 2 floors. Both the airside apron and the check-in hall are located on the ground floor. AUA offers US CBP services, which means that individual storage is required. The arrival pattern at AUA changes over the day. In most hotels on the island, customer need to check-out around 11:00. After 11:00 most people therefore go to the airport, regardless of their departure time. This causes a large peak demand around this time.

Table 6.1 shows the dimensional data of each airport.

Figure 6.3: The new terminal layout of AUA with the new BHS building highlighted in red

Table 6.1: The different airports used for the validation of the model (Grupo Aeroportuario de la Ciudad de México, 2018; HIA, 2018; Aruba Airport Authority N.V., 2018)

Airport	Annual PAX	Area length [m]	Area width [m]	Levels
NAICM*	70.000.000	800	500	5
DOH	35.270.410	400	200	2
AUA	2.504.224	45	90	2

*Under construction

6.2 Gordian placement

To test the Gordian placement, it will be applied to AUA and DOH and see how close the Gordian placement gets to the actual design. To demonstrate the model, AUA will be used as a leading example. For DOH, only the output will be shown.

The first step of the Gordian placement is to define the pins of the terminal. The area of the terminal has a width of 90 meters and a length of 45 meters. As reclaim is excluded from the building, only two pins remain. These are the check-in and aircraft. The entire system at AUA is centralized so for both the check-in and aircraft only one pins is used. The check-in is located at the bottom left of the building, around a length of 10 meters. The aircraft are located at the top of the building. For this a central pin is made at the middle point of the top. Figure 6.4 shows the location of the pins for both AUA and DOH. For DOH, the reclaim is also left out as this is seen as a completely separate system.

With the pins defined, the optimization can start. First, each subsystem must be assigned two decision variables: a x and a y-coordinate. The x and y coordinates are combined in two vectors which are shown in Equation 6.1.

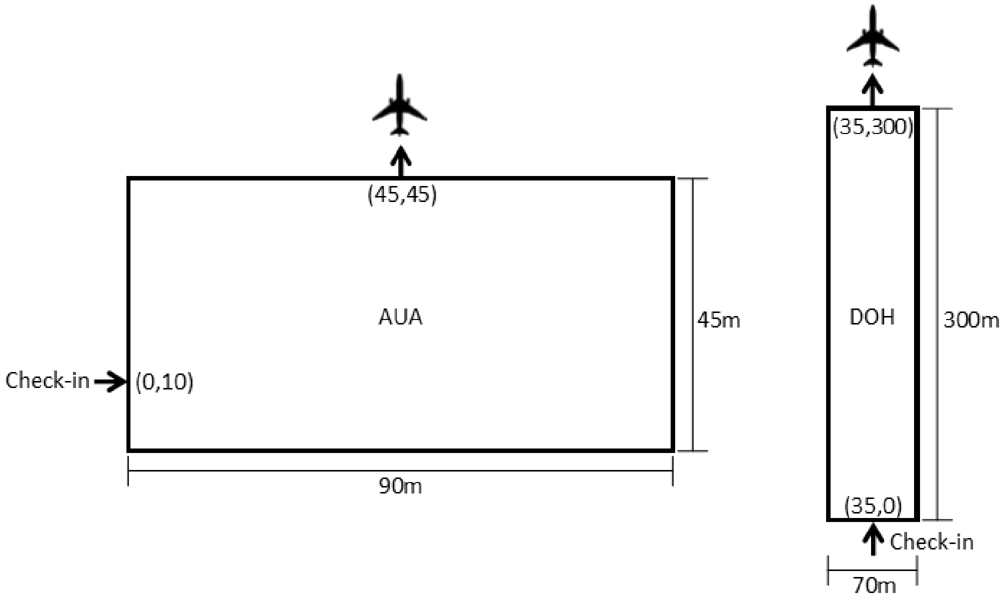


Figure 6.4: The placement of the fixed pins for both AUA and DOH

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} = \begin{bmatrix} x_{HBS1} \\ x_{HBS2} \\ x_{HBS3} \\ x_{MU} \\ x_{OT} \\ x_{EBS} \end{bmatrix} \qquad y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \end{bmatrix} = \begin{bmatrix} y_{HBS1} \\ y_{HBS2} \\ y_{HBS3} \\ y_{MU} \\ y_{OT} \\ y_{EBS} \end{bmatrix} \tag{6.1}$$

Next, the Laplacian C matrix is defined. The matrix is based on the adjacency matrix A and the pin connection matrix P which need the weight of each route between the nodes. The weight is determined using the flight schedule converter. How the converter works can be found in Chapter 7. The flight schedule of AUA does not have any transfer passenger, however, a transfer quay is present. The demand value of the is therefore set at a value of 10 so the model does include the quay. The P matrix in combination with the coordinates of the pins are also used to determine the d_x and d_y vectors. Equation 6.2 shows how the C matrix and the d_x and d_y vectors for AUA.

$$C = \begin{bmatrix} 4936 & -642 & 0 & 0 & -10 & -1716 \\ -642 & 1284 & -321 & -321 & 0 & 0 \\ 0 & -321 & 642 & -321 & 0 & 0 \\ 0 & -321 & -321 & 4926 & 0 & -1716 \\ -10 & 0 & 0 & 0 & 20 & 0 \\ -1716 & 0 & 0 & -1716 & 0 & 3432 \end{bmatrix} d_x = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 115560 \\ 450 \\ 0 \end{bmatrix} d_y = \begin{bmatrix} 25680 \\ 0 \\ 0 \\ 115560 \\ 450 \\ 0 \end{bmatrix} \tag{6.2}$$

The next step is to define the objective function for the optimization model. The objective function is made using Equation 2.13. A QP model is developed using integer decision variables for the x and y coordinates. The result for AUA is given in Figure 6.5. It is visible that all sub systems are placed at (0,0). As this is not the desired solution, constraints are added to the model. These constraint state that the average of the x and y coordinates equals the center of the building. The result of this

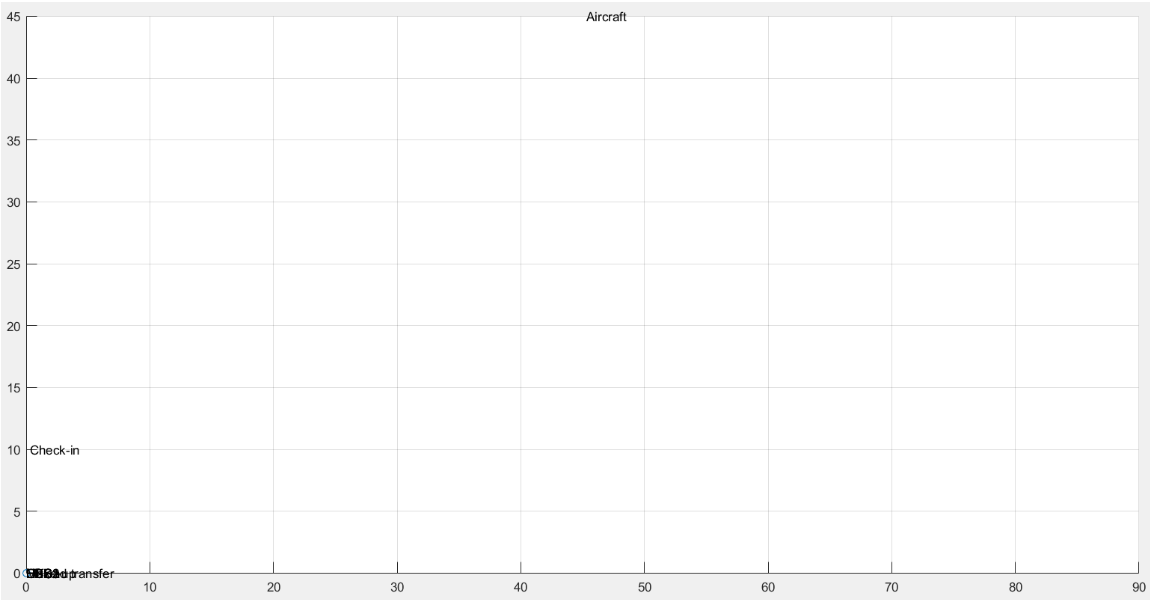


Figure 6.5: The Gordian placement applied to AUA with no constraints

problem is given in Figure 6.6. Now, all subsystem are divided over the central x-axis. Again, the placement does not deliver a desirable solution. Also, changing the pin coordinates of the system does not change the placement as expected. If for example the check-in is moved to the other side of the building, all sub systems remain at (0,0). The model therefore seems unapplicable for AUA.

If the model is applied to DOH, similar results occur. Without any constraints, all sub systems are plotted at (0,0). When adding the center constraints, still no feasible solution is given. The reason why this happens can be found in the objective function. Each section of the objective function for the x and y coordinates looks as a sum of the following: $A * x_i * (...)$, where A is a constant. This means that if the objective function is minimized, the optimal solution would be (0,0) for each node. The reason why this happens probably has to do with the lack of connections and pins within the system. Only the make-up node is connected to many different nodes and the two pins in the system only connect a few other nodes. Plotting everything at the origin is therefore the optimal solution in this case. With this data it is concluded that the Gordian model in this configuration is not valid for BHS placement and the detailed placement model is not developed.

6.3 Droplet placement

To test the droplet placement, the same validation is done as for the Gordian placement. With equal equipment numbers, the placement is performed on both AUA and DOH. Again, AUA is used as the leading example. The droplet model starts by introducing the shape blocks. At AUA, the bottom right section of the ground level cannot be used by the BHS. This block has a width of 40 meters and has a length of 10 meters. At DOH, no shape blocks are needed.

The next step is to define the placement sequence to be performed. For AUA first, the EDS machines (HBS level 1) and make-up are placed as close to the check-in and aircraft respectively. To reserve space for the transport equipment, a route between the EDS and make-up systems should be made. Next, between the two subsystems, the EBS and offloading transfer quays should be positioned respectively. At last, the last two HBS levels can be placed.

With the placement sequence defined, the model can be applied to the airport. Due to confidentiality,

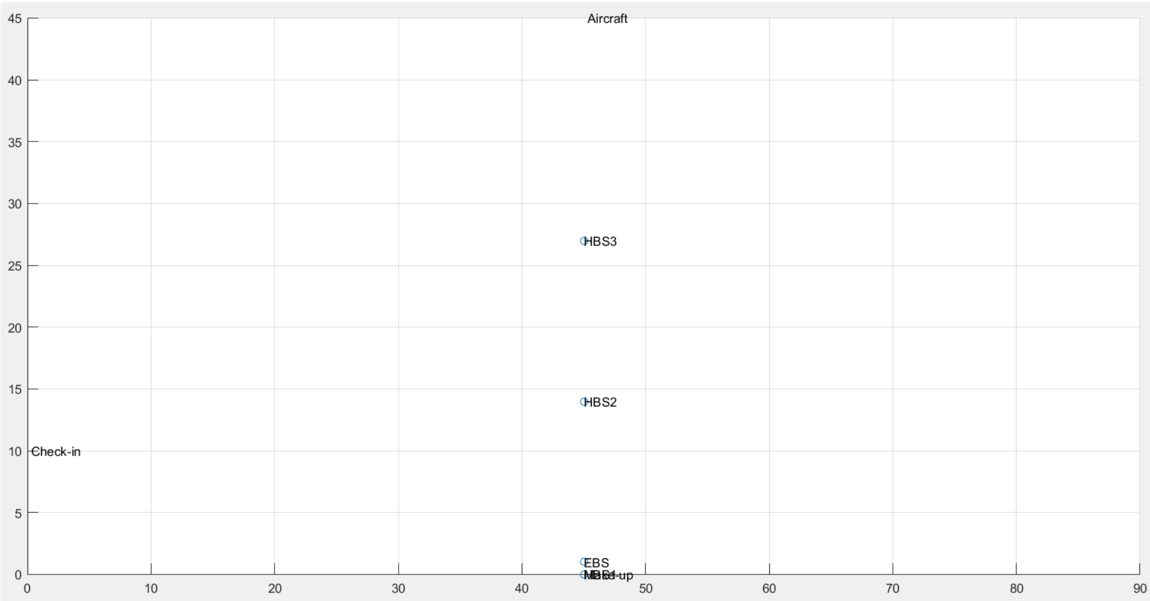


Figure 6.6: The Gordian placement applied to AUA constrained around the center of the building

the actual floorplans of the airports cannot be given. The result of the droplet placement for AUA can be seen in Figure 6.7. Most of the equipment is placed on the ground level. Only the EBS is placed on the second floor. Comparing the outcome of the placement to the actual design of AUA, similarities can be found. Only the OSR and CBRA stations (HBS level 2 and 3) are in the actual design on the second floor. The main purpose of the placement model is to define the space reservation for the BHS. As this space reservation is accurate for the CBRA, the model can be seen as valid for AUA. Also, the blocks of the model can easily be moved manually, so a correct location can given to the blocks . The model also plots the make-up loop above the make-up area and shows the sorting equipment. However, to keep the model more clear, these are not shown in Figure 6.7.

Figure 6.7: The floorplan for AUA given by the droplet placement seen from above, for the color coding see Table 5.5

The same conclusion as for AUA can be given for DOH. The blocks have the right dimensions and are located at a feasible location. And if needed, the blocks can be moved manually. It is therefore concluded that the droplet model is able to develop a feasible BHs concept design.

A downside to the droplet placement is that it is rather slow compared to the Gordian placement. Were solving the QP problem of the Gordian placement takes a few seconds, the droplet placement can take hours. The AUA example is performed in roughly 5 minutes. The DOH example, however, takes roughly two hours. As shown before, the Gordian placement model does not perform as excepted. It is therefore chosen to use the droplet model to generate BHS designs.

6.4 Test cases

To validate the entire model, a few test cases are developed to test if the model acts as expected. First, the equipment calculations are tested. Due to redundancy, if the demand of a system is zero, still one piece of the equipment needs to be determined by the model. When running the model for zero demand, all equipment number equal one. Again due to redundancy, if the demand of a subsystem is below the capacity of an equipment type, still two of the units should be determined by the model. When running the model for a demand of 1 bag, every subsystem has two pieces of equipment. The models equipment calculations can therefore be seen as valid.

To test the optimization part of the model, several tests are developed. The first test is done on the volume price. Two equipment choices are added for a sub system, one of 10 m^3 costing €1000000, and one of 1000m^3 costing €100000. The model should always choose two larger cheaper option if the volume price is below 909 €1/m^3. When running the model, until 909 €1/m^3, the cheaper option is chosen. From 910 €1/m^3 the more expensive option is chosen. This means that the option to add value to the space of a BHS is working in the model. Similar test have been performed on the equipment optimization and in all tests the model behaved as expected. These test include the IST constraint and testing each trade-offs. It is therefore concluded that the equipment choice of the model works as desired and can be seen as valid.

To test the placement model, two test cases are developed. First, several equipment units are placed on a floor which has a grid of columns on it. The model should plot the blocks around the columns and should not overlap. Figure 6.8 shows the result of the test when applied in the model on the left. As is visible, the model plots the equipment around the columns. The second test introduces an uneven border to the side of the terminal area. If the equipment is placed on the edge of the terminal, it should follow the uneven curve. The result of the test case is shown in Figure 6.8b.

Figure 6.8: Two test cases used to validate the placement model, for the color coding see Table 5.5

Next, a test case is developed in which each subsystem has to be placed on a different floor. This means that the size of each subsystem is more then half of each floor. Figure 6.9 shows the result of the test case. As expected, each sub system is placed on an individual floor. Also, for each floor a lift is present which goes the bounding levels. The lifts between two floors are also located in the same positions. So, the model is able to incorporate the availability of multiple levels. In the figure it is also shown that the model is in 3D. From the side view it is visible that the subsystems are of different height and never exceed the top height, which equals the lifting equipment.

It can be concluded that all parts of the model behave as expected. The optimization part works as desired and the placement is able to handle the shape, size and floors of the terminal. The model is therefore ready to be validated by doing several case studies.

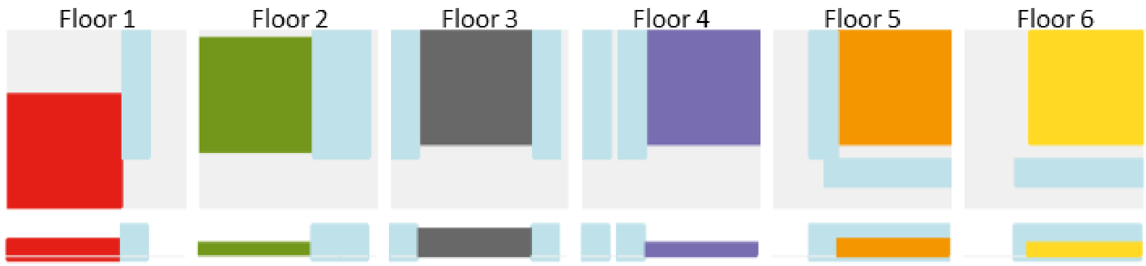


Figure 6.9: The floorspace test case with a top (top part) and front (bottom part) view of the 3D model, for the color coding see Table 5.5

6.5 Summary

This chapter answered the question *"How can the conceptual design stage of BHS be automated using a model?"*. Both the Gordian and droplet model have been applied for BHS applications. As expected, the Gordian placement model turned out to deliver an unusual solutions for the BHS design. This was due to the fact that the optimal solution was always to plot every system at the origin. The droplet model proved to deliver a more desirable solution. The model behaves as expected and delivers a floorplan similar to that of the engineers. It is able to include the stakeholders desires and cope with the terminal layout.

It is therefore concluded that the model is able to developed a design solution keeping in mind the stakeholders desires and terminal layout. As a definition of an optimal BHS is lacking however, it cannot be said that the given solution is the optimal solution. In the next chapter, the validity of the model will be tested.

Chapter 7

Case study

With the model developed and tested, it can be applied and validated against the airports introduced in Section 6.1. Before doing this, the definition of a valid solution should be defined, which will be done in Paragraph 7.1. Next the system demand and first equipment calculations of the model are applied to the different airports in Paragraph 7.2. For each airport the outcome of the model is compared to the final design of the specific BHS. As some data is too large to show in this section, each airport has an Appendix dedicated to them. These are Appendix C for AUA, Appendix D for DOH and Appendix E for NAICM. Next, In Paragraph 7.3, the outcome of the model is shown for each airport, showing the different types of visualization methods discussed in Chapter 3. To show the possibilities of the design model, Paragraph 7.4 will discuss two different material handling applications for the model. These examples will show that the idea behind the model is not only applicable to BHS. This chapter will answer two questions. The first part answers the question: This will answer the question: *"How does the outcome of the model compare to the manually developed conceptual BHS design of different airports?"*. The last part will answer the question: *"To which extend can the concept behind the model be applied to other material handling systems?"*. Paragraph 7.5 will provide the answer to these questions.

7.1 Model validation

The CAPEX is the most important trade-off of the BHS. Therefore, defining an accuracy of the model for the CAPEX is important. As stated before, fully validating the model is impossible. However, if the model gets a CAPEX close to the eventual CAPEX, it can already be of high value to the engineers using it. A research into CAPEX accuracy is therefore performed to see if the model develops a valid solution.

As shown in Figure 7.1 as the maturity of a project grows, so does the accuracy of the CAPEX. As the conceptual design phase is in the early phase of the project, the accuracy of the CAPEX is still low. Christensen and Dysert (2011) provide accuracy ranges based on the maturity of the project which are given in Table 7.1. The output of the concept design is the very first step in the design stage. It therefore falls into the fifth category. The accuracy range of the fifth class is very wide and can be between -50% and +100%. However, for the model a tighter range is chosen. The range chosen is a 40% limit in both directions.

The exact CAPEX values of each airport and equipment type is usually confidential information. It is therefore chosen not to provide the actual CAPEX value of the BHS and only show the total CAPEX defined by the model. The equipment numbers shown in the next chapter do match the initial number defined for the airports. However, the numbers given here are the numbers defined during the conceptual design stage. This means that the final BHS design different equipment numbers can be found.

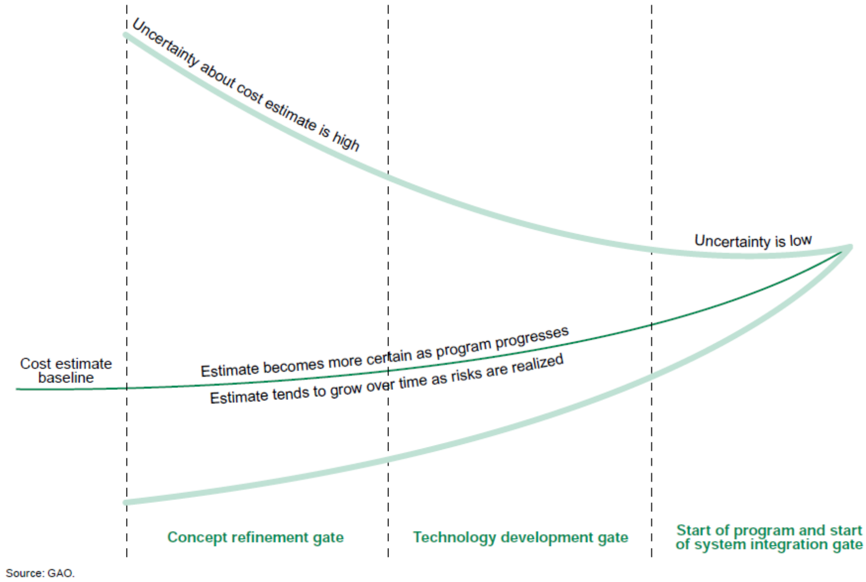


Figure 7.1: The project cost cone of uncertainty (Leonard, 2009)

Table 7.1: CAPEX estimate accuracy range for both the lower and higher limit (Christensen & Dysert, 2011)

Estimate class	Completion of the project [%]	Accuracy range
Class 5	0% to 2%	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	L: -3% to -10% H: +3% to +15%

During the case studies, the values given by the model will be compared to the values determined by engineers. It is not said that the design determined by the engineers is the optimal solutions, so if the model deviates from this it is not necessarily invalid. However, the design by the engineers have proven to create working BHS solutions. If the model therefore creates similar outcomes, it can be seen as a feasible solution.

7.2 Airport application

As stated before, the design process for material handling systems consist of four parts: the system capacity calculations, the equipment calculations, the equipment optimization and the facility sizing. The model developed follows this framework roughly, however, a second equipment optimization is performed after the facility sizing. First, the system capacity will be determined by converting the flight schedule. Thereafter, the ground equipment calculations together with the optimization is performed. Next, the facility sizing is performed by placing the subsystems in the terminal. This will then be used to perform the final part of the equipment optimization. Each stage will be discussed separately. The same sequence will be followed for the other airports.

7.2.1 System capacity

The model starts by converting the flight schedule to a standardized form. The flight schedule of AUA is different to other in two ways. First, the schedule is only for departing flight. The reclaim section of AUA, however, will not be included into the building. This will therefore cause no problem for the end result. The second deviation is that the flight schedule is given in bags per flight, and not passengers. This means that no airline bag ratio is needed, which can be seen in Table 7.2. Figure 7.2 and 7.3 show the passenger arrival distribution and MUP reservation used for AUA respectively.

Table 7.2: The airline bag ratio used for AUA

Airline	O&D	Transfer
Other	1.0	1.0

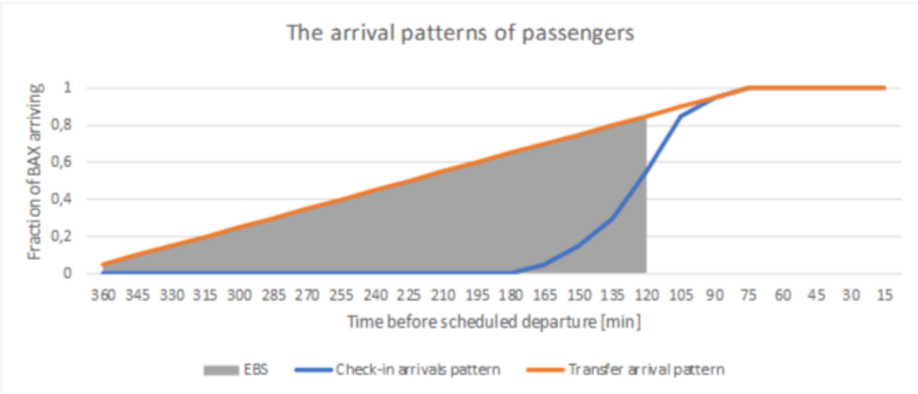


Figure 7.2: The passenger arrival distribution used for AUA

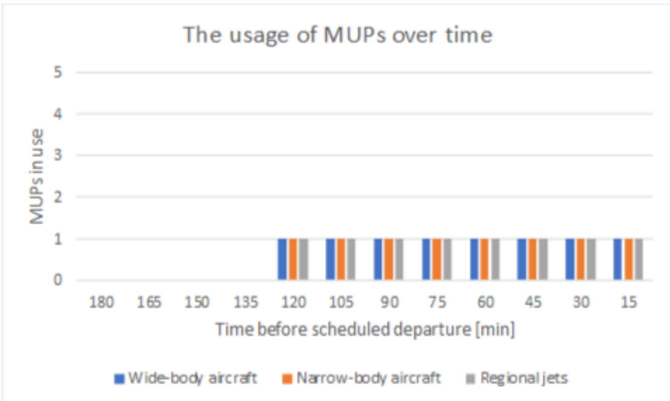


Figure 7.3: The MUP reservation for AUA per aircraft type

The flight schedules for DOH and NAICM do need a bag to passenger ratio. As the reclaim section of the BHS is a complete separate part of the BHS, they will also excluded for these airports. The data used for these airport can be found in their appendices.

Converting the flight schedule of each airport results in the important capacity data. Table 7.3 shows the result of the conversion for each airport. Besides this data, five graphs are made for each airport showing the daily change in demand. These graphs can be found in the appendices. From this data the main focus of each airport is clearly visible. AUA is an airport O&D airport with a large check-in peak. This is also visible in the demand graphs were there is one peak in the day defining the systems capacity needs. As a hub airport, DOH mainly handles transfer passengers and therefore has a high transfer peak and a low check-in peak. The check-in peak at DOH is even smaller then that of AUA which serves 17 times less passengers. The hub function of DOH can also be seen in the MUP demand which clearly shows the wave pattern usually found at large hub airports (de Neufville & Odoni, 2013). NAICM is a large airport serving similar transfer and check-in peaks. This can also be seen in the graphs were the data is more evenly distributed over the day then for example DOH.

Table 7.3: The peak hour demand calculated by the model for each airport in bags per hour, the make-up peak is given in the amount of MUP required

Demand value	AUA	DOH	NAICM
Check-in	2568	1320	5136
Screening	2568	12732	8236
Sorting	2568	4788	7172
Make-up	26	262	350
Transfer arrival	0	11812	4624
Trains inside	14	26	34
Trains outside	17	78	129
EBS size	1716	3752	2124

7.2.2 Equipment optimization and facility sizing

With the system capacity calculated, the ground equipment calculations and optimization can be performed. In this step, the data calculated by the engineers can be compared to that of the model. This is done in Table 7.4, were for each airport (1) represents the value defined by the engineers, (2) the value given by the model and (3) the difference between the two. The optimization has not been performed so the data shown here for the model is retrieved from the data calculations. As already stated in Chapter 6, if the model finds a different value then the engineers this does not mean that the model is invalid.

Table 7.4: The equipment number for each airport, where row 1 represents the values defined by the engineers, row 2 the value defined by the model and row 3 the difference between the two values. A "-" means that the data is not available.

	AUA			DOH			NAICM		
Subsystem	1	2	3	1	2	3	1	2	3
Check-in	66	86	+ 30.3%	96	44	- 54.2%	206	172	- 16.5%
HBS level 1	4	4	± 0%	17	19	+ 11.8%	14	7	- 50%
HBS level 2	4	4	± 0%	-	32	-	21	13	- 38.1%
HBS level 3	31	33	+ 6.5%	-	32	-	15	21	+ 40%
Make-up	26	26	± 0%	22	22	± 0%	38	29	- 23.7%
EBS positions	1200	1716	+ 43%	1400	3752	+ 168%	2000	2124	+ 6.2%
Offload transfer	1	1	± 0%	10	14	+ 40%	6	6	± 0%

For AUA, most data is in accordance with that of the engineers. Only the check-in and EBS data is different. The difference in both peaks is probably caused because the engineers used different arrival patterns over the day. During the day the arrival patterns at AUA changes, however, the model uses only a fixed one. The data can therefore be different.

Similar to AUA, for DOH the check-in and EBS data is different to that of the engineers. Already highlighted by Van Noort (2018), the check-in peak found by the model is of a day with low O&D

passengers. If the a flight schedule is used of a national holiday, the model calculates that 135 check-in desks are needed. This shows that the check-in peak is highly dependant on the day which is chosen. However, if check-in is left out and the 40% difference rule of Section 7.1 is applied, only the EBS is off. When DOH developed their BHS, it was not decided to have no dedicated EBS but to install 70 storage lanes. However stated by an engineer, the capacity these lanes reached are not enough. The model also indicates this statement as it suggests a larger EBS size.

Different to the other two airports, NAICM has large differences in the values defined by the model. The reason for this lies in the fact that the model considers a centralized BHS and the engineers calculated the BHS for a decentralized system. The actual system for NAICM consist of four separate sections each in a corner of the airport. This also means that each of these sections have to reach the redundancy requirements individually. A decentralized systems therefore usually requires more equipment. This is also the case when looking to what the models calculates and what the decentralized systems gives, except for the HBS level 3.

The next step in the model is to optimize the ground equipment. As not all equipment is chosen after this point, the exact equipment choice will be given after all equipment is chosen in the data visualization section.

With the ground equipment chosen, the facility sizing can start. For this a placement sequence should is defined. This placement is based on the main function of the airport. As an O&D airport, AUA starts with the HBS level 1 machines. As a hub airport, DOH starts with the offload transfer quays. After a sequence is defined for each airport, the droplet placement is performed. This will provide a 3D model and the important last data for the transport equipment. The transport equipment choice is then performed to end up with a concept design. The next step is the data visualization.

7.3 Data visualization

Now that the model has been performed on the three airport, the data can be visualized. As described in Chapter 3, three sets of output will be generated: a graph representation, 3D model and a table representation. Each airport will be discussed separately.

7.3.1 AUA

As the table and 3D model are a direct output of the model, these will be discussed first. Because Aruba is on an island, the cubic room price is higher then usual. A cubic price of 375 €/m^3 will therefore be used instead of 160 €/m^3. As transfer operations at AUA has no priority, the maximum IST is not important. This value is set at 15 minutes which is large compared to the size of the building. If the model is run for $\alpha = 1$, the minimum CAPEX solution is provided. By doing this, Table C.6 and Figure 7.4 are developed.

Figure 7.4: A top view of the 3D model developed when minimizing the CAPEX for AUA, for the color coding see Table 5.5

Comparing the result of the minimized CAPEX to the actual design of AUA (Figure 6.7) it can be seen that the model develops a system with a lower system area. This is mainly due to the fact that laterals are used instead of chutes. In Table 7.5 the total outcome of different trade-off are given. The 3D model developed for each of these solutions can be found in the Appendix.

Table 7.5: The outcome of different trade-offs for AUA, the check-in and reclaim data is included in these values

Trade-off	Min CAPEX	Min energy	Min Operators
CAPEX	8.487.870	11.203.520	23.872.920
System area [m^2]	58043	5867	6123,2
Energy consumption [kW h]	1373,4	1238,2	1475,8
Operators	64	79	37
Average LoA	4.73	4,40	5,55
Trade-off	Max Operators	Min LoA	Max LoA
CAPEX	10.096.00	10.989.000	17.095.320
System area [m^2]	8268,8	8268,8	5795,3
Energy consumption [kW h]	2010,2	2064,6	1530,8
Operators	166	166	40
Average LoA	4,1	4.00	6.0

The last data set provided are the 2D graphs. These graphs show the impact of the trade-offs compared to the CAPEX. 11 runs are performed to developed the graphs, ranging the two trade-offs between 1.0 and 0.0. Some trade-off combinations yield the same solution. The graphs therefore can have less then 11 measurement points. The first graph made is the relation between the CAPEX and the energy consumption and can be seen in Figure 7.5. It shows that the lower the energy consumption gets, the higher the CAPEX. This relationship was also expected. Usually, equipment with lower energy consumption have higher equipment costs. Only one measurement point does not follow this trend, which is the point with the highest CAPEX. This is actually the run when fully optimizing the energy consumption ($\beta = 1$). This can be explained by the way the model operates. Because the make-up loop is chosen after the placement, the length of the loop depends on the make-up system chosen. Chutes have the lowest energy consumption of all make-up equipment, however they result in the longest make-up loop. Between $\beta = 1$ and $\beta = 0.2$ laterals still outweigh chutes, however, below this point chutes are chosen. The increase in make-up loop results in a higher energy consumption for the transport sections. This increase is higher then the reduction caused by the make-up equipment.

Figure 7.6 shows the relation between CAPEX and the amount of operators. As the amount of operators can either be minimized or maximized, two sets of data are shown in the graph. It can be seen that when minimizing the amount of operators, the CAPEX goes up. This is as expected since equipment that needs less operators is usually also more expensive. What is interesting to see is that when maximizing the operators, the CAPEX remains relatively unchanged. Between $\gamma = 0.1$ and $\gamma = 0.9$, the same solution is always chosen. Only when fully optimizing the operators, the CAPEX increases due to a different type of transport system that is chosen.

Figure 7.7 shows the relation between the CAPEX and the average LoA of the system. Different to the operator graph, the LoA graph seems to follow a parabolic trend. Although lower level automation equipment cost less, the capacity of the equipment is also lower which results in a high amount of equipment needed. This explains why, even though the equipment is cheaper, the total CAPEX of the lowest automation levels are not the lowest values. High automation usually requires expensive machines. The graph therefore reaches a peak at the highest possible LoA. For the CAPEX, the optimum value for the LoA at AUA is between 4 and 5.

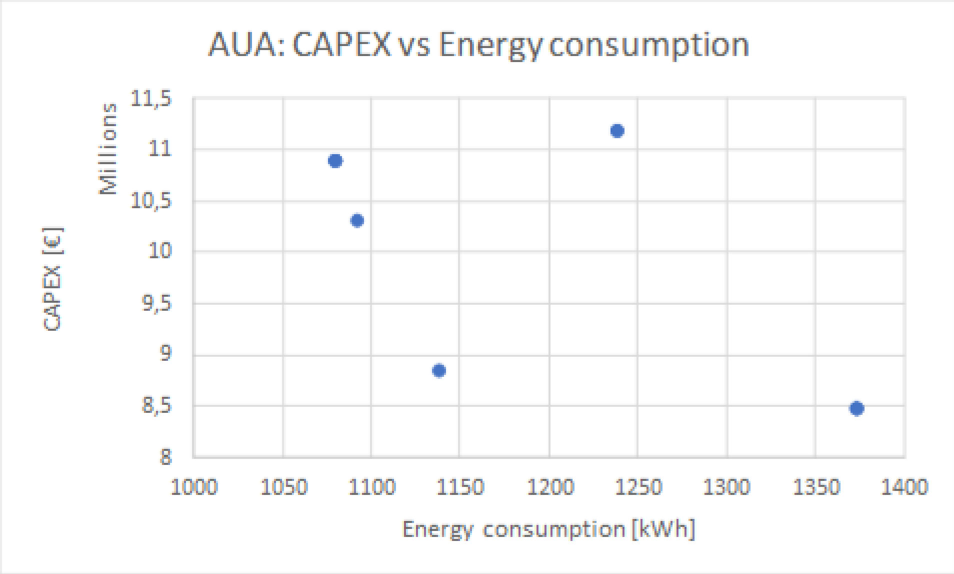


Figure 7.5: The relation between CAPEX and energy consumption for AUA

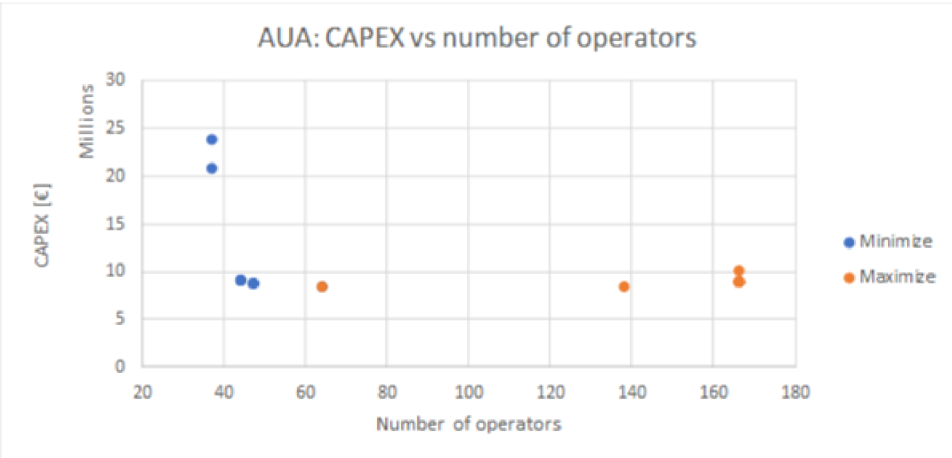


Figure 7.6: The relation between CAPEX and the amount of operators for AUA

The time it takes for each run depends on the size of airport. For AUA, the time it takes to run the model is short, around 5 minutes. However, for the remaining two airports, the time goes up significantly. It is therefore chosen to not develop the trade-off graphs for DOH and NAICM. Similar graphs as for AUA can be expected for these airports.

7.3.2 DOH

For DOH, the standard cubic room price is used. As the main focus of the airport is on transfers passengers, the IST boundary is important. The main airline, Qatar Airways, states to have a MCT of 45 minutes (Qatar Airways, 2019). As this includes the apron driving time, a maximum of 30 minutes is used for the model. In the appendix, the 3D model when minimizing the CAPEX and the table generated by this run are given. Comparing this model to the actual model, it can be seen that if a shuttle rack EBS was used, the EBS capacity was higher and less space was taken by the EBS.

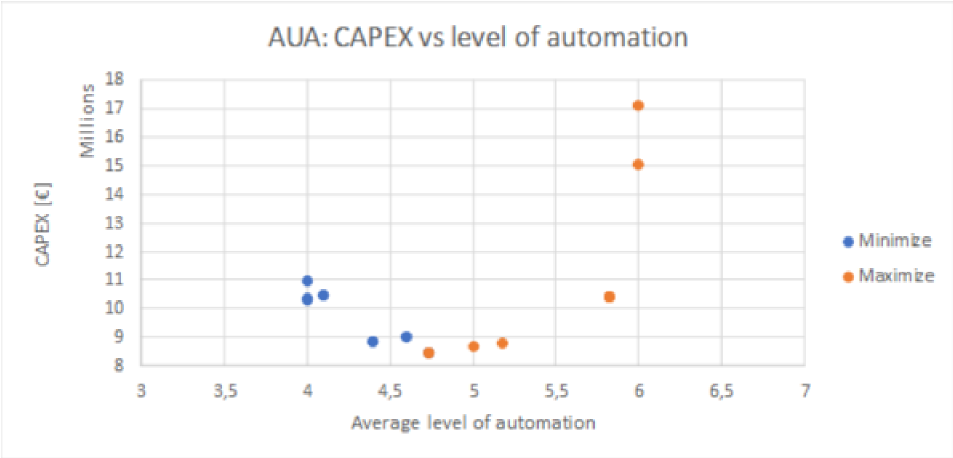


Figure 7.7: The relation between CAPEX and the level of automation for AUA

In Table 7.6, the data for DOH is given when fully optimizing one of the trade-offs. The 3D models of these runs can be found in the appendices. Interesting to see is the placement of the EBS. While in some configurations the EBS can be placed on the ground floor, other configurations place it on the second floor. This could be useful information for the stakeholders.

Table 7.6: The outcome of different trade-offs for DOH

Trade-off	Min CAPEX	Min energy	Min Operators
CAPEX	26.179.600	31.434.160	81.560.670
System area [m^2]	28208	28382	28194
Energy consumption [kW h]	5042,6	3801	5527,4
Operators	190	364	141
Average LoA	4,70	4,50	5,30
Trade-off	Max Operators	Min LoA	Max LoA
CAPEX	29.280.000	37.903.00	84.106.760
System area [m^2]	33794	33794	28118
Energy consumption [kW h]	5307,6	5870	6774,2
Operators	466	466	142
Average LoA	4,20	4.00	6.00

7.3.3 NAICM

Running the entire model for NAICM takes days. It is therefore chosen to run the model for one of the decentralized parts. Due to the integrate shape, the north western part is chosen. This part handles 30% of the entire system. This means that for the model, 30% of the values of Table 7.3 are used. The decentralized part is placed on one floor so the model will be on one floor. The available space is shown in the left part of Figure 7.8 has a width of 240 meters and a length of 220 meters. Accounting for the terminals shape, 21600 m^2 of area is available for the BHS. The right part of Figure 7.8 shows the model when run for the minimal CAPEX. Although the make-up look has been cut-off by the terminal shape, the correct value is used in the rest of the model. The table generated by this run can be found in the appendix. The table only shows the result for the decentralized system, not the entire BHS.

Table 7.7 shows the result when fully optimizing each of the trade-offs. The values here are adjusted

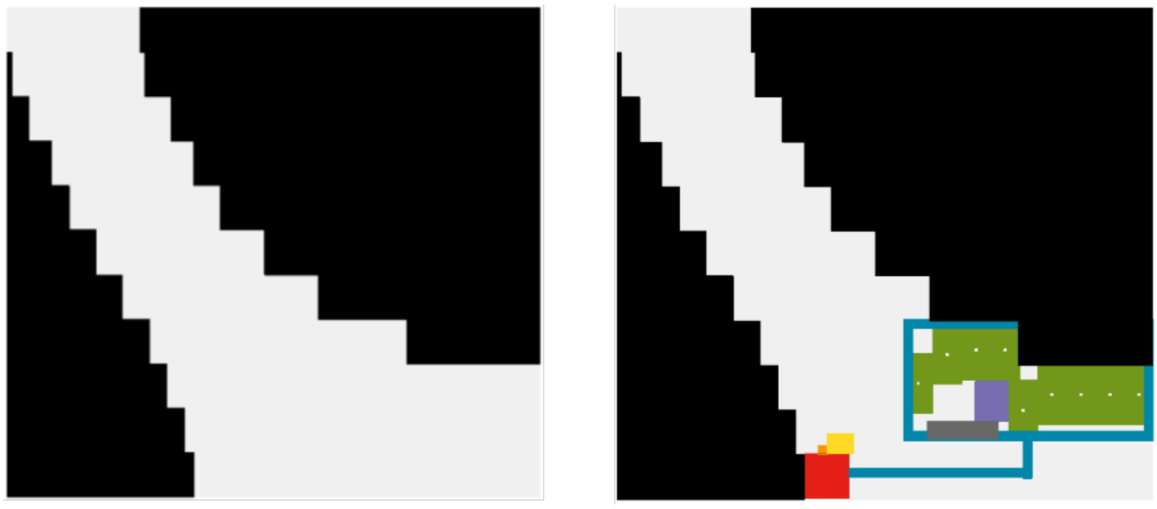


Figure 7.8: The available BHS area (gray) for north west part of NAICM (left) together with the outcome of the model when minimizing the CAPEX

to match the entire airport, meaning that the results of the run are seen as 30% of the total system. Also, since each decentralized part is connected to each other via transport equipment, 3 kilometer of transport equipment is added to the CAPEX and energy consumption. This 3 kilometer is based on twice (redundancy) the distance between all four parts.

Table 7.7: The outcome of different trade-offs for NAICM, the values have been adjusted to match the entire airport

Trade-off	Min CAPEX	Min energy	Min Operators
CAPEX	45.716.300	64.857.733	142.316.667
System area [m^2]	29480	32227	39477
Energy consumption [kW h]	15323	12557	17403
Operators	587	817	280
Average LoA	4,7	4,3	5,3
Trade-off	Max Operators	Min LoA	Max LoA
CAPEX	50.546.000	58.659.333	128.367.733
System area [m^2]	38423	38425	38890
Energy consumption [kW h]	14977	54423	20530
Operators	1007	1007	287
Average LoA	4,10	4,00	6.00

7.4 Other applications

The model has been based on a design framework developed for material handling systems, so not BHS in general. The concept behind the model is therefore applicable to other material handling systems. This paragraph will show two of these examples: one for a warehousing application and one for a container terminal. As the model has been adapted to BHS applications the examples are simplified and the model has been adjusted in some places. However, it will show the possibilities of the model when it comes to other material handling systems.

7.4.1 Warehousing

The warehousing and parcel industry show similarities to the BHS design. This is why most BHS equipment suppliers usually also develop equipment for the parcel and warehousing industry. The example here is of a simple warehouse. Three subsystems that are present in this example are: an infeed area (red), storage area (gray) and an outfeed area (green). The subsystems are connected to each other using transport equipment (blue). Instead of a flight schedule, the in and outbound of delivery vehicles can be used. This would give the capacity requirements of each subsystems. Next, the equipment parameters could be applied and a choice can be made.

The last step would be the placement if each subsystem. To demonstrate how the model does this, four examples runs have been done using the droplet placement model. Like the BHS examples, the fixed point should be defined. The infeed point of the model in all four models is fixed in the upper left corner. For all examples, the outfeed point is placed in each of the other four corners. The storage space is placed in the middle of the infeed and outfeed stations. The results of the four runs are visible in Figure 7.9.

Figure 7.9: Four examples of the droplet search used for warehouse design where the outfeed of the system changes (Red: infeed, gray: storage, green: outfeed, blue: transportation)

it can be seen that for each run, a different solution is found. The model finds a solution and the space reservation for the warehouse can be seen. Actual warehouses consist of more subsystems which can be added to the model. For the example shown here only minor adjustments had to be made to make the model functional.

7.4.2 Container terminal

A completely different material handling system then BHS are container terminals. At these terminals containers are unloaded from ships and stored until their loaded onto the next ship or vehicle. In this example, four different subsystems are the ship-to-shore cranes (red), gantry cranes (orange),storage (gray) and a truck bay (purple). Instead of a flight schedule the arrival data of container ships and trucks can be used. If more transportation modes are present at the terminal these should also be added to the model.

For this example the model is used to see the difference on the terminal space for two different storage orientations. The container are orientated perpendicular or parallel to the shore. If both orientations are run in the model, the left over space can be determined. Figure 7.10 shows the result of both runs. Here, the orange sections are space reserved for the gantry cranes tracks, meaning both sides of a storage lane have a dedicated set of tracks. From the two models it can be concluded that in the perpendicular run (left) 97.3% of the space is used and in the parallel run (right) 95.3%. This could help the stakeholders in their decision making when it comes to the operational decision making of the process.

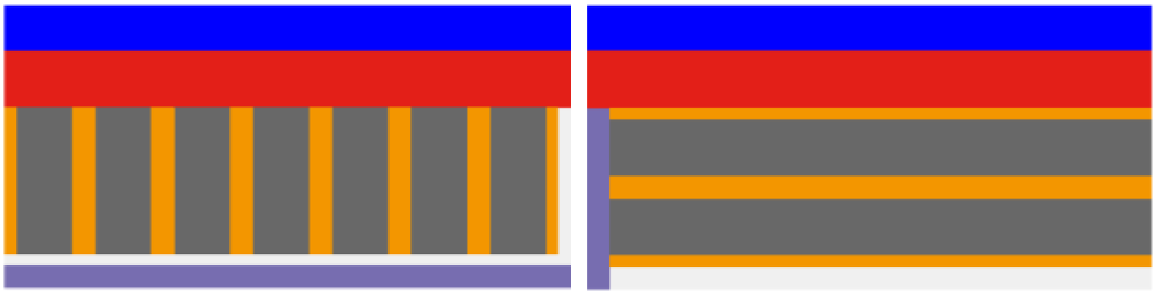


Figure 7.10: An example of the model used for container terminal design using perpendicular storage (left) and parallel storage (right) (blue: water, red: Ship-to-shore cranes, Orange: gantry tracks, gray: storage, purple: truck lanes)

In this example a container terminal is used, however, links can also be made between other port applications. Instead of a container terminal, a similar example can be made for bulk terminals. These examples, together with the warehousing example, are all aimed at aiding the stakeholders during master planning.

7.5 Summary

This chapter has answered two questions. The first question answered is: *"How does the outcome of the model compare to the manually developed conceptual BHS design of different airports?"*. To answer this question, the data from the equipment calculations is compared to that defined by engineers manually in Table 7.4. It can be seen that if the BHS is centralized, the model yields similar results. Only the check-in and EBS calculations are sometimes off. The difference in check-in desks has been explained by Van Noort (2018), which has to do with the flight schedule chosen. The difference in EBS can be explained by the fact that the calculations done by the model are highly simplified. The EBS is a complex system which depends on many factors. However, the model is able to provide a feasible conceptual design.

For decentralized systems, the model becomes less accurate. The model determines less equipment then a decentralized system. This can be explained by the redundancy. The model defines the equipment based on one redundancy requirement for the whole system. However, in a decentralized system, each part of the system has to meet the redundancy requirements. This usually results in a higher equipment count. So, the model is able to develop a valid BHS design if it comes to centralized systems. If a decentralized system is used the designers should expect higher equipment numbers then defined by the model.

Looking at the data visualization another downside of the model can be found. Because the model first chooses the ground equipment without any relation to the transport equipment, the effect of the size of the make-up is not taken into account. For example, chutes have the lowest energy consumption as they consume no power. This, however, results in the largest make-up area resulting in a large make-up loop. This could mean that if the make-up loop is a significant part of the entire transport system, the total energy consumption can become higher than when using other make-up equipment. This is usually the case at small airports like AUA. For large airports, however, this difference is less because the make-up loop length is only a small part of the total transport system

The second question answered in this chapter is: *"To which extend can the concept behind the model be applied to other material handling systems?"*. Although the model is not designed for other material handling systems, it is based on a design framework for material handling systems in general. Two examples are shown in which the facility sizing part of the model is applied to other material handling systems, as this is the only part of the model which is not specifically designed for BHS applications. In both examples, the model is used to show the effect of different design choices. It can therefore be said that for data visualization of design decision, the framework behind the model can be used for other material handling systems. This does mean that the other three parts of the framework have to be adjusted to handle these material handling systems.

Chapter 8

Conclusion

Now that all the sub questions are answered, the main research question can be answered. This will be done in Paragraph 8.1 by first summarizing the answers to the sub questions, and then answering the main research question. This will be done by first revisiting each chapter and finalize by answering the main research question. In the end, several recommendations will be done for further research possibilities and for NACO in Paragraph 8.2.

8.1 Main conclusion

This research started by researching the different design automation models found in literature. Although several models can be found (Nazzal & Bodner, 2003; Duchateau, 2016), the most important model found is that of (Van Noort, 2018). By combining all the literature a generalized design framework is developed for material handling systems which will be used as a basis for the BHS design model which consists of four steps. The first step is to define the system demand. For this the material supply data and operational requirements of the system needs to be known. In the second step for each possible equipment type the important data is calculated using the equipment parameters. The third step is to choose the equipment based on facility dimensions and stakeholder desires. Combining these two data sets define the optimal solution which can then be chosen by a BIP problem, based on the work of Ölvander et al. (2009) and Van Noort (2018).

The last step of the framework is the facility sizing. During this step, each subsystem is placed inside the facility based on reducing the routing distances between each subsystem. Previous research by Van Noort (2018) already suggested a placement model based on adjacency rules. However, adjacency rules are not enough, the capacity of each connection is more important. Therefore, further research was performed on different types of placement models, starting with VLSI placement models. From multiple VLSI models, the Gordian placement model was deemed to fit the BHS application best. However, VLSI placement reduces the routing distances based on the amount of connections a node has. As stated before, for facility sizing a placement model based on the capacity of each connection is needed. Therefore, a self-made placement model is introduced which is specially developed for the facility sizing step. This self-made model is named the droplet search and works by first finding the optimum location where a subsystem can be placed. If there is no place at this location, an algorithm searches for the closest possible location were there is space available. This search algorithm propagates through the area similar to a surface wave created when a droplet breaks a liquid surface, hence the name droplet search. When defining the placement sequence in which the subsystems are placed, the capacity of each connection can be used to determine which system is placed first.

The next step in the research was to define the desired output and how to visualize this. For this, first the important trade-offs were defined. Three main trade-offs are distinguished: the CAPEX, OPEX and LoA. The CAPEX shows the investment costs related to the BHS equipment. The OPEX shows the operational cost and is divided into the energy consumption in kWh and the amount of operators. For the LoA, seven levels are distinguished based on the work by Fasth et al. (2008) which represent the amount of human involvement into the equipment. Other trade-offs like redundancy and IST are also found. These trade-offs, however, can be introduced as input parameters and define the operational boundaries. To visualize the data, three sets of output are developed. The first output set will be a 3D model of the BHS layout. This model will show the design of the BHS. As the model is mainly for space reservation, representing everything in rectangular blocks is sufficient. To show what each subsystem is built of, a table is also given by the model which shows the data of each individual subsystem. At last, by combining multiple model runs, a 2D graph can be made showing the relation between each trade-off.

With the models framework and output defined, the next step in the research was to define the required input which is needed to develop a conceptual BHS design. In total, 38 input parameters are defined and a total of 38 equipment types are distinguished. These 38 equipment types combined give 62208 possible BHS designs.

With each section of the model defined, the actual model was developed and tested. Two models were developed, one using the Gordian placement model and one using the droplet search model. Both models are different to the generalized framework developed for material handling systems as they both add a step to the framework. The Gordian placement model has an extra step between the system demand and equipment calculations. In this step the Gordian placement is performed. The detailed placement is performed in the facility sizing step. For the droplet model, the transport and sorting equipment is separated from the equipment calculations and optimization. This has to do with the fact that the length of the transport equipment depends on the size of the make-up and the placement of each subsystem. The transport equipment calculations and optimization are therefore performed after the facility sizing. As the Gordian placement already defines the placement of subsystems before the equipment calculations, the transport length can be retrieved when calculating and optimizing the equipment.

To decide which model to use for the conceptual design phase, both placement models were tested. From this it became clear that the Gordian placement, as expected, gives an unusual outcome. All subsystems are placed in the origin. When looking into the reason for this it was found that the objective function developed by the Gordian models always has the origin as the optimal solution. This does not mean that the solution is not the optimal solution, however, the Gordian model in the developed form cannot be used for facility sizing. The droplet model does give a more desired outcome. When comparing the outcome of the model to the manually made BHS designs, similar design are made. The droplet model is therefore chosen to use as the placement model for the facility sizing. When testing the entire model for multiple test cases, it also behaved as expected.

With the model developed, it can be applied to different airports in several case studies. The case studies are performed on Queen Beatrix International Airport (AUA), Hamad International Airport (DOH) and the New Mexico City International Airport (NAICM). From the case studies it became clear that the model is able to develop feasible BHS design with similar results to that of the actual BHS designs implemented or developed for AUA and DOH. What these two airports have in common is that they have a centralized BHS. If a decentralized BHS is used, the model becomes less accurate. This became clear from the case study on NAICM, which has a decentralized BHS. This could be explained by the fact that in a decentralized BHS, each part has to meet the redundancy requirements which usually results in more equipment than in a centralized system. The model defines the equipment based on the redundancy and for a centralized BHS, meaning that the model determines less equipment needed.

Another downside of the model is that because of the separation of the transport equipment optimization, the model can become inaccurate for small airports. At AUA for example, the make-up loop is a significant part of the entire transport system. If the trade-offs are chosen to only minimize the energy consumption, the model chooses chutes as the optimal make-up equipment as these use no energy. As chutes have a low capacity, the amount of chutes needed is high, which usually results in a larger make-up area compared to other make-up equipment. A larger make-up area requires a larger make-up loop. The loop, however, becomes so large, that the increase in transport length it yields results in a higher energy consumption than when laterals are used for example. So, the increase in the energy consumption of the transport system is higher than the decrease the chutes give. This effect, however, is smaller for larger airports as the make-up loop is only a small part of the entire transport system.

The main research question *"How can the development of concept designs for greenfield baggage handling systems be automated using a predefined set of input parameters?"* can now be answered. The answer to this question can be seen in Figure 8.1. Here, the framework of the developed model is shown. The model consists of a five stage process. First, the flight schedule has to be converted into the system demand. This demand is then used in the second stage to perform the first set of equipment calculations. This includes all equipment with exception of the transport and sorting equipment. Based on the stakeholders desires and the terminal layout, the optimal solution for the equipment is chosen in the third stage. Thereafter, in the fourth stage, a placement model is used to determine the location of each equipment unit. In the last stage, these locations are used to define the transport equipment. In the end a concept design is provided in a 3D model and a table. If multiple runs are performed with the model it is also possible to develop a 2D graph which shows the relations between different trade-offs.

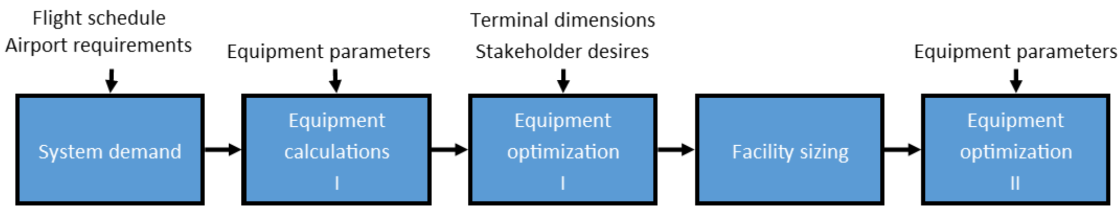


Figure 8.1: The design process the proposed model follows

The work by Van Noort (2018) can be seen as a proof of concept for automated BHS concept design. This research is the next step in this process and proposes a tool which can aid the designers in the conceptual design phase by automatically developing concept designs. Were the model of Van Noort has the CAPEX and system area as trade-offs, this model includes the system area into the CAPEX and adds the OPEX and LoA as new trade-offs. With an extension of the trade-offs, the model is able to define a better optimal solution, as more distinction can be made between different solutions. By introducing a self-made placement model, the droplet placement, the model is no longer restricted to rectangular areas but can now also be applied to various terminal shapes. Besides the shape of the terminal, the availability of levels is also introduced into the model. So in the end, a more complete model is developed which can be applied to a wider range of airports. However, this increase in complexity comes with a price. As the old model was finished in a few minutes, this model can take several hours. But keeping in mind that the manual process takes weeks, several hours is still a large improvement. As shown in the case studies, the idea behind the model is also applicable to other material handling systems. This does require adjustments to the model aimed at the specific material handling systems. So, this research does not only provide a functional conceptual design model for BHS applications, it is also a proof of concept for other material handling systems.

8.2 Recommendations

This research has delivered a conceptual design tool for BHS which can be used by designers. However, this does not mean the end of this research. To further develop the model and its applications, recommendations are done for further research. As this research has been developed together with NACO some recommendations are given in the end specifically for NACO.

8.2.1 Recommendations for further research

The main recommendation done for further research is to go from a five step design framework towards the generalized four step framework. The reason a five step framework has been used has to do with the optimization software used, Windows Solver Foundation. This is a software package by Windows, however, it is old and is no longer subject to updates. The amount of decision variables is also limited for this optimization package. Because of this last limitation, the transport equipment for the make-up loop is done after the facility sizing. An attempt was done to include the make-up loop before the facility sizing, however, the amount of decision variables then increased to 432. As the package was not able to handle this, the equipment choice was done after the facility sizing which caused some inconsistencies in the model. The package, however, was used because it is able to perform as desired and is free. A better package such as CPLEX by IBM for example cannot be used by everybody for free. For further research it is therefore recommended to research other possible optimization packages which could be used for the model.

A different package, however, does not mean that the four step framework is reached. As stated above, a different package could move the make-up loop to the first equipment optimization. This includes the sorting equipment and the transport equipment used for the loop. The transport equipment used between each subsystem is still dependant on the facility sizing. To include these into the first equipment optimization can therefore be a focus point for further research.

It is also recommended to further improve the data of each individual sub system. This is mainly aimed at the energy consumption. As Van Enter (2018) already showed, BHS energy consumption is a whole thesis by itself. In the model, the energy consumption is added in a simplified manner. With the increasing attention for environmental issues, being able to develop low energy systems can become important. All other equipment parameters should also be checked. This will improve the accuracy of the model. Also further researching in different subsystems could enhance the model. The EBS for example is subject to a lot of assumptions and is hard to define. Replacing these assumptions by more accurate calculations could enhance the model.

The output presented by the model is based on an optimal solution. By increasing the amount of trade-offs from two to four, a more accurate definition of the optimal solution can already be determined. However, more research into the decision making process of the stakeholders could further enhance the outcome of the model. This could be focused on the trade-offs defined, but for example also on the uncertainty of the input parameters. Also, providing a model which can run all different scenarios in one, instead of multiple separate runs at the moment, could further enhance the model.

At last, as already stated before, the model framework can be applied to different material handling systems. However, this requires individual research into the specific material handling system. This report starts with a wide perspective, automation of material handling design in general. If the model was to be developed for another material handling system, the focus should then be towards that specific system. Meaning that the same model structure can be used, but with a different focus.

8.2.2 Recommendations for NACO

The model provided to NACO is functional and can be used by their BHS engineers for the conceptual design process. This, however, does not mean that the development of the model for NACO should stop. Besides the research recommendations done before, other improvements to the model can be made. The previous model required a lot of hard coding inside the model when applied to a different airports. For this, the user would need programming knowledge which not everybody has. The new model already improves this. Each input parameter can be adjusted outside of the model in an Excel file and does not need hard coding in the model. This requires no new programming knowledge, as most designers are able to work with Excel. Only, if a different placement sequence is required for the facility sizing, hard coding inside the model is still required. By also removing this from the process, a more user-friendly model is created.

Parts of the model can also be useful for other departments at NACO. The flight schedule converter for example can also be used by terminal planners. The other way around, the 3D model developed by the architects could also be used by the model to define the available space and floors. It is therefore recommended to search for links between each department regarding the model.

As NACO is part of Royal HaskoningDHV, the companies field is not only limited to airport development. The recommendation regarding the model possibilities for other material handling systems therefore also applies for Royal HaskoningDHV. This could also be linked to new research, in which the model is applied to different material handling systems. This would further improve the model which is also beneficial to the current model, as limitation of the model might be solved by looking at other systems.

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Appendix A

Research paper

Automated conceptual design generation of baggage handling systems

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Dr.ir. D.L. Schott

ABSTRACT
Baggage handling systems (BHS), are complex and integrate systems hidden within an airport. In this paper, a model is developed which can generate BHS concept design automatically. This means that the model defines the type and amount of equipment and is able to develop a 3D model that can be used for volume reservation. The model takes into account the stakeholders desires, operational preferences and the terminal shape and size and can therefore define the optimal solution for the stakeholders.

1 Introduction

Although unknown territory to most airport passengers, BHS are a vital part of the airport. This was shown when in 1994 , due to a BHS failure, the opening of Denver International Airport had to be delayed by 16 months costing around $500 million (de Neufville, 1994). This failure could have been prevented during the design phase of the BHS. A crucial part of this design process is the conceptual design phase. As described by Pahl, Wallace, and Blessing (2007), in this stage the basic solution path is laid down through the elaboration of a solution principle. The importance of this phase is shown by Hsu and Liu (2000). They state that the decisions made during the conceptual stage account for more than 75% of the final product cost. Although the impact of design decisions is high during this stage, tools are lacking (L. Wang, Shen, Xie, Neelamkavil, & Pardasani, 2002).

Literature on BHS design is lacking. Most research into BHS is aimed at the control system or simulation models. Research on individual subsystems can be found (Joustra & van Dijk, 2001; Leone & Liu, 2005), however, only a few articles on the BHS as a whole. Lemain (2002) looks at the economical aspects of BHS design, while Pielage (2005) uses BHS as an example when discussing freight transport. Grigoraş and Hoede (2007) do research BHS design, however, their focus is mainly on the routing aspect of the BHS.

Models which are able to aid during the conceptual design stage of a BHS can be found in literature (Antoine & kroo, 2005; Fitzgerald, Herrmann, & Schmidt, 2010; de Aguiar et al., 2017). A model which is able to develop BHS design, however, cannot be found. The goal of the research is therefore to create a tool which is able to automatically generate a concept design based of a predefined set of input parameters and the designers preferences. This resulted in the following research question:

How can the development of concept designs for greenfield baggage handling systems be automated using a predefined set of input parameters?

The scope of this research is limited to BHS operations within the terminal. This means that tail-to-tail transport of baggage and gate check-in will be excluded. Out of gauge baggage is also excluded from this research as this is usually done with a separate system.

This paper is organized as follows. In Section 2, the model development will be discussed which was done in two steps. Section 3 shows the results of applying the model to different airports. In Section 4 provides an discussion on the research. Finally, in Section 5 the paper will be concluded by answering the research question.

2 Model development

The model development consisted of two stages. First, literature research was done regarding the automation of design and how to apply for BHS applications. Thereafter a design model was developed. Both parts will be discussed separately.

2.1 Literature study

Before developing any model, a literature study was done in automated design. Two design methods for automated design can be found. The first is parametric design were the designer manually explores different design solutions by varying individual parameters and evaluating the generated designs (Nagy et al., 2017). The outlines of the design are already known and the designer changes certain parameters to see the outcome. The second design method is generative design were a complete design is automatically generated. Krish (2011) provides three components for generative design:

1. A design schema which contains the design rules
2. A means of creating variations
3. A means of selecting desirable outcomes

For the conceptual design generating of BHS design, the generative method is deemed most suitable. As the outcome of the design is unknown in this phase, parametric design could not be used.

Different automated design models can be found in literature. Ölvander, Lundén, and Gavel (2009) developed a model for the conceptual design stage of aircraft development. Their model is able to generate different concepts and is able to define the desired solution. Cardarelli and Pelaggage (1995) and Montoya-Torres (2006) describe models for the generation of automated material handling systems for the wafer fabrication facilities. Their models, however, is aimed more to the operational side of the material handling system and not the layout. Duchateau (2016) and Rose (2017) both developed models for the conceptual design stage of ship building. Their models aim at automating the concept exploration and production planning respectively.

Combining the different researches, a generalized design framework for material handling systems can be developed. This framework is depicted in Figure 1. Here it can be seen the first step is to define the system demands based of the supply data and operational requirements of the system. Next, by introducing the equipment parameters, the amount of equipment for each subsystem can be determined. With this data, all possible solutions can be developed. To define the desired solution, the stakeholders desires and the facility dimension should be introduced. These will set the constraints and boundaries to find the optimal solution. This will result in a design which is then developed into a 3D model during the facility sizing stage. For this last step, a placement model is required.

For the facility sizing, two models will be tested. The first model is retrieved from the very large scale integration (VLSI) algorithms. These algorithms aim at placing billions of components on circuit board while reducing the production costs. The model chosen for the BHS applications is the Gordian placement model (Kleinhans, Sigl, Johannes, & Antreich, 1991). This model aims at reducing the routes between each subsystem given a set of fixed sub systems. Overlapping of subsystems can happen so a secondary detailed placement model is needed. A downside of the Gordian model is that it reduces routing based of the amount of connections each subsystem has. For facility sizing however, the routing should be based of the capacity of each line. It is therefore expected that the Gordian placement model does not provide a desirable outcome. A second self-made placement model is therefore introduced, the droplet model. In this model, the optimum location for an equipment unit is given as an input. This point is either directly after a certain subsystem, like the last step of the process directly at the exit of the terminal, or the middle point between two subsystems. The model then checks if this location is available and places a single the unit, so not the entire system. If no space is available, the model will search in a circular pattern around the location for the closest available position. This algorithm propagates through the area like a wave created by a droplet which breaks a liquid surface, hence the name droplet search.

With the concept of the model defined, the definition of the optimal solution should be defined. This is done by first defining the stakeholders involved in the process. Using the research by Schaar and Sherry (2010) two main stakeholders can be found: the airport organization and the service providers. Three secondary stakeholders are also identified: the air carriers, federal government and custom, and the passengers. Looking at the main stakeholders, six trade-offs can be identified which define the optimal solution. These are: the capital expenditure (CAPEX), operational expenditure (OPEX), in-system-time (IST), flexibility, redundancy and level of automation (LoA). The IST, flexibility and redundancy can be implemented into the operational requirements. The importance of the CAPEX, OPEX and LoA, however, should be defined by the stakeholders them self. The designer should therefore show the stakeholders the effect of these trade-offs on the BHS design. The CAPEX will be defined as a monetary value, the OPEX is split into energy consumption and the amount of operators. For the LoA, seven different levels are created based of an article by Fasth, Stahre, and Dencker (2008). These range from level 1 which is a complete manual process, to level 7 which is a fully automated system which has the ability to process information.

As the model should be applicable to BHS, a research was done in defining the input parameters and equipment needed for the BHS design. Three different bag flows can be found at an airport: the departing flow, the arriving flow and the transfer flow. For these three flows 9 subsystems are defined: check-in, hold baggage screening (HBS), sorting, make-up, offloading arrival bags, offloading transfer bags, reclaim, transportation and early baggage storage (EBS). Some of these subsystems can be further split into more subsystems. The HBS, for example, can be a multilevel system (TSA, 2017). For the 9 subsystems, a total of 38 input parameters and 38 different types of equipment have been identified. The lists are made by combining literature (IATA, 2004; Jenks et al., 2010; de Neufville & Odoni, 2013; TSA, 2017; Leone & Liu, 2005; Abdelghany, Abdelghany, & Narasimhan, 2006; Hallenborg, 2007; CBP, 2014; Bradley, 2010; Edwards, 2005; Kazda & Caves, 2015; Fasth et al., 2008) with the knowl-

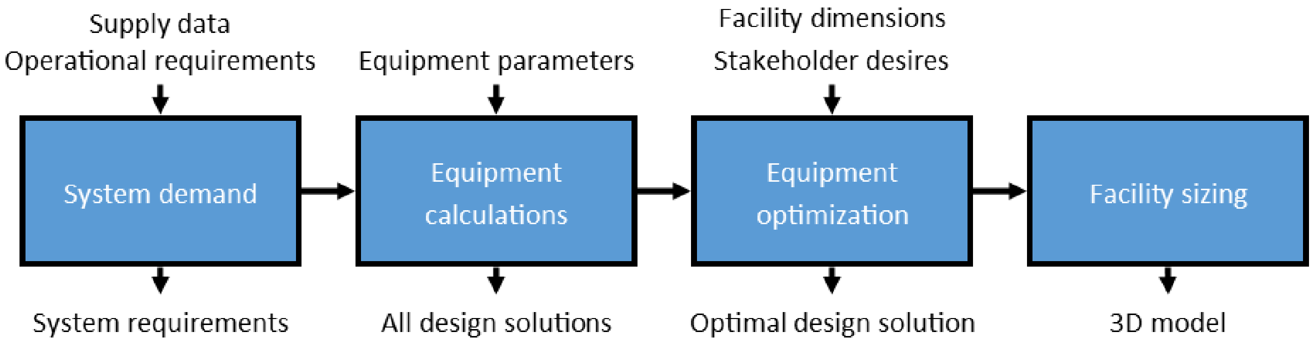

Figure 1: The design framework that can be used for designing material handling systems, with the input on top and the output at the bottom, the output of each block is also used in the next step of the design process

edge of BHS experts at NACO, The Netherlands Airport Consultants.

2.2 Model definition

With a model defined, the model can be developed. The developed model is based of the design framework shown in Figure 1. Due to a link that has to be made for BHS between the equipment optimization and the facility sizing, the designed model has a fifth step after the facility sizing which can be seen in Figure 2. Each parts of the model will be discussed separately.

1) System demand: The first step in the design model is to convert the supply data and operational requirements into the system demand. To do this, the flight schedule should be converted to a standardized from. The standardized form should contain the following data for each flight: scheduled time of departure or arrival, the airline, flight direction (inbound or outbound), aircraft type, transfer PAX and local PAX. This data is then converted into the important demand data for each subsystem.

2) Equipment calculations I: The next step in the design process is the first equipment calculations. These calculation define the amount of equipment needed for all subsystems with exception of the transportation and sorting equipment. This is done using the calculated capacity requirements for the subsystem in which the equipment is used and dividing this by the equipment capacity. This figure is rounded up and adjusted according to the required redundancy. Next, for each equipment type the following data is calculated: the system area, the CAPEX, the energy consumption, the amount of operators needed and the IST. To the CAPEX of the system an extra value is added. As the space of the BHS building has a monetary value, a volume price is added to the CAPEX. This means that large equipment types will see a bigger addition to their CAPEX then smaller equipment. The average volume price per cubic meter BHS space is defined by NACO architects to be 160 €/m^3. This data is then send to the next step of the model.

3) Equipment optimization I: For each of the subsystem form the previous step, only one type of equipment can be chosen. This means that of the 62208 possible BHS configurations, one should be chosen. The first equipment types chosen are the ground equipment. This is all equipment which is located on floor of the building with exception of the transport equipment. The equipment choice will be done by developing a binary integer programming model. This model can be described as following, based on the work by Ölvander et al. (2009):

Decision variables: The binary decision variables represent each equipment type choice. If an equipment type j is chosen to fulfill the function of subsystem i, the value of the decision variable is 1 else the value is 0.

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

Objective function: The next step is to define an objective function. Here a trade-off is made between the CAPEX (c_{ij}), energy consumption (E_{ij}), number of operators (Op_{ij}) and level of automation (LoA_{ij}). To make this trade-off, each trade-off should be given a weight. For each of the trade-offs, a weight is assigned in the form of α, β, γ and δ of which the sum equals 1. To prevent the model from choosing a random option when two design yield the same objective solution, 0.01 is added to all trade-offs. If two solutions then score the same, the model will choose the solution which scores a better average over all the trade-offs. As each trade-off is expressed in a different measurement unit, the sum of each trade-off is divided by the minimum possible sum of that trade-off. The amount of operators and level of automation are correlated negatively to each other, meaning that if one of the values is minimized, the other should be maximized. Therefore the value μ is introduced. If μ is 1, the operators are minimized and the LoA maximized, if μ is -1 this

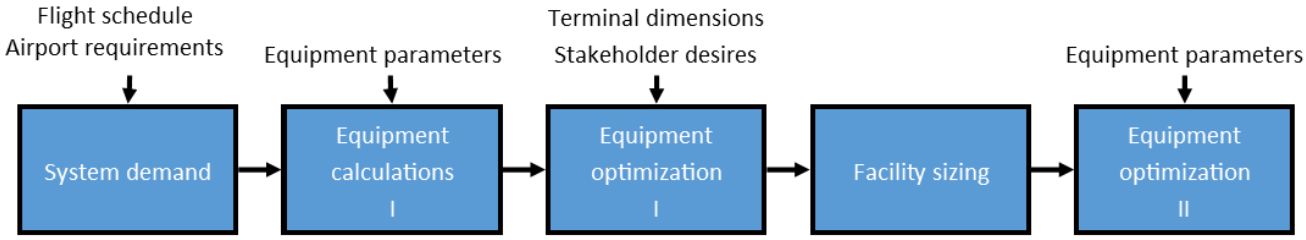

Figure 2: The design process the proposed model follows

is reversed. The objective function is the sum of Equation 2 to 5.

$$min\left((\alpha + 0.01) * \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} c_{ij} * x_{ij}}{\text{minimum value } CAPEX}\right) \quad (2)$$

$$min\left((\beta + 0.01) * \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} E_{ij} * x_{ij}}{\text{minimum value } Energy}\right) \quad (3)$$

$$min\left(\mu * (\gamma + 0.01) * \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} Op_{ij} * x_{ij}}{\text{minimum value } Operators}\right) \quad (4)$$

$$min\left(-\mu * (\delta + 0.01) * \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} LoA_{ij} * x_{ij}}{\text{minimum value } Automation}\right) \quad (5)$$

Constraints: The constraints define the rules to which the design solution should comply. As for each subsystem only one type of equipment can be chosen, Equation 6 has been added to the model as an constraint.

$$\sum_{j=1}^{m} x_{ij} = 1 \quad \forall i \quad (6)$$

The next constraint is that the IST of the system cannot exceed the predefined boundary max_{IST}. This boundary usually depends on the desired transfer time the airport want to offer. This constraint is given in Equation 7.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij} * x_{ij} \leq max_{IST} \quad (7)$$

The next two constraints concern the area and height of the BHS building. This means that before the equipment optimization, the terminal area should be fully defined. This is done by defining the area as a cuboid, in which shape blocks are placed. The floor area of these shape blocks is subtracted from the total area. The area constraint added to the model is given in Equation 8. The height constraint is similar with only A_{ij} and max_{area} being replaced by h_{ij} and max_{height}.

$$\sum_{i=1}^{n}\sum_{j=1}^{m} A_{ij} * x_{ij} \leq max_{area} \quad (8)$$

4) Facility sizing: The next step of the model is to place each subsystem into the terminal area. As discussed before, two placement models are tested: the Gordian placement model and the droplet placement model. As a validation test, both models were applied to two existing airport: Aruba International airport (AUA) and Hamad International Airport (DOH).

For the Gordian model, adjustments were made to fit the BHS purposes. The original model uses the amount of connection between nodes as the weight of the route. For the BHS model, this was changed to the demand of each route, so it would better fit the facility sizing purposes. When applied to both airports, all subsystems were plotted at the origin. When adding placement constraints, as described in the original model (Lim, 2008), the outcome of the model was not as expected. The reason for this is that the objective function of the model is build up in such a way that plotting everything (0,0) is always the optimal solution.

When applying the droplet model to both airports, the outcome is similar to the results actually installed at the airports. A downside to the model, however, is the time it takes compared to the Gordian model is longer. Were the Gordian model takes seconds, a small airport like AUA takes the droplet model around 5 minutes. Also, the placement sequence has to be manually coded into the model before running it. However, the droplet model does provide a more desirable outcome compared to the Gordian model. It is therefore chosen to use the droplet model as the placement model for the facility sizing.

Although no transport equipment is chosen yet, during the droplet placement, space is reserved for several transport lines. This is to be able to have a fully defined BHS in the end. When the placement is done, the location of the mid-point of each subsystem is used to determine the data needed for the next step, the transport equipment optimization. These data are the total transport length needed, the length a transfer bag has to follow and the length of the make-up loop which is located above the make-up area.

5) Equipment optimization II: With the transport data defined, the transportation equipment can be chosen. First, the equipment data of the transport, sorting

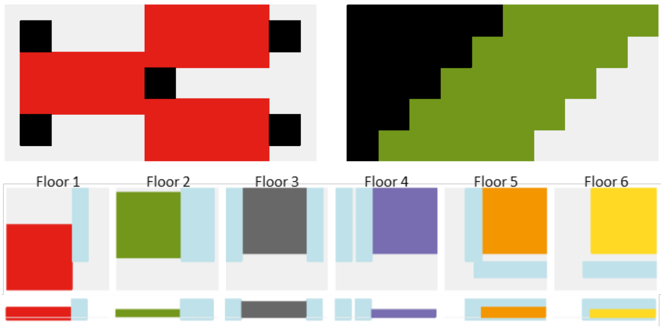

Figure 3: The three test cases done to validate the model

and loading equipment is determined. As each transport equipment has specified loading and sorting equipment, 27 different equipment combinations are calculated. To make a choice between these 27 options, the same optimization model is used as used for the the first equipment optimization. After the optimization is done a concept design has been developed which is visualized in a 3D model and a table containing the data of each subsystem.

To validate the model, three test cases were performed which are shown in Figure 3. In the first test case, the equipment (red) was placed in a grid of columns (black). If the model behaves as expected, the equipment should be placed around the columns. In the second case equipment (green) was placed along an uneven border (black). Again, the equipment should be placed without overlapping the border. In the last test case six different equipment types were placed on a six floor terminal. Each subsystems was larger then half the area of each floor, meaning that each floor houses a subsystem. Also, lifts (light blue) should be placed connecting the floors. As is visible in Figure 3, the model behaved as expected.

3 Model application

To see how the model performs against the work of engineers, the results from the equipment calculations are reviewed for three different airports. These three airports are AUA, DOH and the New Mexico City International Airport (NAICM). For each airport, the flight schedule of a normal day were used. Table 1 shows the equipment amount defined by the model when using the similar equipment as the engineers chose. As the conceptual design phase is still at an early stage, being within a 40% difference of the final figure is still within a reasonable range (Christensen & Dysert, 2011).

For AUA, most data is in accordance with that of the engineers. Only the check-in and EBS data is different. The difference in both peaks is likely caused because the engineers used different arrival patterns over the day. The model, however, uses only a fixed one. The data is therefore different but only the EBS is outside of the 40% range.

Similar to AUA, for DOH the check-in and EBS data is different to that of the engineers. This difference in check-in can be explained by applying a second flight schedule of the highest peak day that year, the national holiday of Eid, to DOH. If the second flight schedule is used, a total of 135 check-in desks is needed which is 41% above the engineers value. In Table 2 the trade-off data of both scenarios is shown, were scenario 1 is of a normal day and scenario 2 of the busiest day. It can be seen that the entire BHS is effected by using a different flight schedule. It is however not advised to use the highest peak day of the year when designing for an airport (P. T. Wang & Pitfield, 1999). This example shows the importance of which flight schedule is used for entire design and not only the check-in. At last, when the EBS for DOH was designed, it was already known that the capacity was too small. As is visible, the model also defines a larger EBS, no conclusion however can be made for this.

Different to the other two airports, NAICM has large differences in the values defined by the model. The reason for this can be explained by the fact that the model considers a centralized BHS and the engineers calculated the BHS for a decentralized system. The actual developed BHS for NAICM consist of four separate sections each in a corner of the airport. This also means that each of these sections have to reach the redundancy requirements individually which usually requires more equipment. Looking at the models outcome, most values are below the engineers value, except the HBS level 3.

The second test case done was on AUA, were the effect of the OPEX and LoA on the CAPEX were determined. This was done by taking the CAPEX and one of the other trade-offs and alternating their weights between 1.0 and 0.0 with steps of 0.1. So, 11 runs in total. In Figure 4 the results for running the CAPEX and energy consumption can be seen. As some weight configurations yield the same design, the graphs does not show 11 different points. It can be seen that when a low energy consumption is desired, the CAPEX goes up. Only one measurement point does not follow this trend, which is the point with the highest CAPEX. This is the run when fully optimizing the energy consumption ($\beta = 1$). This can be explained by the way the model operates. Because the make-up loop is chosen after the placement, the length of the loop depends on the make-up system chosen. Chutes have the lowest energy consumption of all make-up equipment, however they result in the largest make-up area. The larger the make-up area, the longer the make-up loop becomes. The increase in energy consumption resulting from the longer loop therefore outweighs the decrease in energy consumption the chutes bring.

Next, the relation between the CAPEX and amount of

Table 1: The equipment number for each airport, where row 1 represents the values defined by the engineers, row 2 the value defined by the model and row 3 the difference between the two values. An "-" means that the data is not available.

	AUA			DOH			NAICM		
Subsystem	1	2	3	1	2	3	1	2	3
Check-in	66	86	+ 30.3%	96	44	- 54.2%	206	172	- 16.5%
HBS level 1	4	4	± 0%	17	19	+ 11.8%	14	7	- 50%
HBS level 2	4	4	± 0%	-	32	-	21	13	- 38.1%
HBS level 3	31	33	+ 6.5%	-	32	-	15	21	+ 40%
Make-up	26	26	± 0%	22	22	± 0%	38	29	- 23.7%
EBS positions	1200	1716	+ 43%	1400	3752	+ 168%	2000	2124	+ 6.2%
Offload transfer	1	1	± 0%	10	14	+ 40%	6	6	± 0%

Table 2: The outcome of the two scenarios for $\alpha = 1$ for DOH

Scenario	1	2
CAPEX [million €]	26.2	33.2
System area [m^2]	28208	37907
Energy [kWh]	5043	4494
Operators	190	217
Average LoA	4.70	4.70

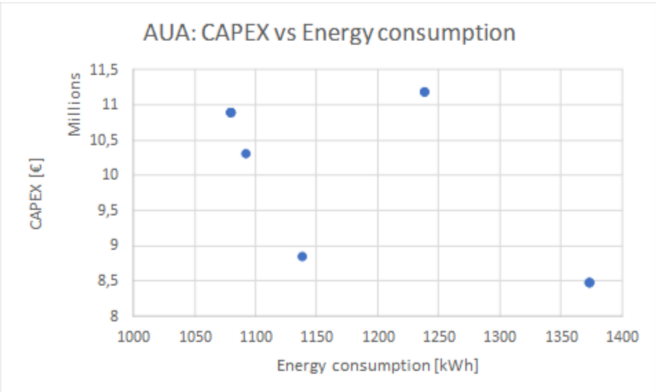

Figure 4: The relation between the CAPEX and the energy consumption

operations is researched. The similar approach is used, however, as the operators can both be minimized and maximized, two sets of data points are plotted. The results are shown in Figure 5. It can be seen that if the operators are minimized, the CAPEX go up which is logical since automation comes with a cost. What is interesting to see is that when maximizing the operators, the CAPEX remains relatively unchanged. Between $\gamma = 0.1$ and $\gamma = 0.9$, the same solution is always chosen. Only when fully optimizing the operators, the CAPEX increases due to a different type of transport system which is chosen.

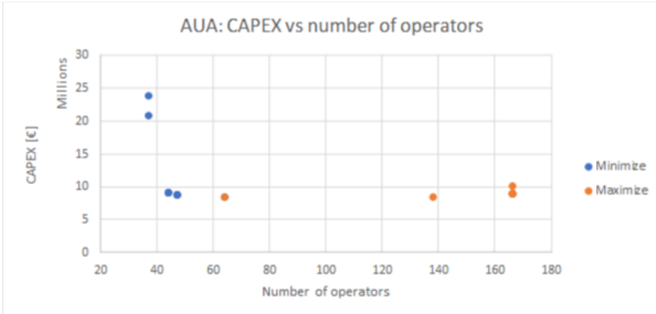

Figure 5: The relation between the CAPEX and the energy consumption

At last, the relation between the CAPEX and LoA is researched. Again the same approach is used, both minimizing and maximizing the LoA. The graph has a more parabolic trend, suggesting a minimum CAPEX between the automation level 4 and 5. The fact that as the LoA goes up, the CAPEX increases has already been explained: automation comes with a cost. However, as the graph shows, as the LoA goes down, the CAPEX will also go up. This is because lower level equipment usually has a low capacity. This means that a lot of the equipment is required, which can result in a higher CAPEX.

To highlight the difference in the outcome of the model, two 3D models are shown in Figure 7. The two runs that are shown are that for the minimum CAPEX ($\alpha = 1$) and the minimum energy consumption ($\beta = 1$). It can be seen that both runs yield a different outcome, but similar design are developed. In both runs the EBS for example, is placed on the second floor. Because different equipment is used for each design, the sizes of the subsystems differ. The figure also shows the earlier mentioned limitation of the model related to the make-up loop. The CAPEX run uses laterals and the energy consumption run chutes. As chutes consume less energy, they are chosen. It can be seen, however, that this results in a large make-up area

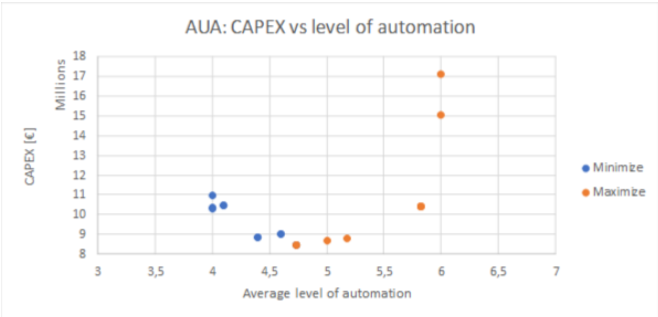

Figure 6: The relation between the CAPEX and the energy consumption

which gives an larger make-up loop.

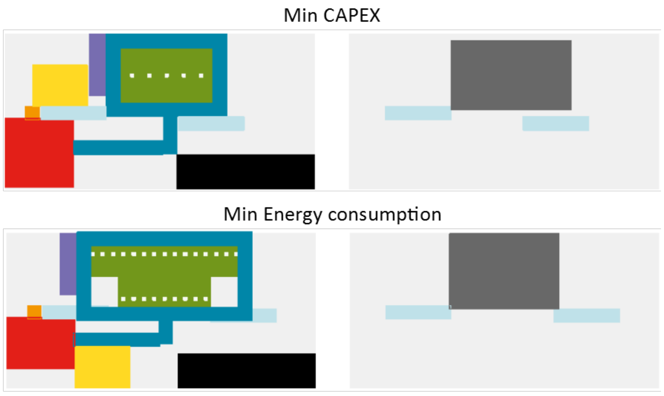

Figure 7: A top view of the 3D models develop for two different runs at AUA (Shape blocks = black, HBS level 1 = red, HBS level 2 = orange, HBS level 3 = yellow, Make-up = green, Transportation = blue, EBS = gray, Transfer offloading = light purple, lifting equipment = light blue)

So, comparing the current system with the generated systems, it can be observed that none of the configurations is an exact match to the current system. However, multiple sub-systems match in equipment choice and only show a slight difference in scaling. Multiple reasons can be the reason for that. The first is that check-in and reclaim are usually over engineered and on normal days are quiet. The high level of service standards in a country like Qatar may cause this difference. The model has also been applied to the New Mexico City International Airport. Since a decentralized system is used there, bigger differences in scaling were found. However, as the amount of trade-offs already suggests, defining an optimum BHS is difficult. The model is therefore capable of providing a feasible solution and not necessarily the optimum solution.

4 Discussion

The proposed model is able to define a optimal solution by taking into account three trade-offs, CAPEX, OPEX and LoA. As already stated in the results, it is able to find a desirable solution, not necessarily a optimum solution. This chapter will discuss the use of the model; what can it be used for and what not.

A few demonstrations on how the model could be used for the design process have already been given in the results. The model can show the difference between different days and can show the relationship between the trade-offs. The model could be used for more applications. When master planning, usually different scenarios are developed with a flight schedule. The model could then be used to show a BHS design for each of the scenarios. Parts of the model can also be used for other aspects of the airport. The flight schedule converter for example can also be used by terminal planners.

The framework behind the model is based of a design framework for material handling system in general. Although the model is developed for BHS applications, adapting the model to other material handling systems is possible. For example, the model has been adjusted to work for container terminals. Then by running two different container configurations, parallel or perpendicular to the shore, the model could be used to define the space usage of both orientations. This example however, was only done using the droplet placement model as the rest of the model is designed for BHS purposes and not applicable to the container terminal.

The model still needs further development. As the design framework is a four step process, the model is a five step process. As shown in the energy consumption example graph for AUA, with certain cases the fifth step causes a less favourable design. Adjusting the model so it can be done in four steps would fully finalize the model.

5 Conclusion

The objective of this research was to develop a method to automatically develop BHS concept design using a predefined set of input parameters. For this, a generative design framework for material handling systems was proposed which takes into account the supply data, operational requirements, equipment parameters, stakeholders desires and the facility dimensions. By converting this framework into a BHS applicable model, a 5-step design model has been develop.

The model starts by converting a flight schedule and the airports requirements into the system demand of the BHS. The next step is to take this system demand and define for each possible ground equipment type the amount needed. Next, based of the ground equipment data, a optimum design configuration must be made. This is done by introducing a binary integer programming optimization model which uses CAPEX, OPEX and level of automation as trade-offs. The stakeholders desires are represented by these trade-offs. With the ground equipment chosen, a placement model is used to place each equipment unit inside the terminal. For this placement model, a search algorithm is developed which searches the closes ts possible point to the optimum location. With each position known, the model defines the transport equipment and chooses the best possible solution, based of the same optimization model as before.

In the end a model is presented which is able to develop a BHS conceptual design which takes into account the desires of a stakeholder. It can be used for giving a direct optimal solution or to show the impact of certain design decisions and trade-offs, as shown in the results. A design process which took weeks has been reduced to a matter of hours, depending on the size of the airport.

As shown in the discussion, the model is not only restricted to BHS application. As most material handling systems have similarities, only a few changes have to be made to the model to make it usable for other applications. The model is therefore not only an conceptual design tool for BHS applications, it can be used as a basis for a conceptual design tool for material handling system in general.

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Appendix B

A Schematic overview of a BHS

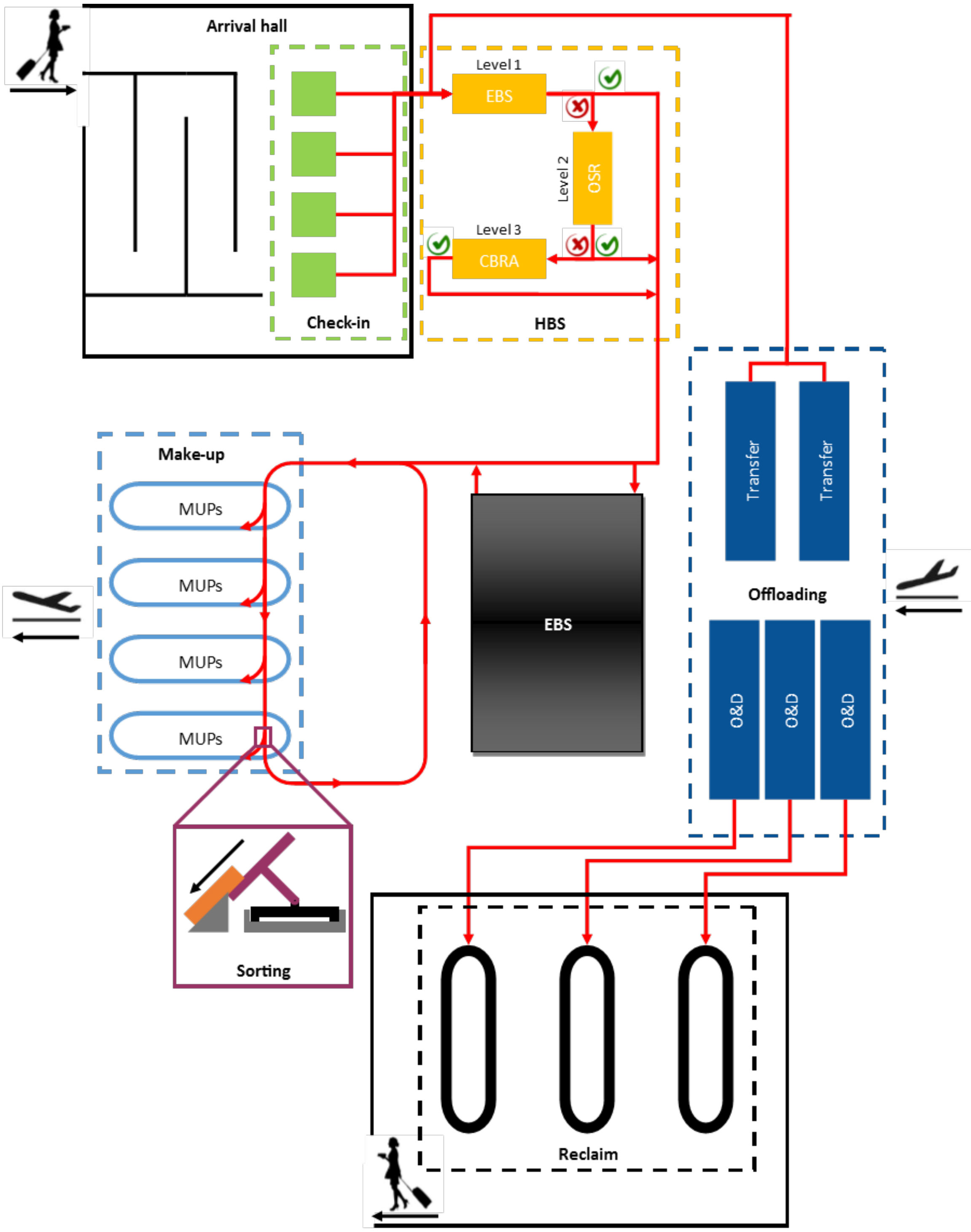

Figure B.1: A schematic overview of a complete BHS

Appendix C

Case study on AUA

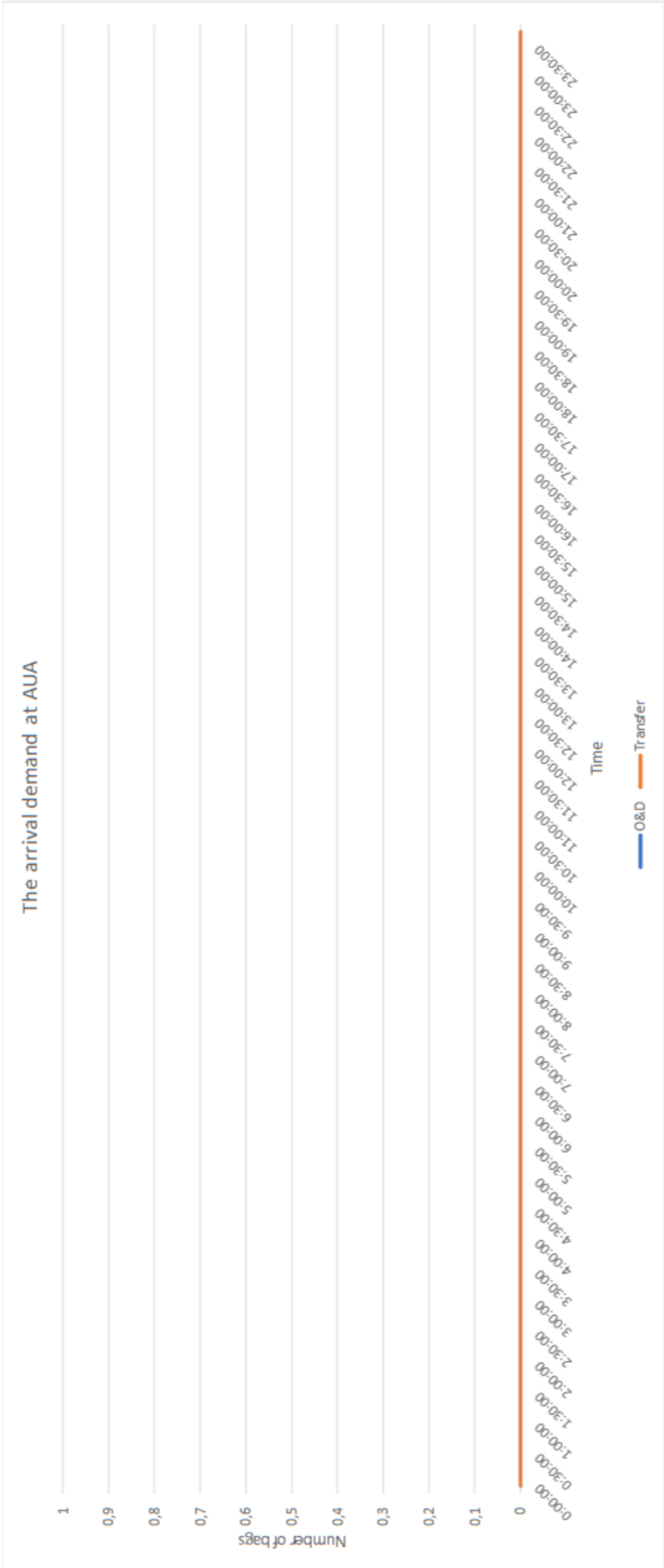

Figure C.1: The arrival demand at AUA

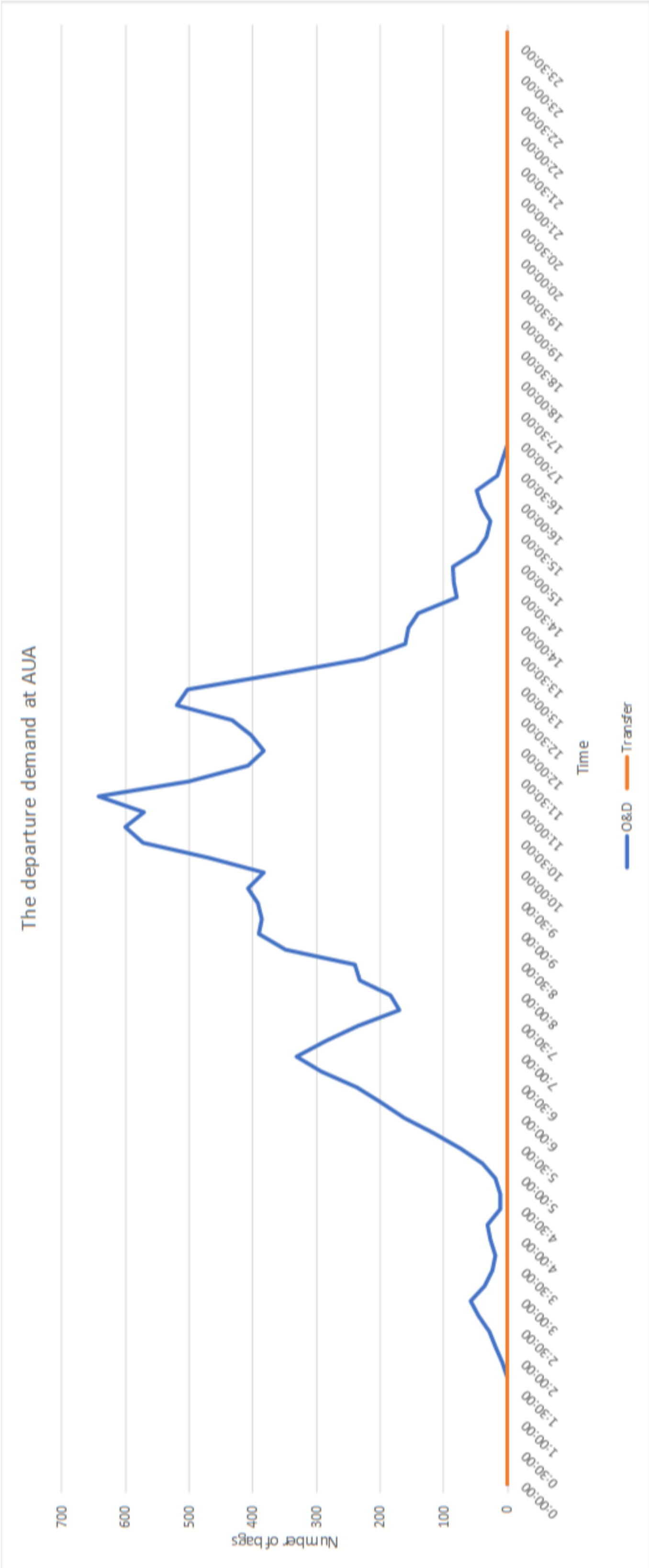

Figure C.2: The departure demand at AUA

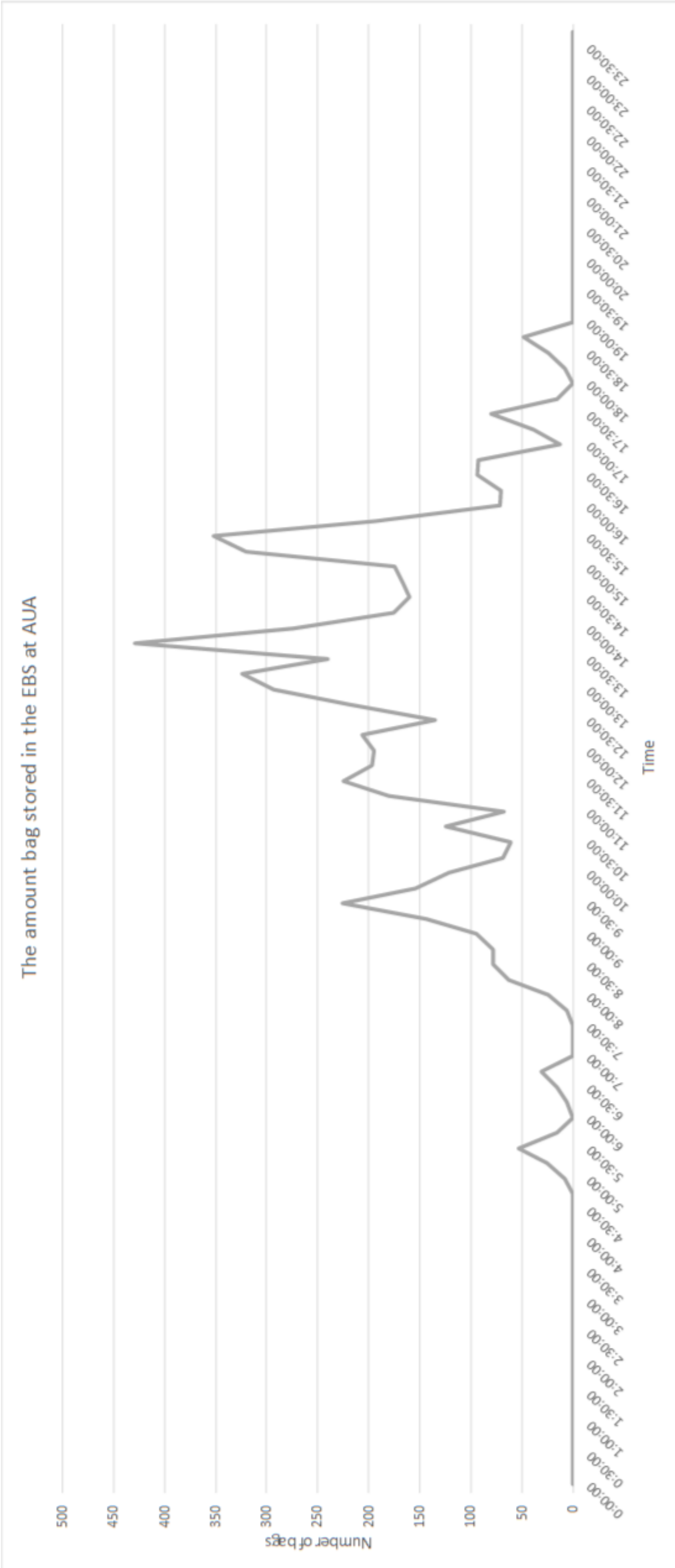

Figure C.3: The EBS demand at AUA

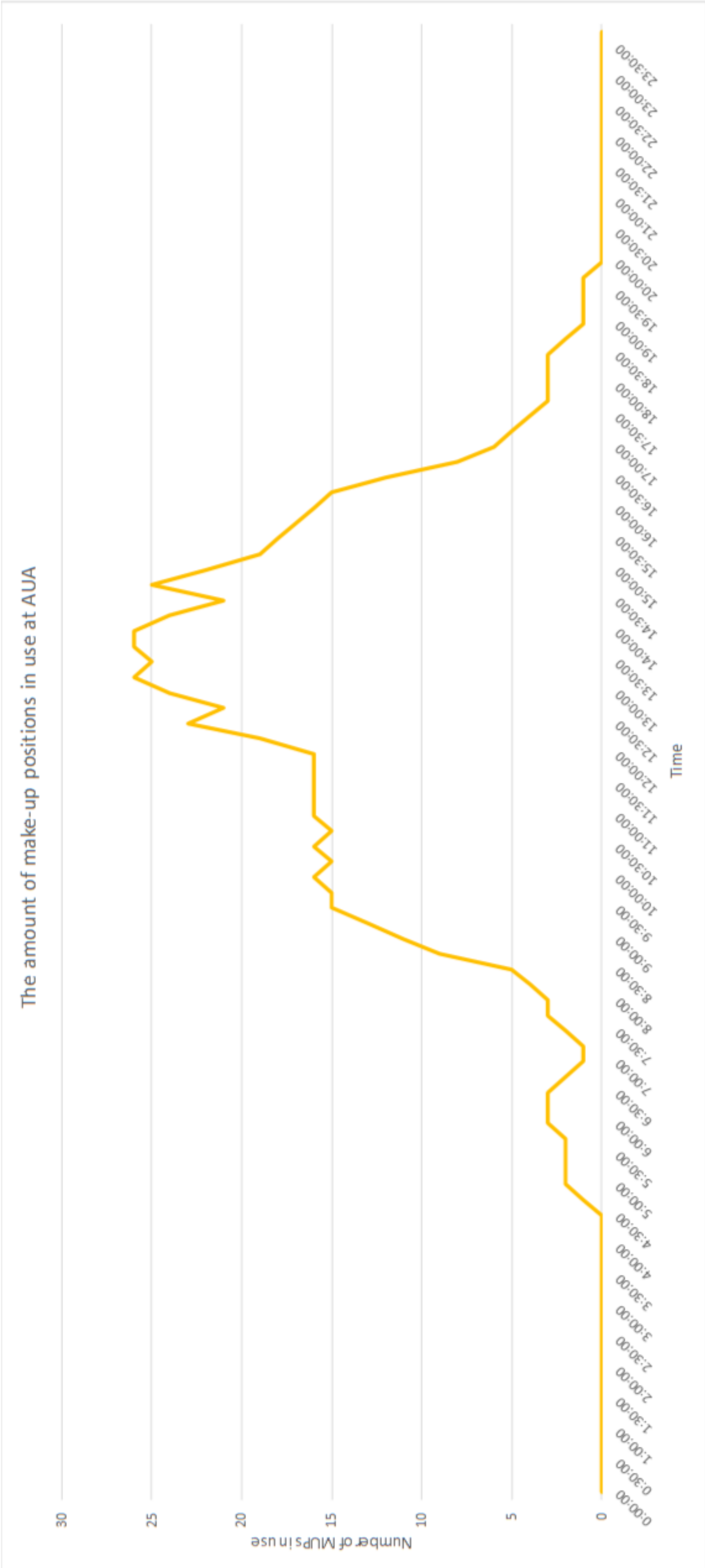

Figure C.4: The MUP demand at AUA

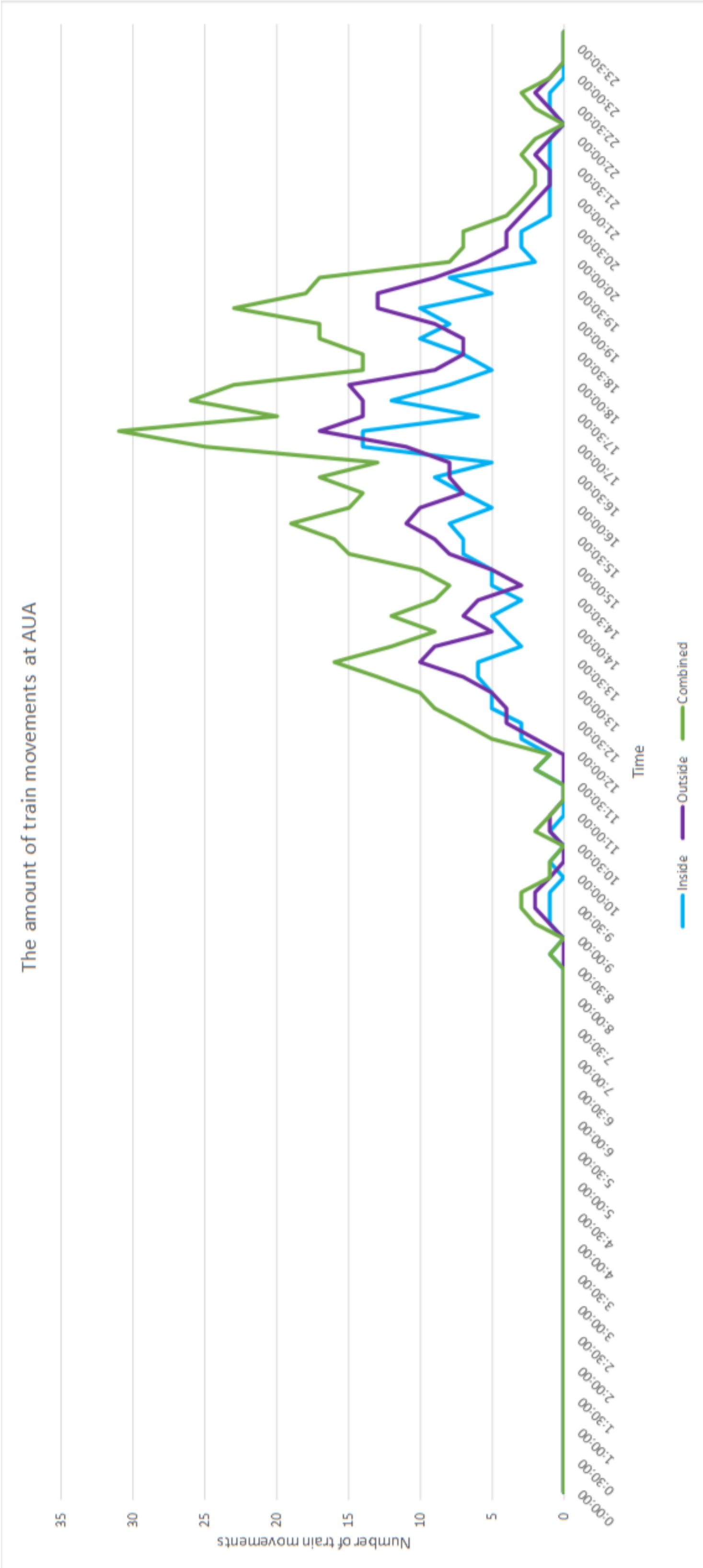

Figure C.5: The train movements at AUA

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfer	Transportation	Loading	Sorting	Total
Equipment type	Two-Step-Drop-	Medium speed EDS	OSR	ETD normal search	Lateral+Train	Shuttle rack	Manual_OD	Manual_T	DCT	DCT side loader	Static discharge	-
Equipment amount	29	4	4	14	7	1	2	1	-	3	7	72
System area [m^2]	827,316	400	64	2688	840	700	180	90	-	14,4	-	5803,716
Capacity [bags/h]	2610	2800	800	336	28	1760	1800	900	-	6000	12600	-
Redundancy [%]	100%	80%	90%	100%	90%	98%	-	-	-	160%	420%	80%
CAPEX	-	-	-	-	-	-	-	-	-	-	-	€ 8.487.870,00
Energy consumption [kWh]	58	80	0,8	25,2	15,4	44	4,4	2,2	1125	3	15,4	1373,4
Operators	12	0	4	14	28	0	4	2	0	0	0	64
LoA	4	7	4	3	6	7	2	2	6	6	5	4,73
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	2,01115942	0,03	0,02	3,324651484

Figure C.6: The table generated for AUA when optimizing for a minimum CAPEX

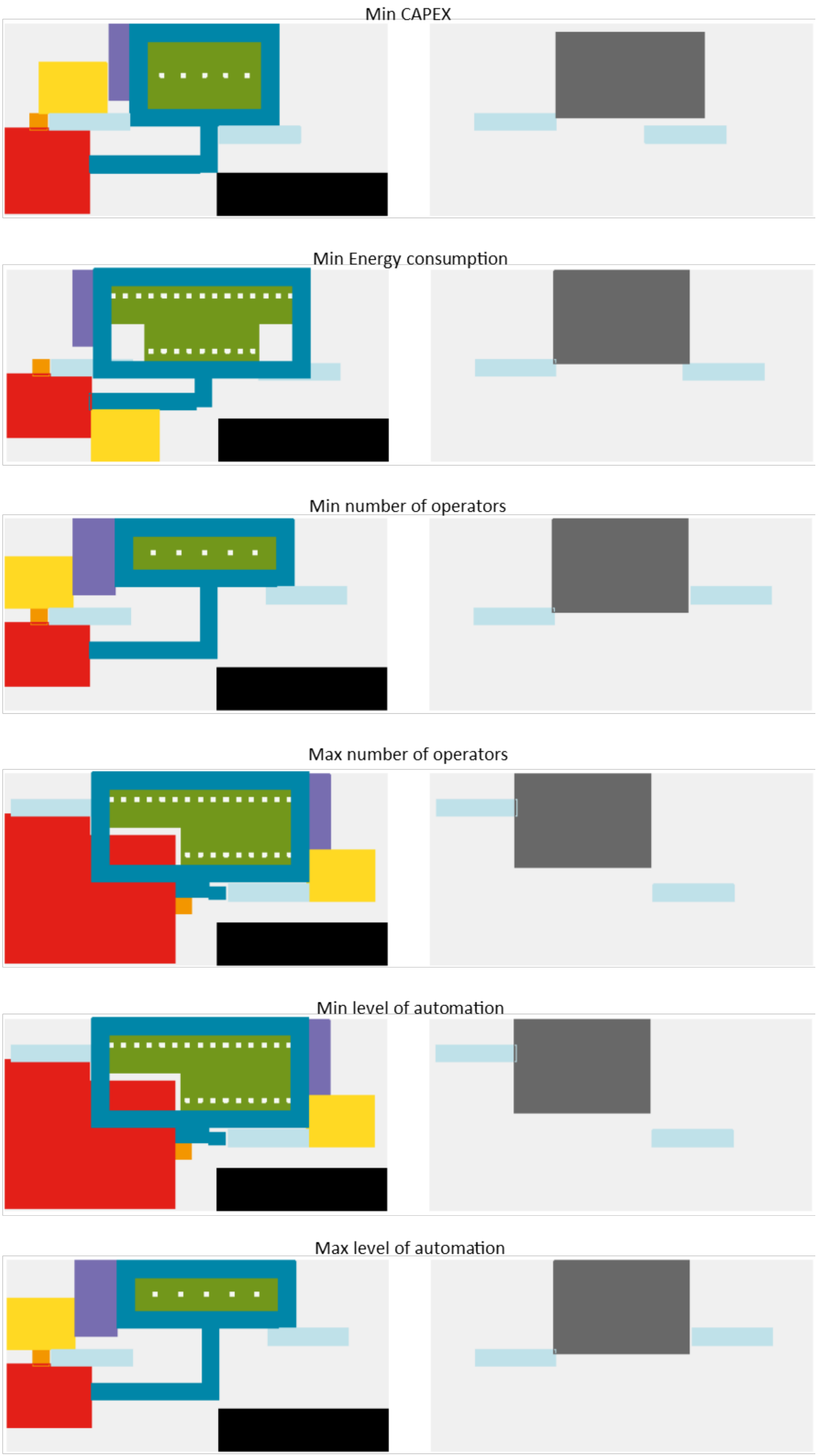

Figure C.7: Top view of the 3D models developed for AUA when optimizing for one trade-off

Appendix D

Case study on DOH

Table D.1: The airline bag ratio used for DOH

Airline	O&D	Transfer
QA	1.9	1.2
Other	1.3	1.3

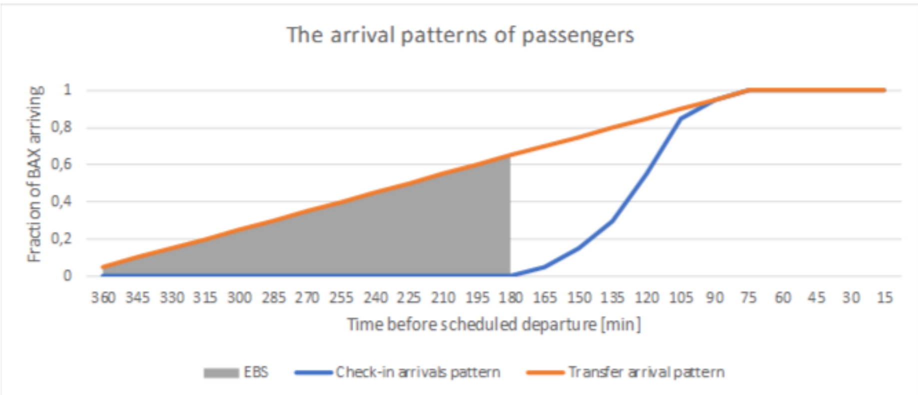

Figure D.1: The passenger arrival distribution used for DOH

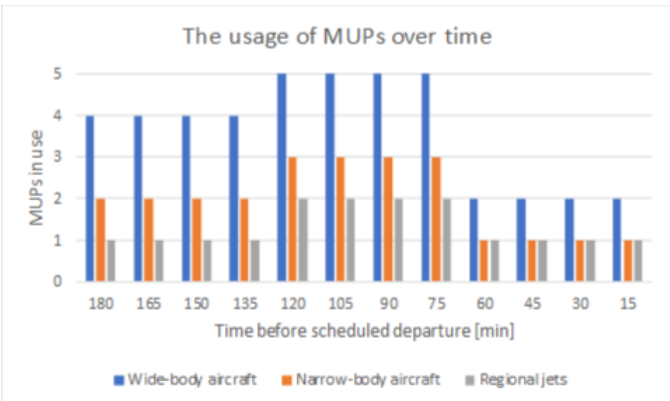

Figure D.2: The MUP reservation for DOH per aircraft type

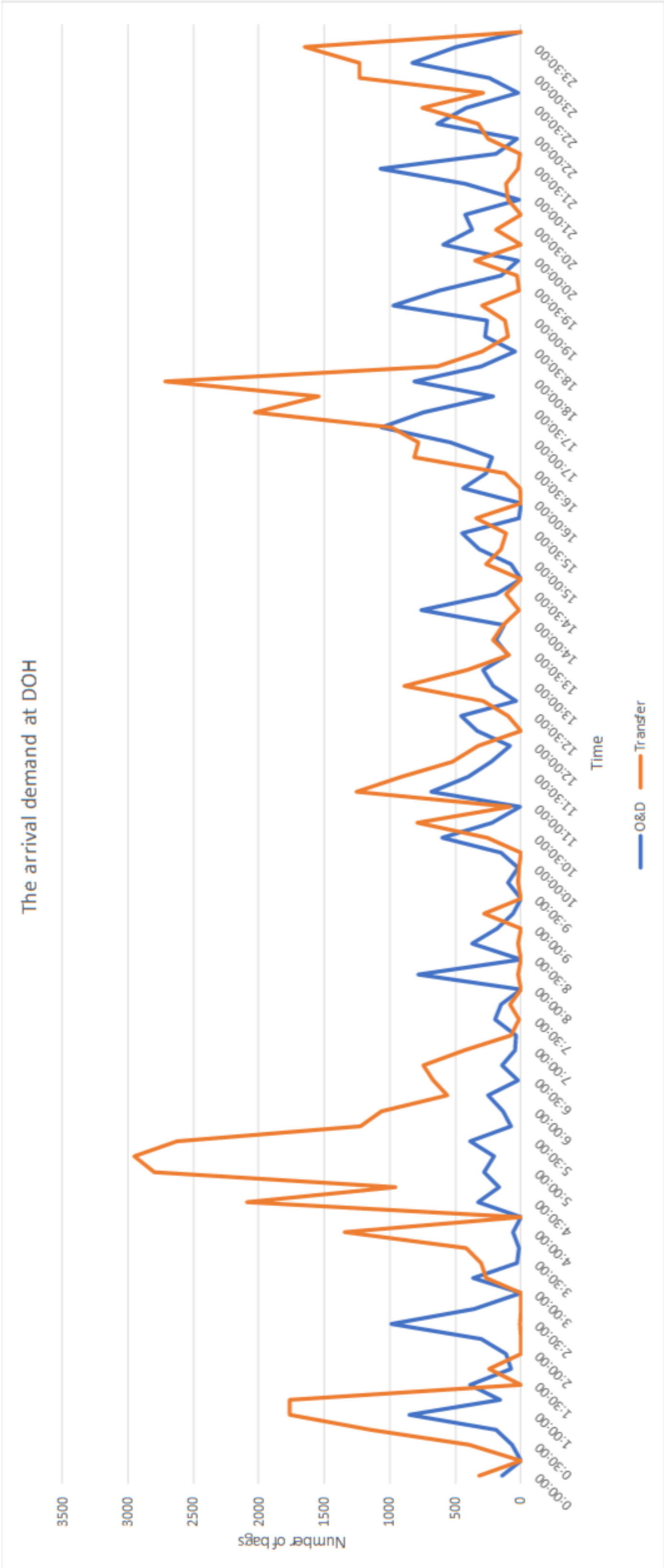

Figure D.3: The arrival demand at DOH

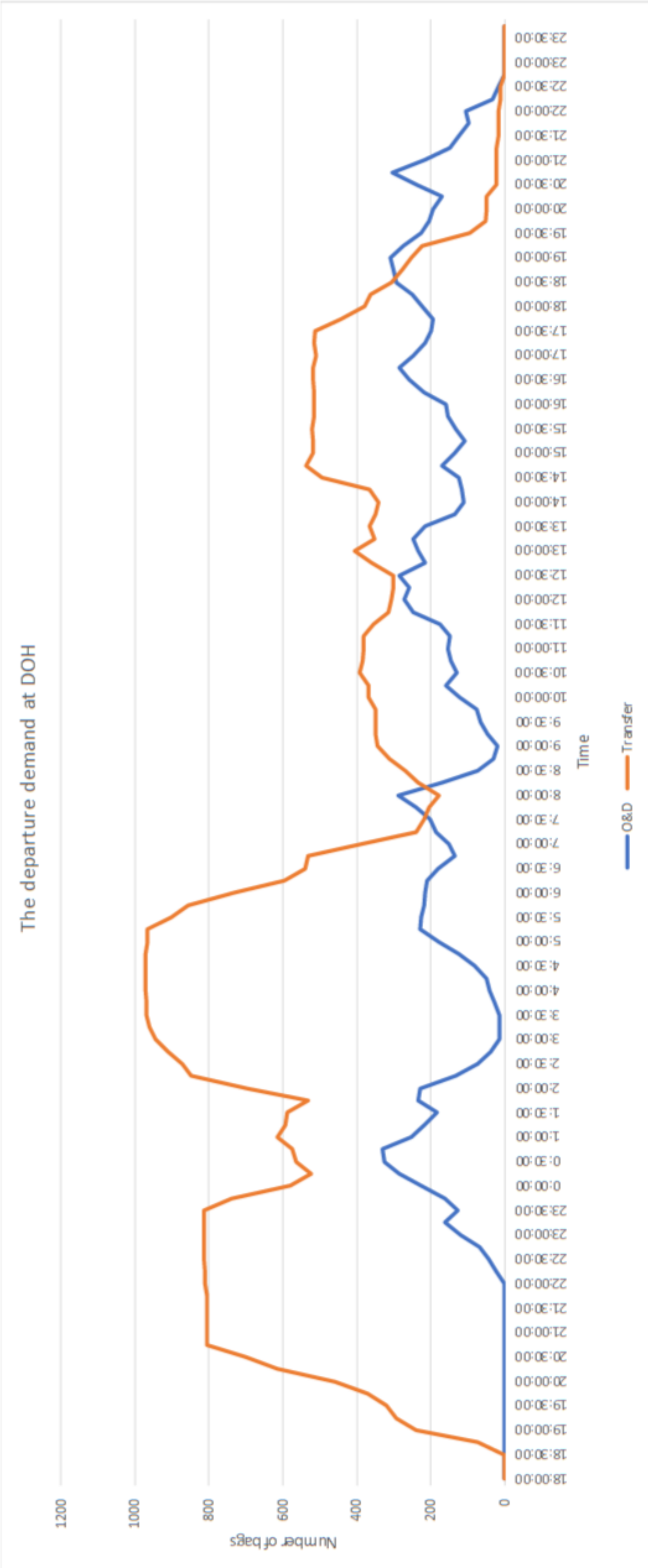

Figure D.4: The departure demand at DOH

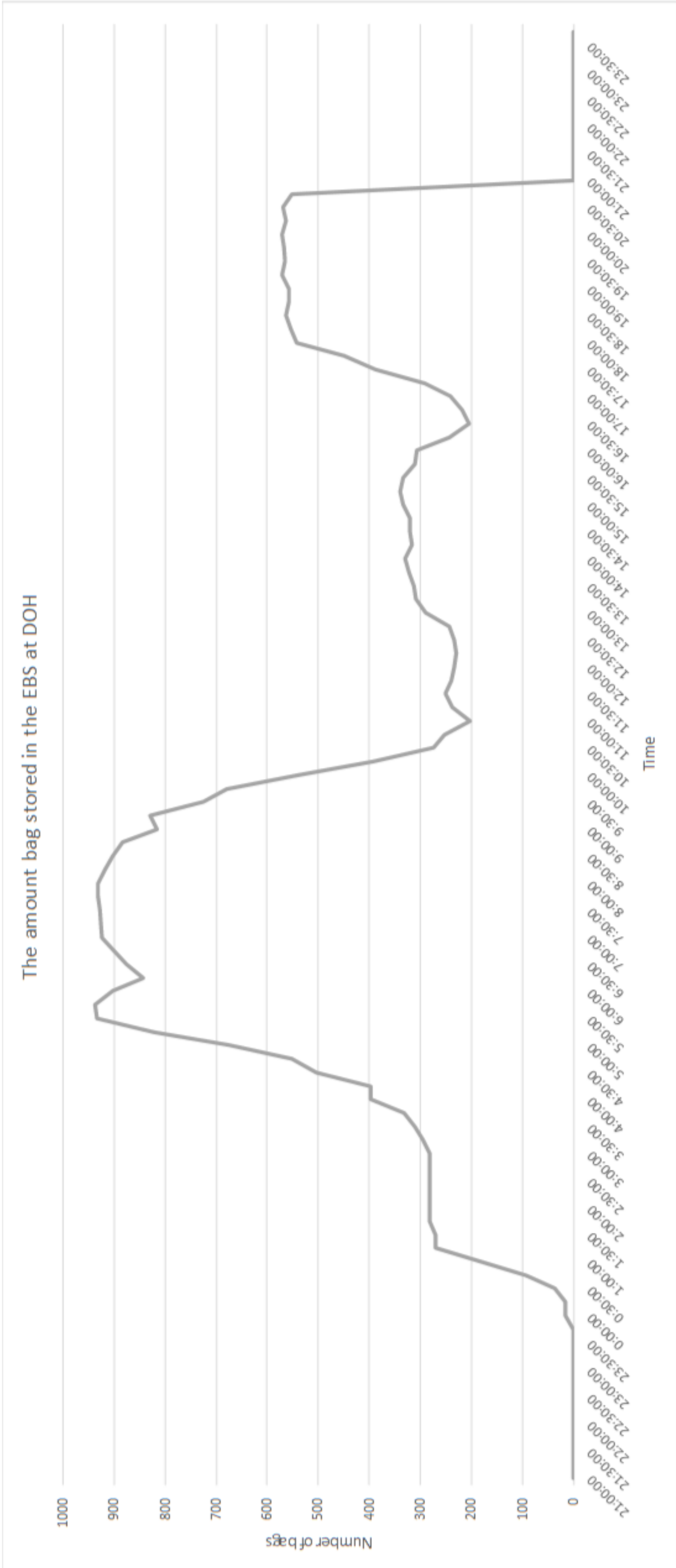

Figure D.5: The EBS demand at DOH

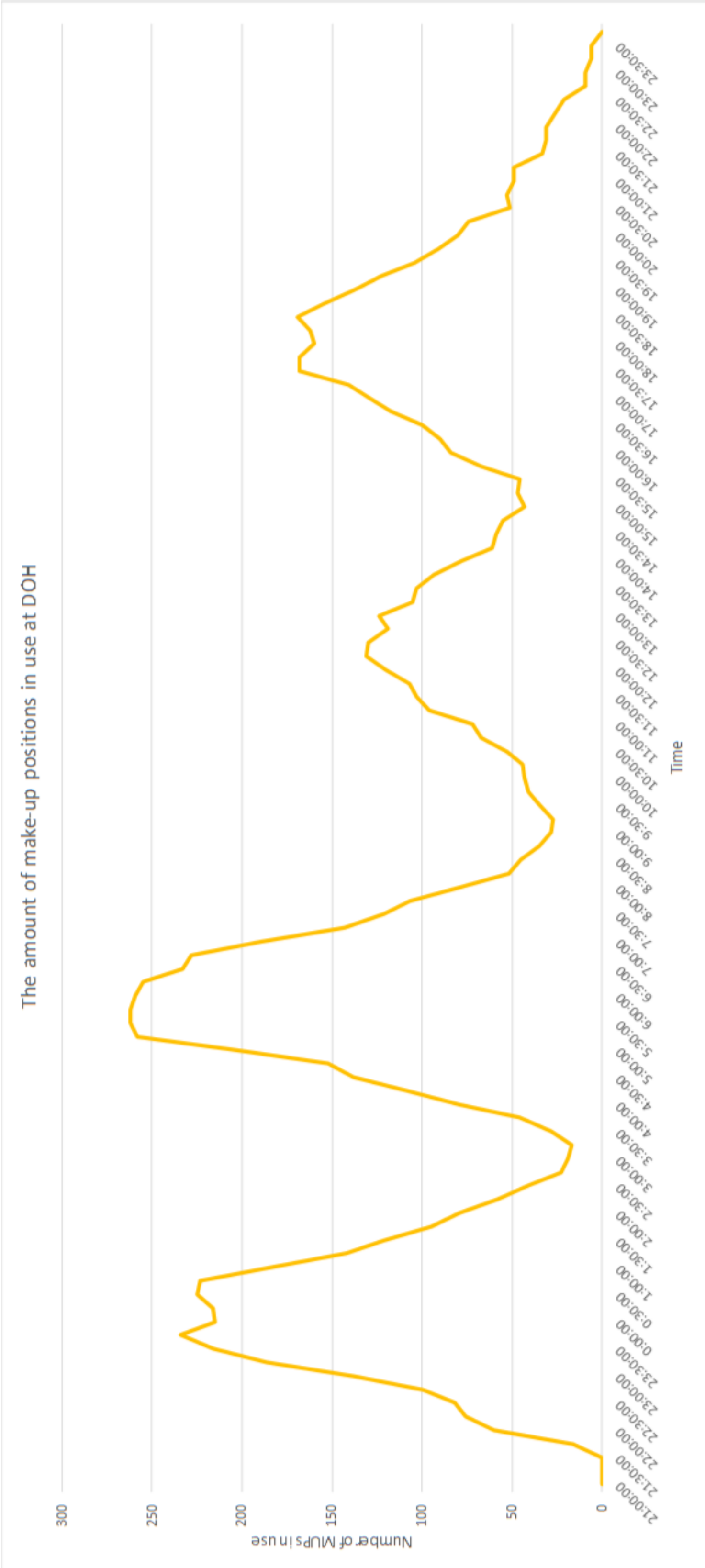

Figure D.6: The MUP demand at DOH

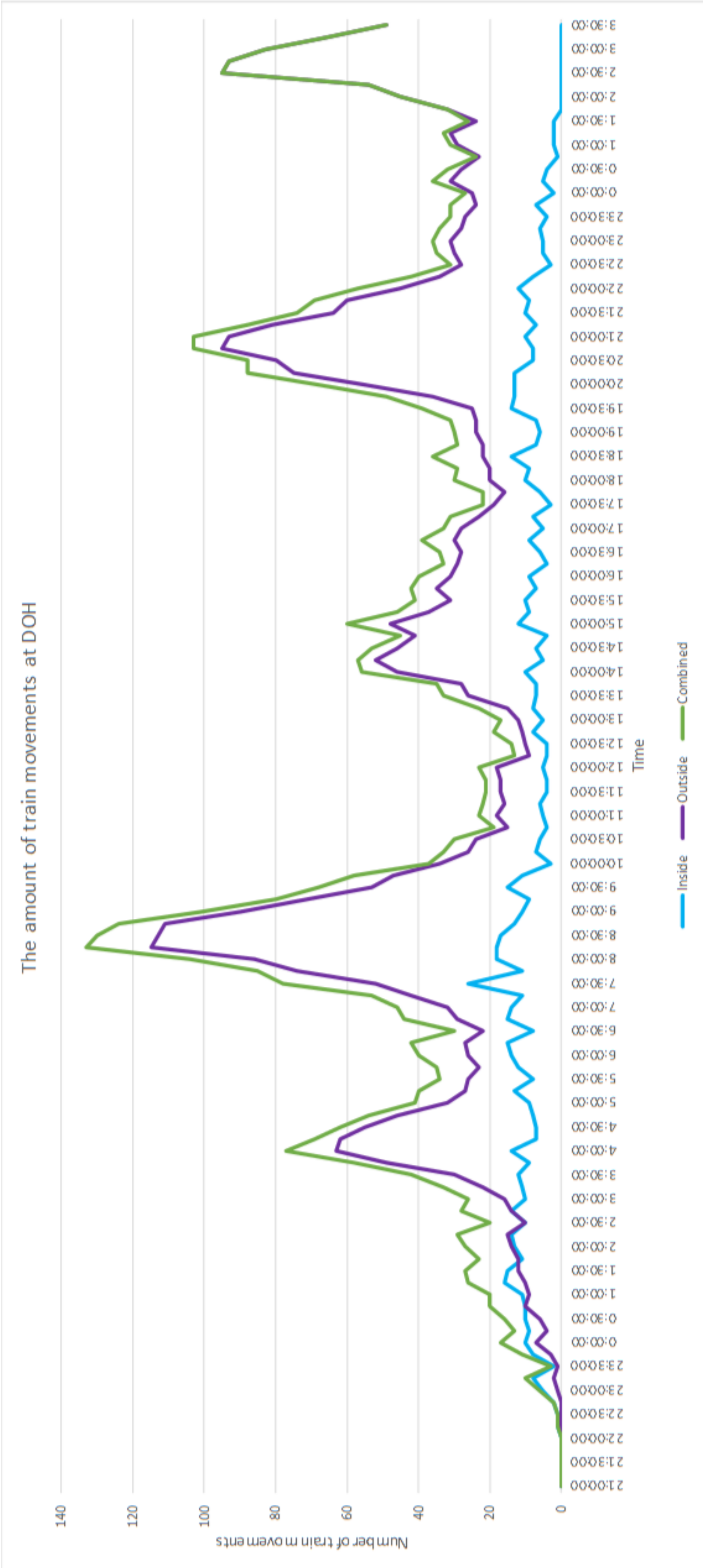

Figure D.7: The train movements at DOH

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfer	Transportation	Loading	Sorting	Total
Equipment type	Two-Step-Drop-Off	Medium speed EDS	OSR	ETD normal search	Carousel+Non-driven ALT	Shuttle rack	Manual_OD	Manual_T	DCT	DCT side loader	Static discharge	-
Equipment amount	15	19	20	32	22	1	8	14	-	8	30	169
System area [m^2]	82,404	1900	2000	13824	6864	1520	720	1260	-	38,4	-	28208,804
Capacity [bags/h]	1350	13300	4000	768	264	3760	7200	12600	-	16000	54000	-
Redundancy [%]	100%	100%	100%	100%	100%	98%	-	100%	-	110%	1090%	98%
CAPEX	-	-	-	-	-	-	-	-	-	-	-	€ 26.179.600,00
Energy consumption [kWh]	30	380	4	57,6	96,8	94	17,6	30,8	4257,8	8	66	5042,6
Operators	6	0	20	32	88	0	16	28	0	0	0	190
LoA	4	7	4	3	6	7	2	2	6	6	5	4,7
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	9,328405797	0,03	0,02	10,64189786

Figure D.8: The table generated for DOH when optimizing for a minimum CAPEX

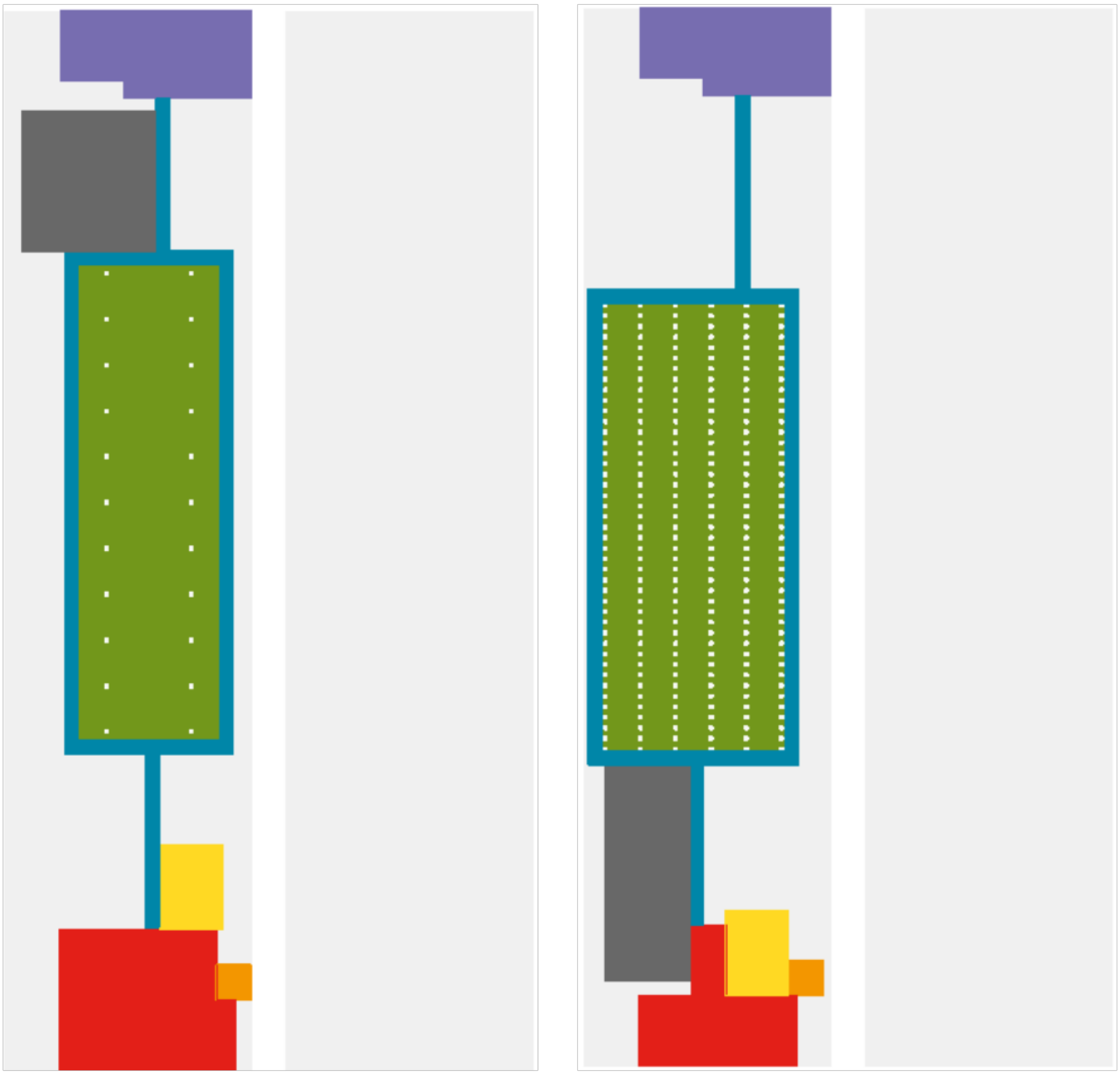

Figure D.9: Top view of the 3D models developed for DOH when minimizing the CAPEX (left) and when minimizing the energy consumption (right)

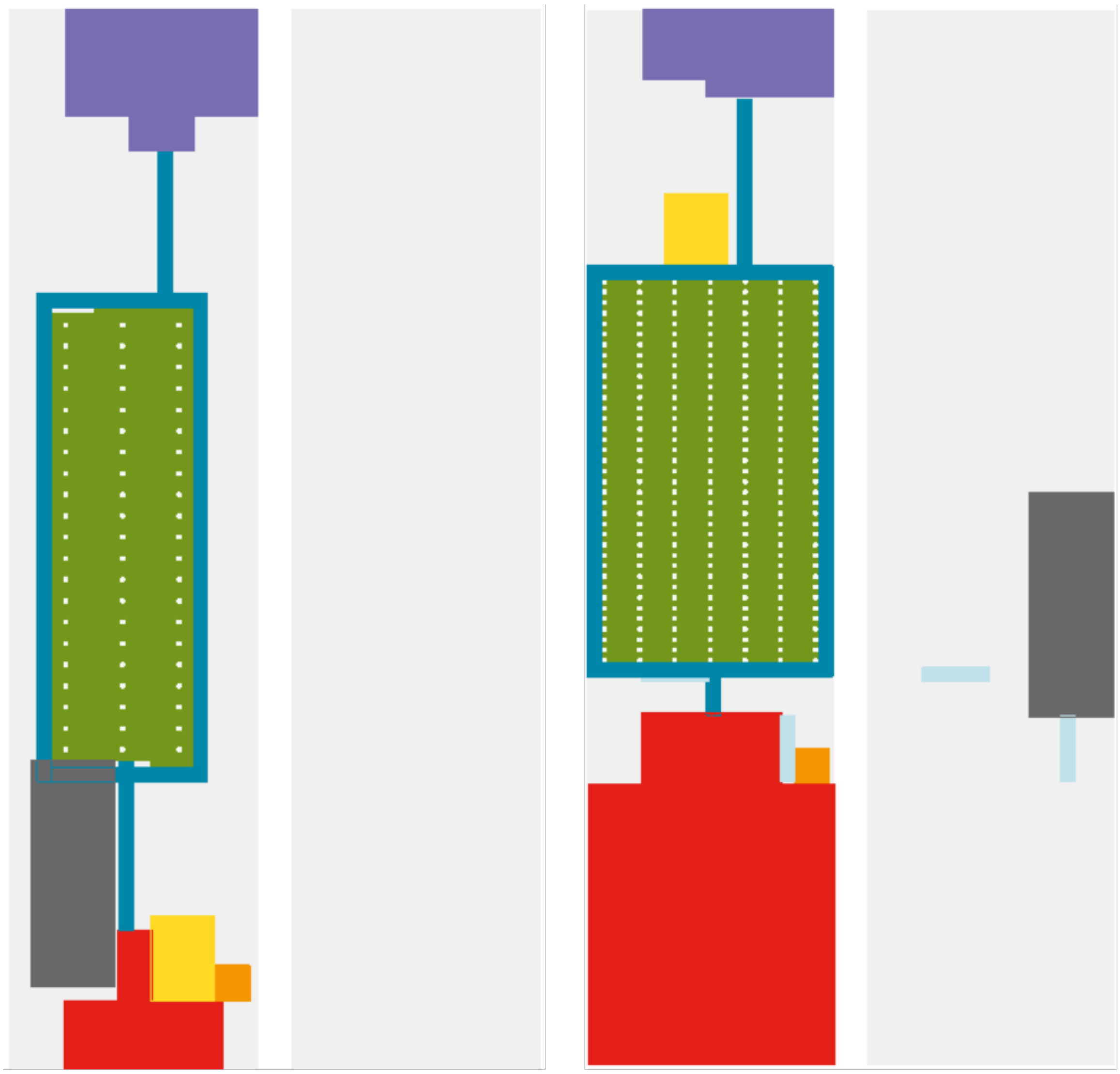

Figure D.10: Top view of the 3D models developed for DOH when minimizing the Operators (left) and when maximizing the operators (right)

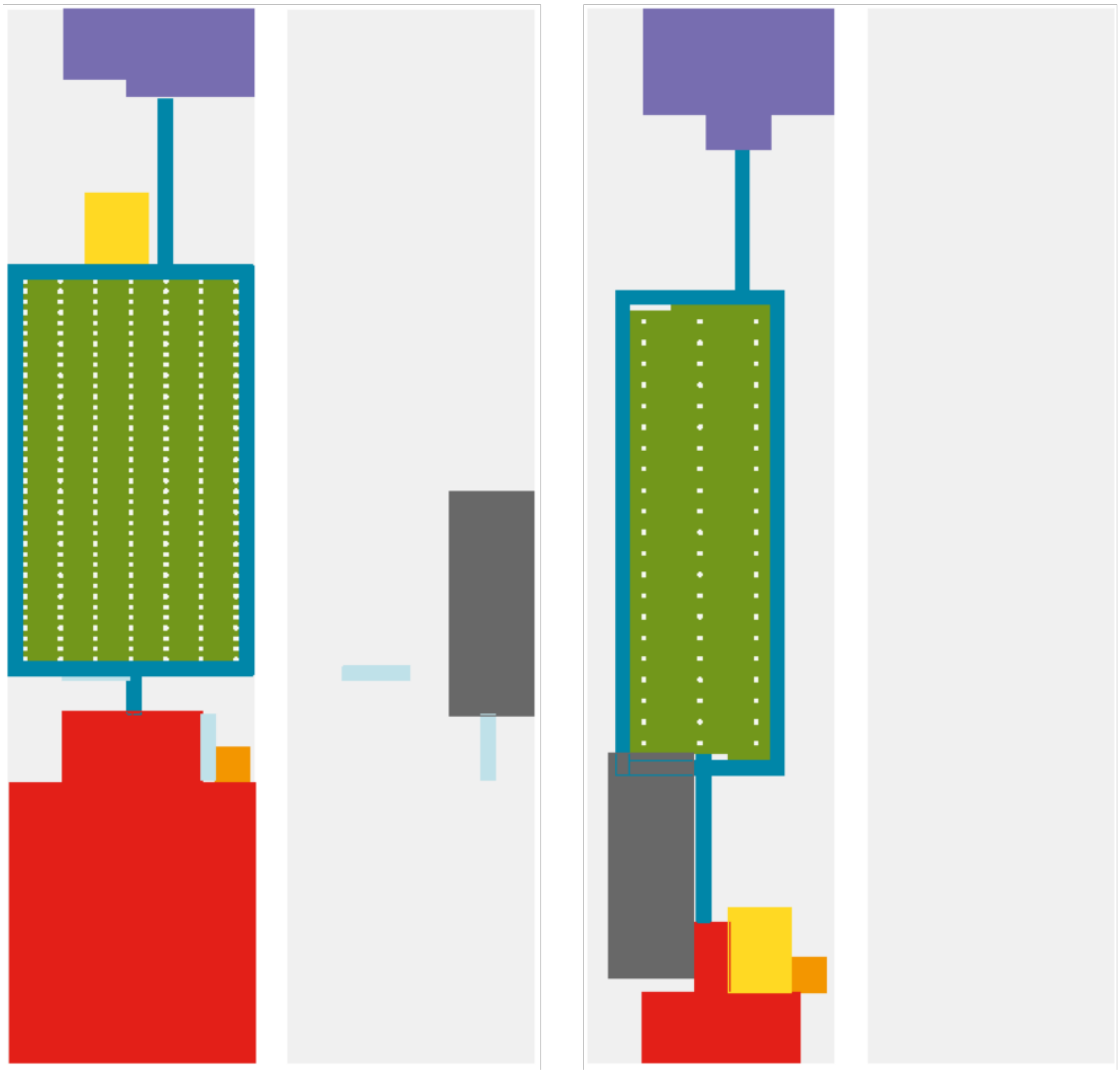

Figure D.11: Top view of the 3D models developed for DOH when minimizing the LoA (left) and when maximizing the LoA (right)

Appendix E

Case study on NAICM

Table E.1: The airline bag ratio used for NAICM

Airline	O&D	Transfer
AM	0.84	1.24
Other	0.84	1.24

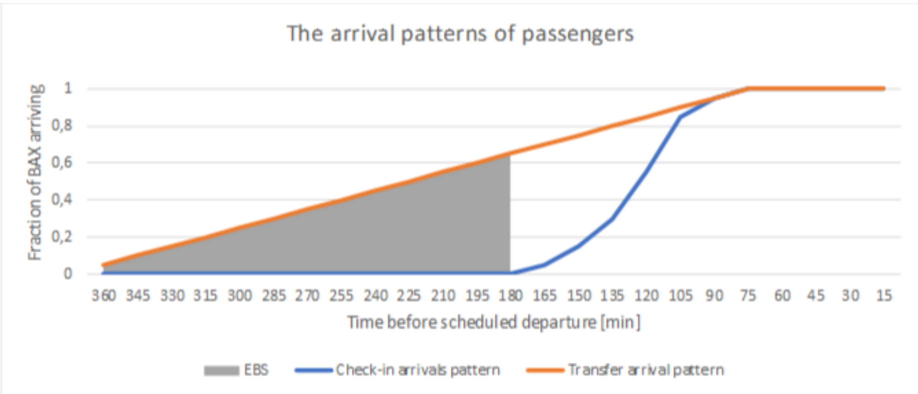

Figure E.1: The passenger arrival distribution used for NAICM

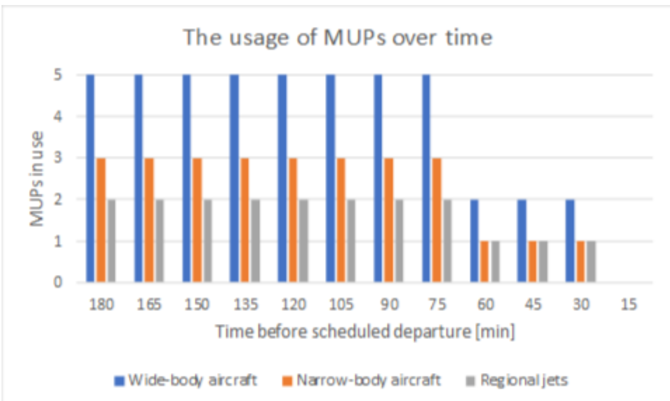

Figure E.2: The MUP reservation used for NAICM per aircraft type

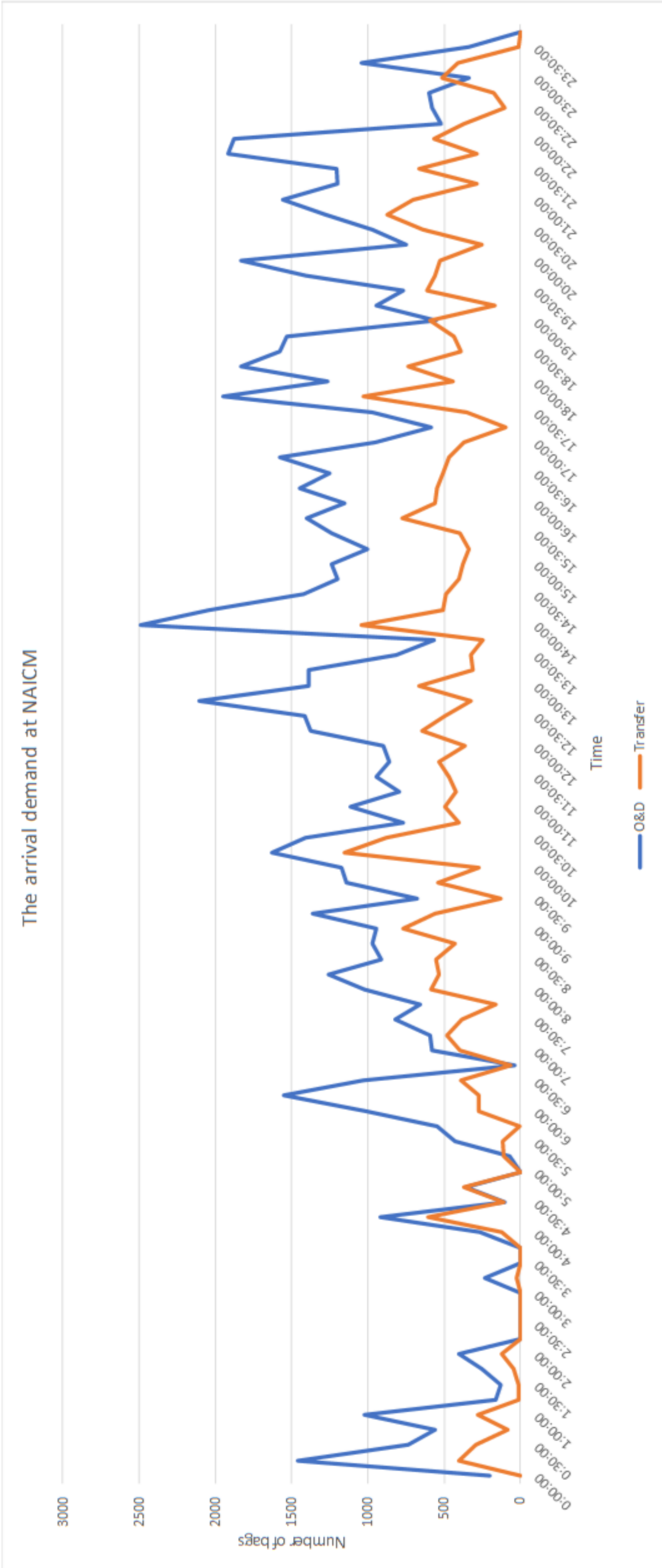

Figure E.3: The arrival demand at NAICM

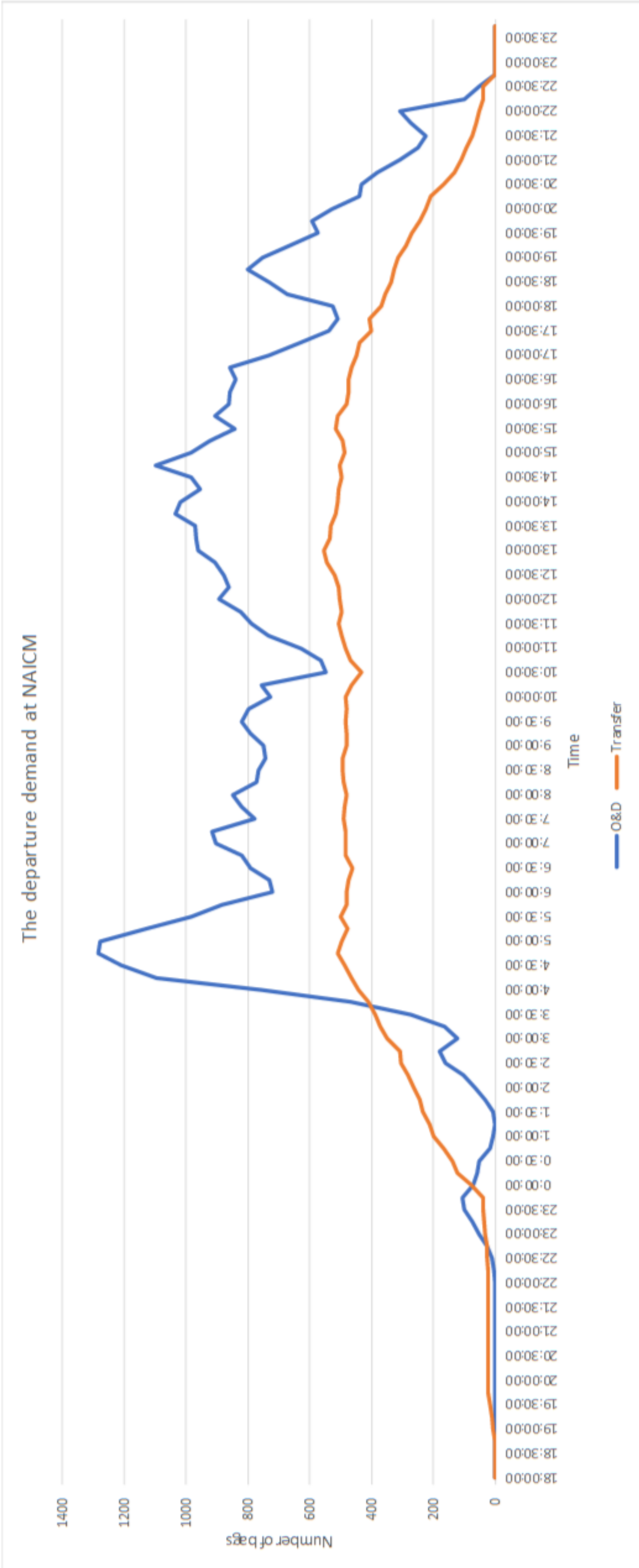

Figure E.4: The departure demand at NAICM

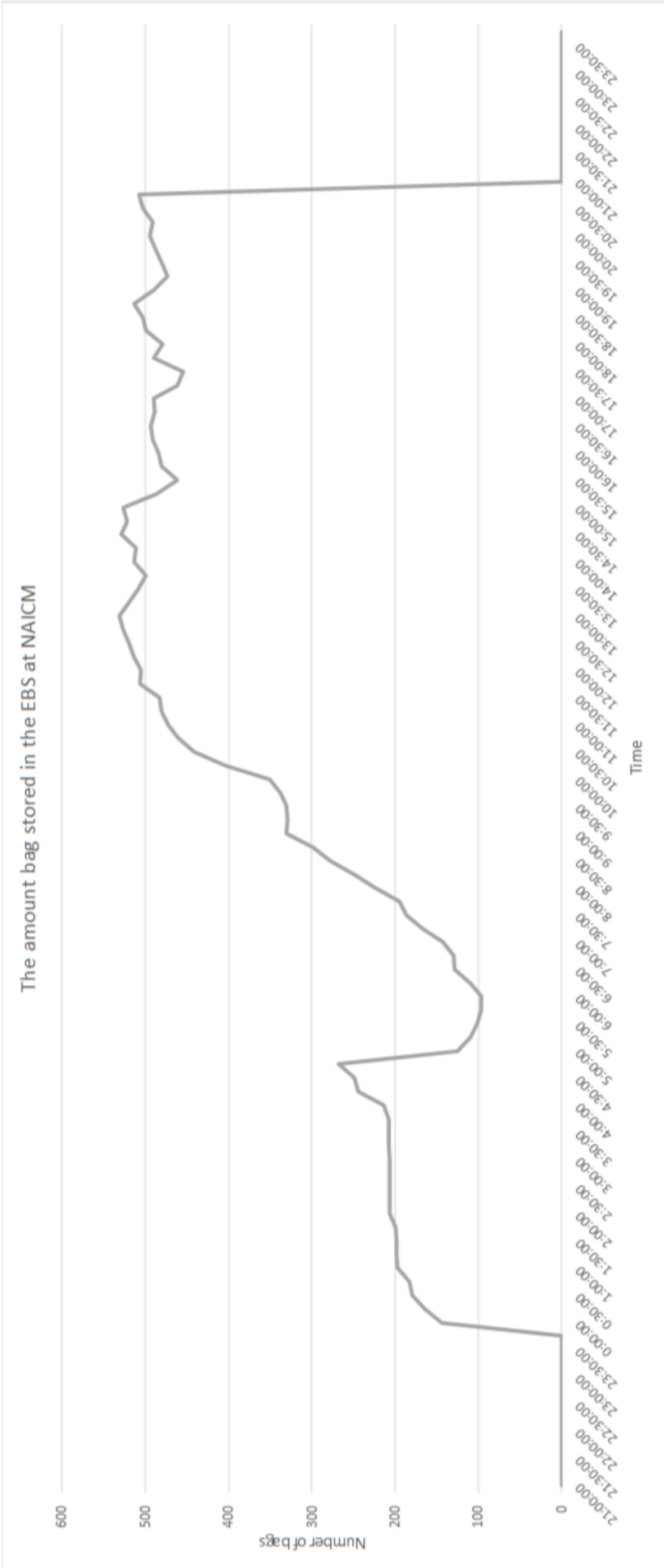

Figure E.5: The EBS demand at NAICM

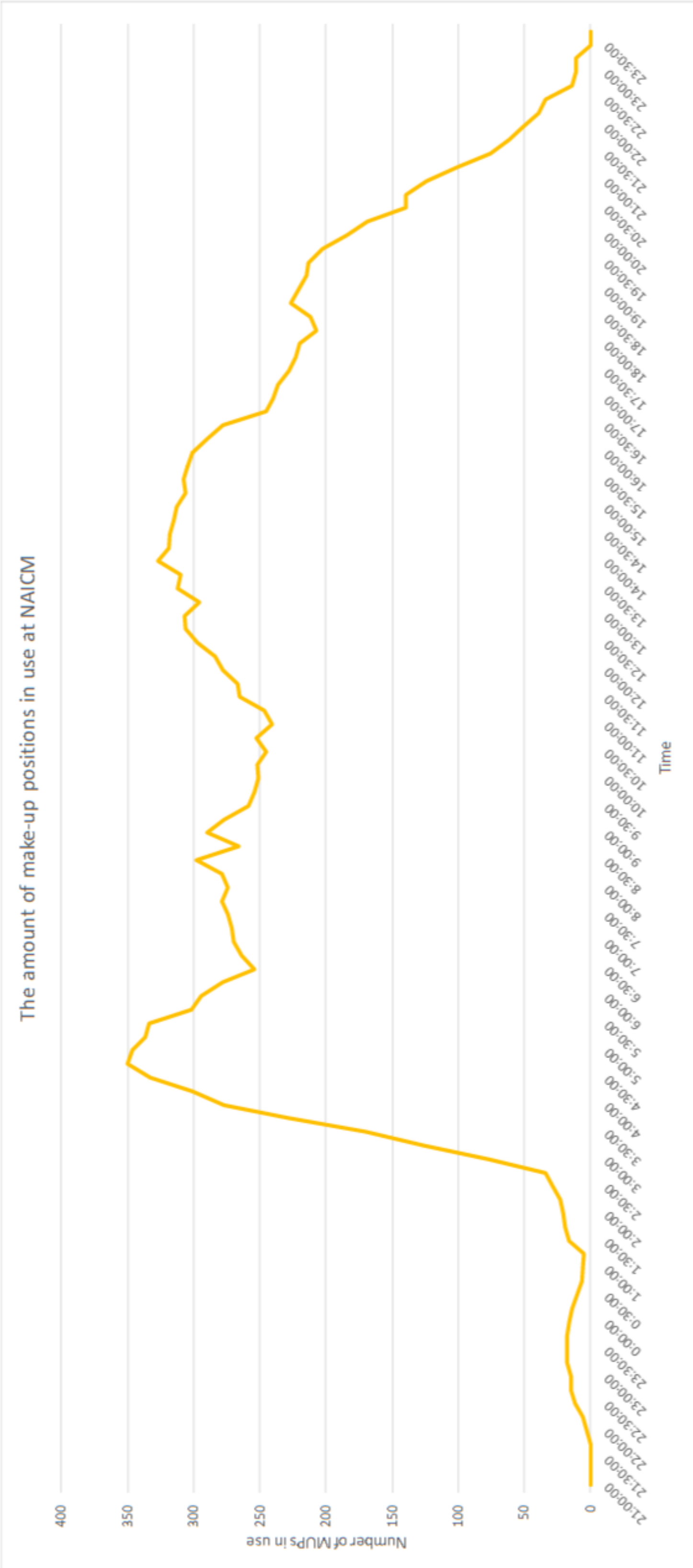

Figure E.6: The MUP demand at NAICM

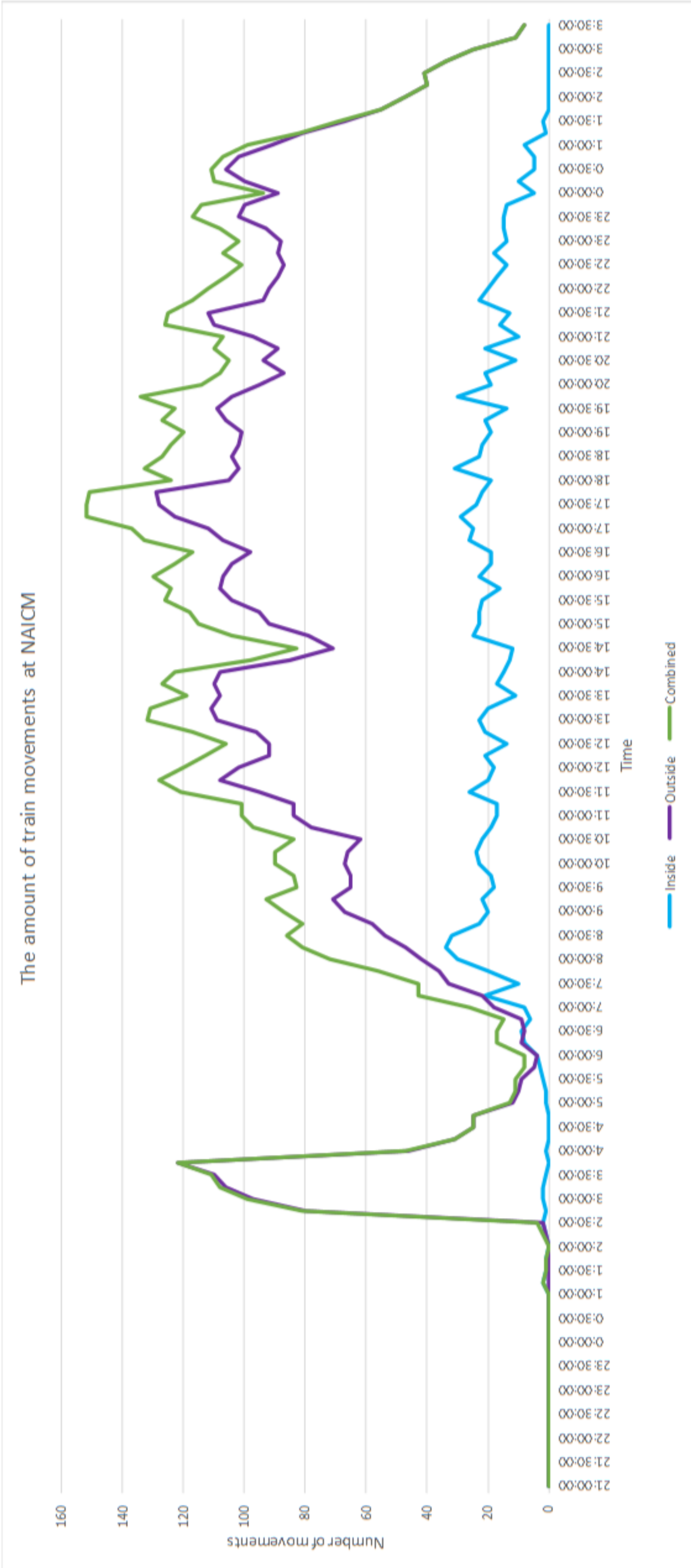

Figure E.7: The train movements at NAICM

	Check-in	HBS level 1	HBS level 2	HBS level 3	Make-up	EBS	Offloading O&D	Offloading transfer	Transportation	Loading	Sorting	Total
Equipment type	Two-Step-Drop-Off	Medium speed EDS	OSR	ETD normal search	Carousel+Train	Shuttle rack	Manual_OD	Manual_T	DCT	DCT side loader	Static discharge	-
Equipment amount	18	4	4	7	9	1	38	3	-	4	12	100
System area [m^2]	499,4136	400	64	756	3159	256	3420	270	-	19,2	-	8843,6136
Capacity [bags/h]	1620	2800	800	168	108	640	34200	2700	-	8000	21600	-
Redundancy [%]	100%	80%	80%	100%	90%	88%	-	130%	-	200%	920%	80%
CAPEX	-	-	-	-	-	-	-	-	-	-	-	€ 9.214.890,00
Energy consumption [kWh]	36	80	0,8	12,6	39,6	16	83,6	6,6	2311,6	4	26,4	2617,2
Operators	8	0	4	7	75	0	76	6	0	0	0	176
LoA	4	7	4	3	6	7	2	2	6	6	5	4,7
In system time [min]	-	1,196825397	-	-	-	-	-	0,066666667	5,112898551	0,03	0,02	6,426390614

Figure E.8: The table generated for NAICM when optimizing for a minimum CAPEX

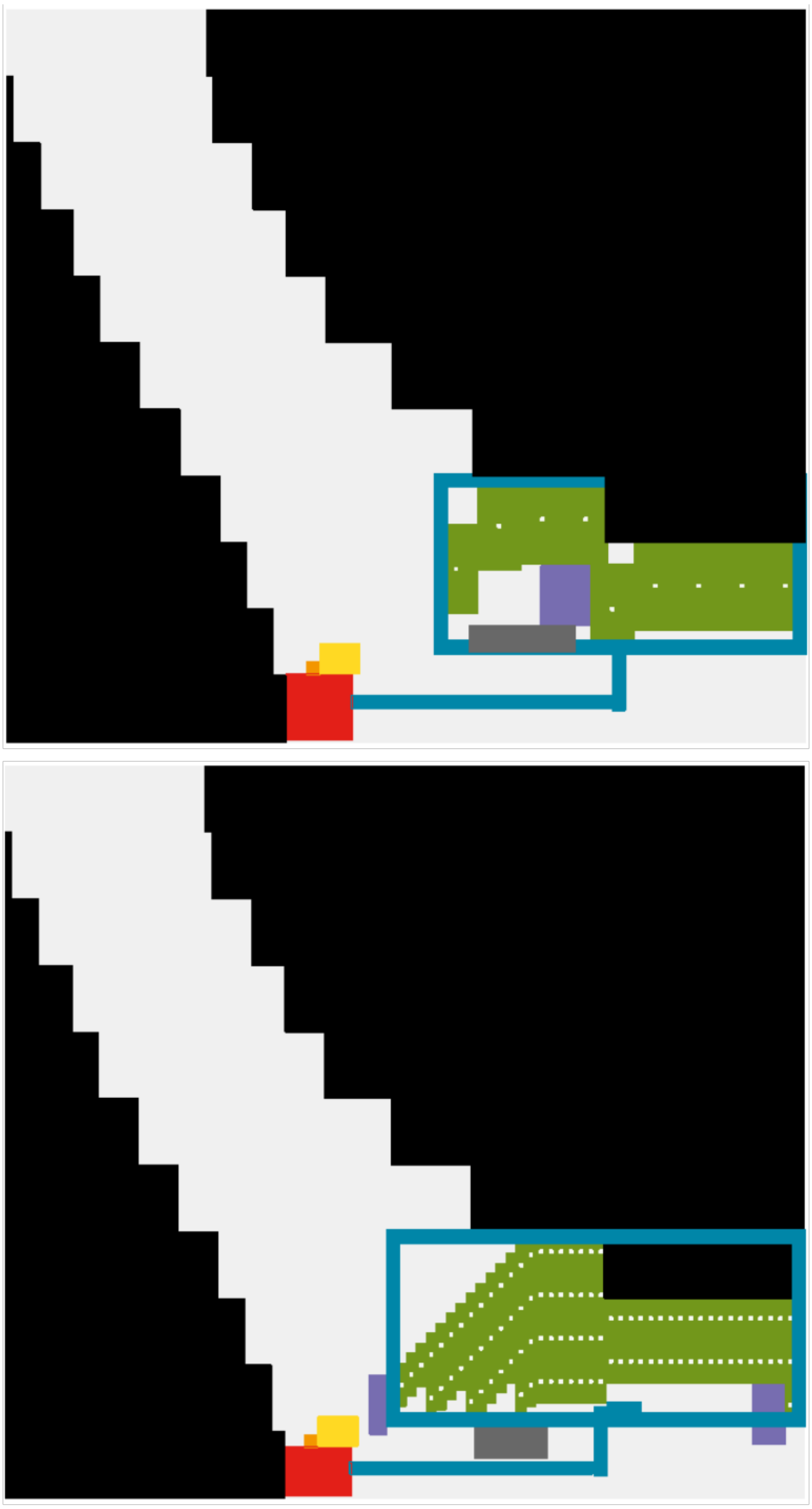

Figure E.9: Top view of the 3D models developed for NAICM when minimizing the CAPEX (top) and when minimizing the energy consumption (bottom)

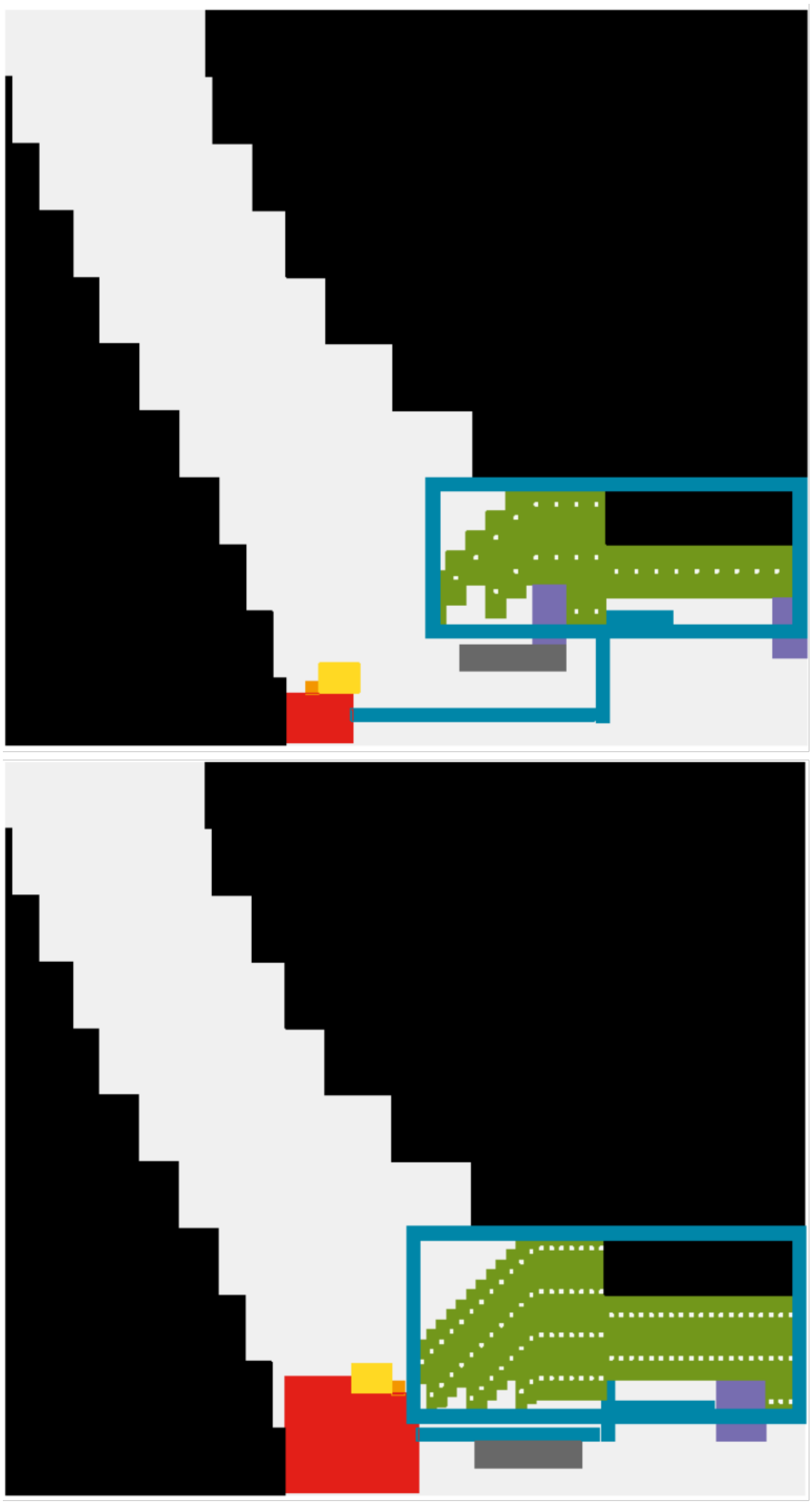

Figure E.10: Top view of the 3D models developed for NAICM when minimizing the Operators (top) and when maximizing the operators (bottom)

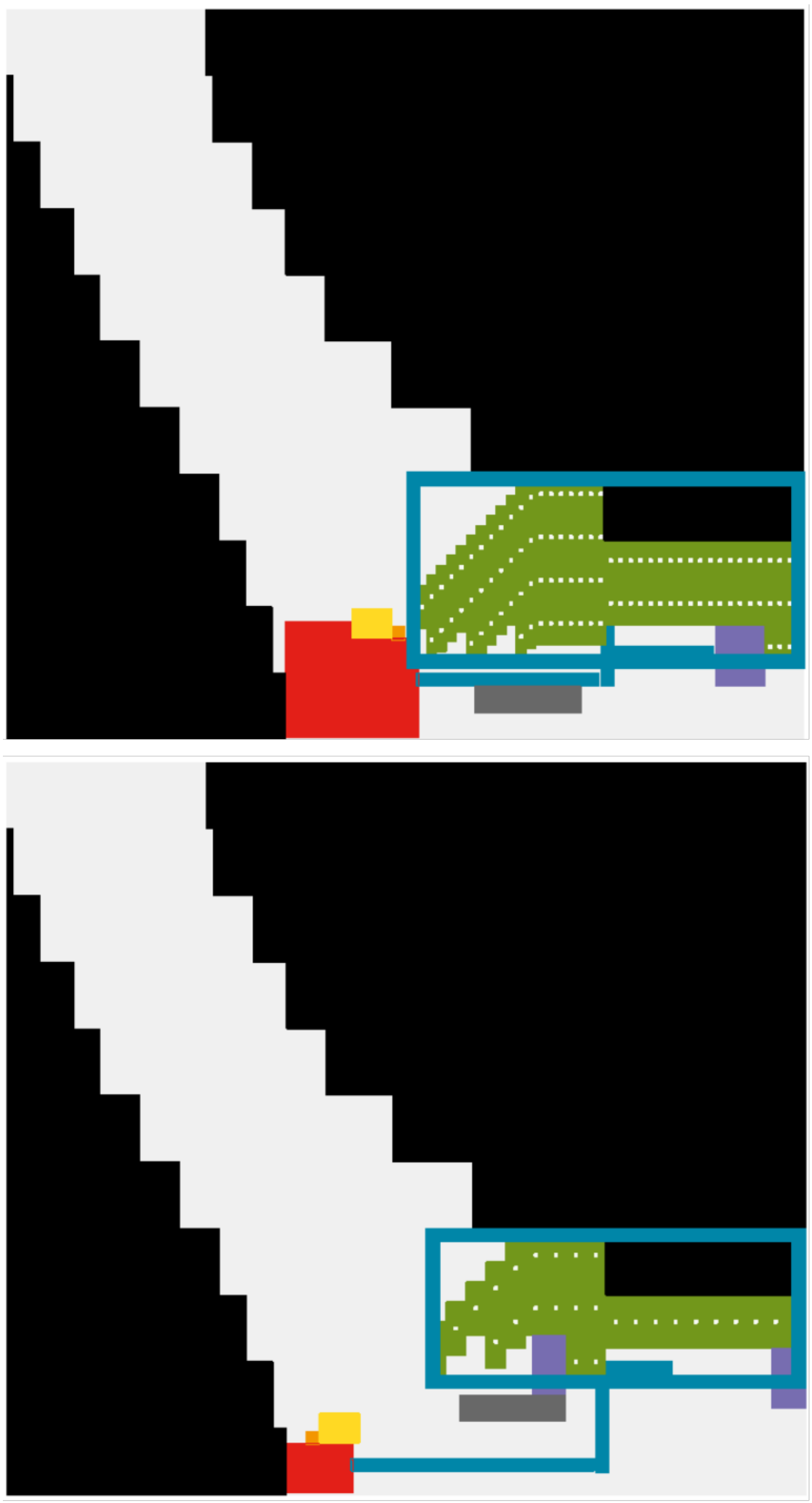

Figure E.11: Top view of the 3D models developed for DOH when minimizing the LoA (top) and when maximizing the LoA (bottom)