Energy consumption of baggage handling systems

Impact assessment on the effect of taking into account energy consumption during preliminary design stage

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Graduation assignment

Delft University of Technology

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Preface

Before you lies the report of my master thesis. During the course of this work I got to know new things about myself and also increased skills on how to tackle complex problems.

Prior to starting with my thesis I knew in which direction I wanted to perform research. On one hand I wanted to perform research on a complex logistic system but I was also looking for a technical challenge, preferably in combination with a focus on increasing sustainable operations of a system or design method.

With this thesis I conclude my time at the Delft University of Technology. A time during which I transformed from a boy into an adult and also into an engineer who is ready to apply obtained knowledge in working life.

I am grateful to everyone who supported me during this project. Especially, my supervisors at RoyalHaskoningDHV, initially Marnix van der Heide and halfway through the project Hugo Huges took over. Also, a special thanks to Hans Veeke for his critical but fair comments on my work throughout the project. Finally, I would like to thank Rudi Negenborn for his efforts to increase the quality of my work by making valuable comments during progress meetings, they really increased the quality of my thesis and last but not least the support from friends and family.

Eric van Enter

May 30, 2018

Abstract

With 7 billion passengers transported in the year 2016 and an expectation for this number to double by the year 2029 pressure on airport facilities is likely to rise as well [1]. The largest airports are energy intensive buildings and consume 100 to 300 GWh anually [2]. Within airports operations the Baggage Handling System (BHS) is categorized as an high energy consuming system [2]. As for the BHS conveying equipment are the main consumers of energy (55% to 70%) [3].

From the perspective of a designer it is very hard to estimate energy consumption in the *preliminary design stage*, where the designer(s) evaluate(s) potential conceptual designs and chooses the most promising one. The first reason is found in the fact that the system should be able to deal with dynamically changing demands. Secondly, measuring system performance involves many dependent variables [4]. Currently it is hard to estimate the impact of design changes on the energy consumption. In order to obtain insight in the energy consumption of conceptual designs the use dynamical models is necessary [5]. This research aims to investigate the impact of taking into account energy consumption in preliminary design stage of baggage handling system design on system performance. The created model has been applied to two research cases: (1) Conveyor based system;(2) conveyor and cart based system.

By performing experimental runs it is found that for both evaluated design concepts energy consumption per piece of luggage decreases with system load. Furthermore, it is noted that the conveyor and cart based concept is more energy efficient than the conveyor based concept, particularly at low system loads. The reason that the difference decreases with increasing load is found in the fact that conveyors operate increasingly efficient with increasing system load while carts are less sensitive to changes in system load since one cart always transports one piece of luggage. Lastly, in case the conveyor based concept a decrease in energy consumption of 25 % has been monitored for the case where all pieces arrive in about three hours in comparison to the situation where luggages arrives more evenly distributed along the day. From this result it is concluded batching poses an interesting solution to decrease energy consumption.

Samenvatting

In het jaar 2016 zijn 7 miljard passagiers per vliegtuig vervoerd. Het is de verwachting dat dit aantal in het jaar 2029 verdubbeld is. Hierdoor zal de druk op de faciliteiten van luchthavens toenemen [1].

De grootste vliegvelden ter wereld zijn energie intensief. Het energieverbruik varieert tussen de 100 and 300 GWh per jaar [6]. In het totale energieverbruik zijn de baggage afhandelingssystemen van deze vliegvelden gedifinieerd als grote verbruikers [2]. Binnen deze systemen wordt het grootste deel van de energie verbruikt door de transport equipment, (55% tot 70%) [3].

Gedurende het design proces is het de taak van de designer van het bagage afhandelingssysteem om conceptontwerpen te evalueren en de naar zijn mening beste te kiezen. Het is vanuit het oogpunt van de designer een lastige opgave om dit te doen. Ten eerste vanwege de grote varieteit in de hoeveelheid bagage en ten tweede doordat de prestaties van het system afhangen van veel variabelen [4].

In de huidige situatie is het lastig inzicht te krijgen in het energieverbruik, om dit te verkrijgen is het gebruik van dynamische modellen nodig [5]. In dit onderzoek is een eerste stap gezet naar het meenemen van het energieverbruik in vergelijking van verschillende concepten. Het gecreeerde model is getest op twee concept ontwerpen: (1) Lopende band concept; (2) Lopende band en kar concept.

Uit de gedane experimenten is gebleken dat het lopende band en kar concept energie zuiniger is dan het lopende band concept. Dit is vooral het geval ten tijde van lage doorvoer van koffers. Het verschil in energievervruik neemt af met toenemend aantal bagage. Dit komt doordat lopende banden energie zuiniger worden bij een hogere doorvoer van bagage terwijl de railkarren minder gevoelig zijn voor het aantal stuks bagage dat wordt afgehandeld.

In het geval van het lopende band concept is een vermindering van het energieverbruik van 25 % geobserveerd tussen de situatie waar alle bagage kort na elkaar het systeem ingaat en de situatie waar het meer verspreid over de dag aankomt. Vanwege deze observatie is het batchen van bagage een veelbelovende oplossing om het energieverbruik te verminderen.

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Chapter 1

Introduction

While many passengers travel via commercial airlines, many do not realize how their luggage is handled by the BHS after handing it in at the check-in desk. While the BHS of an airport is one of the most important factors to the airport's efficiency and reliability [12]. Most of the passengers desire to take some sort of luggage onto their flight. If it qualifies as carry-on luggage the passenger is allowed to take the luggage into the airplane. However, in case luggage does not qualify as carry-on luggage it has to be handed in at the check-in desk and is considered as hold luggage and is handled by the BHS.

A major factor that makes a BHS a challenging area of research is found in the highly dynamically changing demands. It is an effect of the volume of luggage entering the BHS, the multitude of different airplane capacities, changing flight schedules, lost luggage, barcode misreads, early luggage, late luggage and equipment downtime. The result is a highly stochastic and dynamic operational environment [13].

1-1 System description

The purpose of Baggage Handling Systems (BHSs) is to enable an increased comfort-level to passengers during their travel due to the fact that they do not need to carry their hold luggage after check-in in an efficient manner. When considered as a black box, as illustrated by Figure 1-1, the function of the system is to transform incoming luggage (input) into handled luggage (output).

Figure 1-1: Black box of BHS

In more detail; airports make use of a BHS to provide both fast and comfortable handling of passenger bags by collecting, sorting and finally delivering hold luggage to the correct location while fulfilling requirements on system performance. A visualization of a simplified BHS is represented in Figure 1-2.

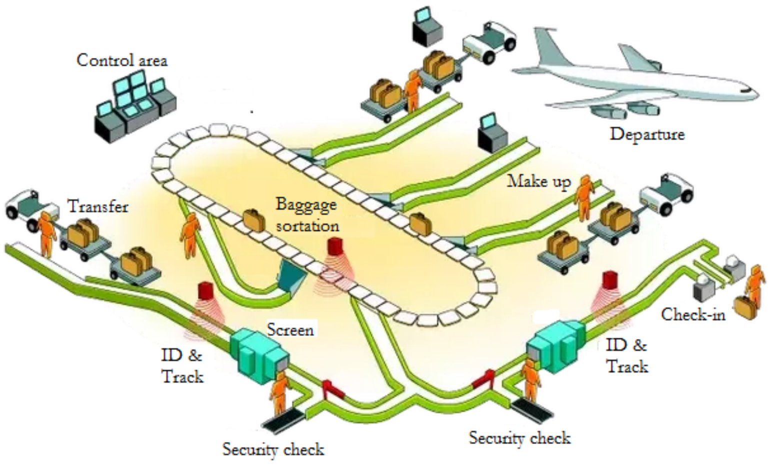


Figure 1-2: Rich picture of BHS [14]

From an operational point of view an airport can be divided into two main areas of activity, as can be seen in Figure 1-3. As for this research focus is on a part of the landside operations, specifically the BHS which is located in the Airport Terminal Building (ATB).

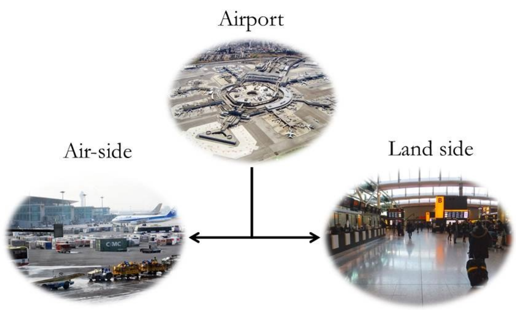


Figure 1-3: Division of airport operations [15],[16], [17]

Its position within the building is illustrated by Figure 1-4, where a section view of the Chennai airport ATB and its BHS are found. According to [18] the BHS typically fills about 10 % of the ATB area.

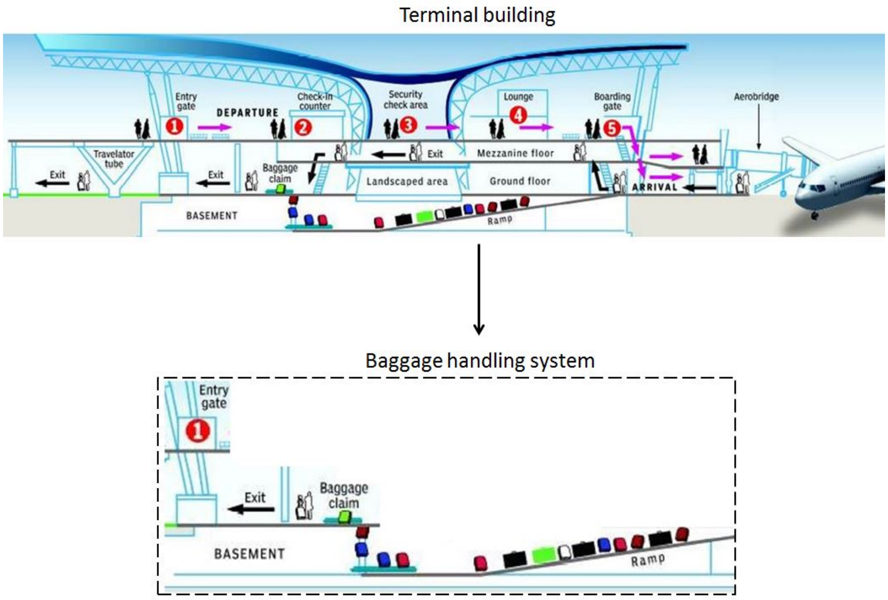


Figure 1-4: Section view of Chennai airport terminal, India [19]

From the figure it can be seen that departing passengers arrive at the ATB via "the entry gate" (1). After that passengers are required to visit "the check-in area" (2). At this moment in time pieces of luggage which are destined for the luggage compartment are separated from the passengers and travel towards the airplane by the BHS which is often located in the basement area. Several flows of hold luggage may exist within the BHS [20]:

1. Moving luggage from the check-in to the boarding gate (Check-in luggage)
2. Moving luggage from one airplane to another during (Transferring luggage)
3. Moving luggage from the arrival gate to the baggage reclaim area (Reclaim luggage)

An airport is classified as a hub in case its main function is to transfer luggage. Otherwise, an airport is classified as a point-to-point or Originating and Departing (OD) if its main purpose is to handle passengers who start or end their journey at the airport [21].

1-2 Research context

Market growth As a consequence of globalization and developing economies becoming more mature, airports face increasing passenger numbers [1]. According to PwC airports are important to regions and countries due to the fact that: "Air connectivity is key to unlocking a country its economic growth potential, in part because it enables the country to attract business investment and human capital. An increase in air connectivity also spurs tourism, which is vital to many countries' economic prosperity." [19]. With 7 billion passengers transported in the year 2016 and an expectation for this number to double by the year 2029 pressure on airport facilities is likely to rise as well [1].

As a result existing BHSs have to be modified and new ones are going to be built. Since global warming, depletion of natural resources and scarcity of energy [22],[23] are becoming increasingly important it is of critical importance to perform operations in a sustainable manner in order to minimize its contribution to global warming.

Sustainability trend Over the last years, focus towards sustainability has increased within society, governments and companies. Not only airports themseelves but also manufacturers of equipment have increased their focus on sustainability by developing equipment which is increasingly energy-efficient.

As a result of this increased focus on sustainability across the world, new initiatives have been introced. Leadership in Energy and Environmental Design (LEED) certificates for instance have been introduced since 2010, a rating system for green building, design, construction, operations, and maintenance. LEED ratings recognize several performance levels: LEED, LEED silver; LEED gold; and the highest rating, LEED platinum [24].

Another example is the Airport Carbon Accreditation which has been launched by ACI in the year 2009, aiming at the assessment and recognition of participating airports efforts to manage and reduce their CO2 emissions. By the year 2015, 156 airports have been rated by "Airport Carbon Accreditation", these airports together handle 2.1 billion or 31.3 % of global air passenger traffic [25].

Airport energy consumption A European research project funded by the European Union, CASCADE, performed extensive research on the energy consumption of multiple airports. One of the outcomes from this research is that the BHS is categorized as an high energy consuming system within airport operations [2], as listed in Appendix B.

According to CASCADE the typical electricity consumption of a large airport ranges between 100-300 GWh per year which equals to 25,000 to 75,000 average households consisting of two parents and one child in the Netherlands [6].

Table 1-1 summarizes the energy consumption of the largest airport in the Netherlands, Schiphol. Typically , about 7 % of the total energy consumption is due to baggage handling [6].

Table 1-1: Energy consumption BHS Malpensa airport, januari 2011 - terminal 1

Airport energy consumption	kWh ($*10^6$) / year	Households equiva-lent	Passengers ($*10^6$)	kWh / passenger	Nr of bags ($*10^6$) [26]	kWh/ bag
Schiphol	183.18	46,000	79.3	2.3	50	3.66

Within the BHS conveying equipment typically consumes between 55% and 70% of the total system energy consumption, depending on the size of the airport and occupation rate of the BHS [3].

As can be seen in Figure 1-5, Rotterdam airport which is a relatively small airport, more than half (55 %) of the total energy consumption is due to conveying of luggage. In case of

Rotterdam airport 34 % of the energy consumption is due to Hold Baggage Screening (HBS).

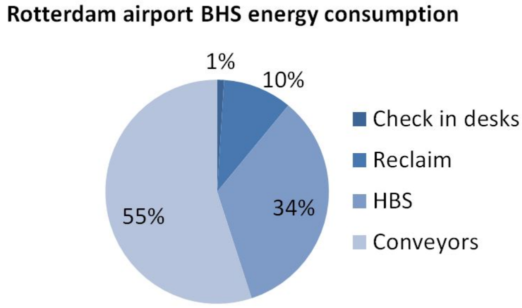


Figure 1-5: BHS energy consumption Rotterdam airport

1-3 Problem description

Currently, energy consumption is not given the attention it deserves during the design of a BHS and a change in mindset is needed. During the design process typically five phases are distinguished, as illustrated by Figure 1-6. It can be seen from the figure that the freedom of choice decreases as the project proceeds, while the costs of implementing changes to the design increase as the project progresses. It is expected that the same trend holds for energy consumption. Within this research focus is on the second stage, that of the *preliminary design*, where the designer(s) aims to develop the created conceptual systems into preliminary systems. At this stage the most promising ones are evaluated in more detail. The researches

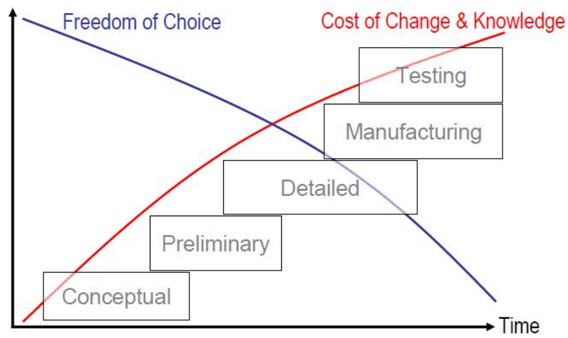


Figure 1-6: Cost increase with project phase [7], [8]

on baggage handling evaluated during the course of this research often focus on parts of the BHS and in most cases does not focus on energy consumption. Firstly, within reseach on baggage handling, following the terrorist attacks on September 11, 2001, focus on research on improving the security of the BHS is seen [27].

Secondly many other researches focus on increasing the capacity of the BHS, by for instance performing research on optimization of gate assignments [28], soft starting of conveyors [29] or a new method to load narrow body aircraft [30], increasing the transfer performance [31] and research on how to optimizing check-in conditions [32].

The literature on energy consumption of BHSs often focus on parts of the system and assume an existent structure. P. Vogel for instance performed an investigation at Rotterdam airport and managed to decrease conveyor activity by 67 % and system energy consumption by 30 % [3]. Another research performed by G. Lodewijks investigated the possibility of saving energy consumption by reducing the delay time of conveyors [33]. Those researches focus on systems which already purchased, built and are in operation.

However, it could not be retrieved from literature what the impact is of obtaining more insight in energy consumption of the BHS in the early stage of the design process where the lay out is not yet definitive while it is expected that it is here where measures in reducing energy consumption are expected to be effective.

In practice, often performance indicators other than energy consumption are considered more important. For instance handling peak capacity, system reliability, ease of maintenance, security and investment costs.

Furthermore it is the case that suppliers of equipment are not yet involved in the project since they are not allowed to cooperate in the project prior to tendering of the project. At the moment in time they come into play, much of the decisions on resources and structure have already been made.

1-4 Research objective

"To investigate the impact of taking into account energy consumption in preliminary design stage of baggage handling system design on system performance"

1-5 Research questions

This research is performed to answer the following main question: *"What is the impact of considering energy consumption in the preliminary design stage within the design process of baggage handling systems on performance?"*

By answering the following questions:

1. What is the current state of baggage handling?
2. What design considerations affect energy consumption in BHS design?
3. What is the value of - and difference in energy consumption of selected BHS design concepts in response to varied input characteristics?

1-6 Research scope

Scope

This research focusses on the impact of obtaining insight on energy demand of a BHS in preliminary stage stage of the design process.

Limitations to scope

Passenger behaviour is beyond the scope of this research. Surroundings of the BHS such as lighting and HVAC systems are not taken into account in obtaining system energy consumption. The loading of the airplane is beyond the scope of this research. During this research only equipment which is commonly used in baggage handling is investigated.

1-7 Research approach

During this research literature on both the BHS and factors influencing its energy consumption have been assessed. Information is also obtained by conducting interviews with employees from: RoyalHaskoningDHV, NACO, Schiphol and SEW Eurodrive. Furthermore, parts of the Delft System approach have been used to gain more insight in the functions and processes performed by the BHS [34]. Also, an analysis of the BHS has been performed by making use of the process chain model", as proposed by Blecker in "Innovative methods in logistics and supply chain management" [35].

1-8 Research outline

Firstly, "Chapter 2: The baggage handling system" discusses the BHS processes and key performance indicators of the system. After that it describes the current situation on the level of sustainability. Hereafter the design stages of system design are evaluated in more detail.

Secondly, "Chapter 3: Energy consumption of the baggage handling system", focusses on design considerations in baggage handling regarding system energy consumption from the viewpoint of the designer.

Thirdly, "Chapter 4: Introduction towards research case", a research case is proposed based on the knowledge obtained in the previous chapters.

Before putting this research case to the test "Chapter 5: Model design" discusses the research case in more detail. Next, in, Chapter 6: Experimental plan", the model verification is performed, research scenarios are defined and standard input characteristics are discussed.

The next step is to evaluate results of the defined research scenarios, they are discussed in "Chapter 7: Results". Finally, the report closes off with "Chapter 9: Conclusion" and Chapter 10: "Recommendations".

Chapter 2

The baggage handling system

Initially, this chapter discusses the functions performed by a BHS. After that its performance indicators are investigated in more detail.

A visualization of the BHS considered as a black box is displayed by Figure 2-1. As indicated in the figure the purpose of the BHS is to transform incoming luggage into handled luggage and by doing so it aims to fulfil a set of requirements, to which extent it succeeds in doing so is expressed by its performance indicators or Key Performance Indicators (KPIs). Then, in the next part of the chapter factors affecting the level of sustainability of the system is evaluated in detail. Finally, the design stages of a BHS are discussed.

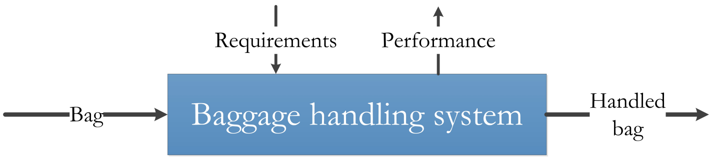


Figure 2-1: Black box of BHS

2-1 The baggage handling process

Separation of hold luggage and passengers at check-in causes the necessity of a complex BHS. The reasons for creating such a BHS are multiple [36]:

1. To ensure that maximum time is available to sort and screen bags
2. To ensure smooth central search and immigration processes and minimize throughput time
3. To ensure that passengers who are at departure areas do not need to handle large and heavy pieces of luggage
4. To promote a convenient trip to passengers and above all to provide the opportunity for passengers to spend their money at the airport

By further opening up the black box, Figure 2-2 is obtained. It can be seen that the BHS performs 3 sub-functions in its environment. At first when a piece of luggage enters the system, the piece of luggage is identified and screened (Collect). Then, the luggage is sorted out (Sort) and finally luggage is delivered and ready to be loaded onto a airplane (Deliver).

After opening up the sub-functions, the processes as displayed in Figure 2-3 result. The input of the system either originates either from luggage brought by a passenger, "check-in", or originates from a transferring flight and the "load process is performed on system entry. The

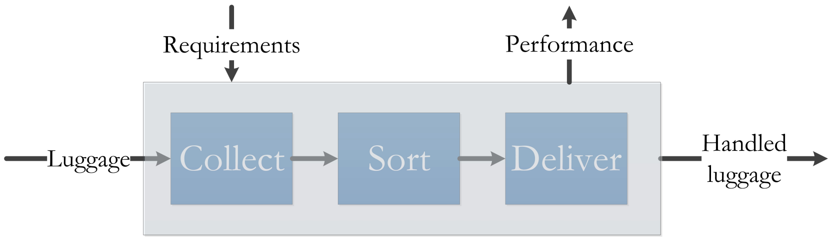


Figure 2-2: Functions performed by BHS and discrete transportation systems

next step is to identify each piece of luggage, so that it is known who owns it and what its destination is.

Each piece of luggage putted into the system at check-in passes through HBS. While in case luggage originates from an arriving airplane it only needs to be checked only in some occasions, for instance when a passenger behaves suspicious or when the airplane originates from high risk countries.

The next step is to sort out the pieces of luggage, temporarily store them if necessary. Finally, luggage is delivered to either a passenger via reclaim or to a departing flight via make up.

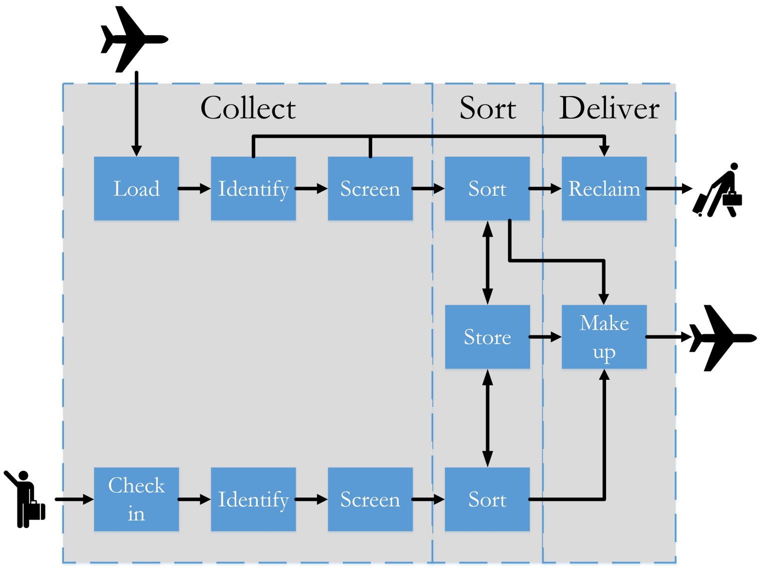


Figure 2-3: Processes in baggage handling [9]

Check-in

The departing passengers are required to complete the check-in process by handing in their hold luggage. The process is either performed by making use of a self check-in desk or otherwise a conventional check-in desk (Figure 2-4a & Figure 2-4b). After being checked in, passengers travel towards the security check, while their luggage is handled by the BHS. In case passengers perform check-in themselves, they should scan their ticket, sub-consequently a tag is printed by the self check-in desk which should then be attached to the hold luggage. If placed correctly, the piece of luggage is putted into the BHS automatically.

(a) Self check-in desk [37]

(b) Conventional check-in desk [38]

Figure 2-4: Types of check-in desks

According to IATA a conventional check-in desk consists of the following sub-components: Check-in counter, weighing conveyor ,label conveyor, dispatch conveyor and label printing facilities. Furtermore, check-in desks are often allocated to one airline and at times when no flights are scheduled they are closed. It is common that checking in luggage is possible from 3 hours prior to departure up to 30 minutes prior to scheduled departure time of the airplane [39]. Their throughput depends on: passenger queue management; speed of the receiving conveyors and time needed to manually label hold luggage.

Load

The transfer luggage arrives at the BHS in a container where-after unloading of a container is either done manually or automatically. In case of manual unloading employees empty the container while a container tipper is used in case of automatic unloading. In Figure 2-5a & Figure 2-5b an image of both types of unloading is presented.

(a) Luggage tipper

(b) Manual unloading

Figure 2-5: Transportation equipment in baggage handling [40]

Identify

In order to identify a piece of luggage, traditionally a tag consisting of both a 10-digit code and a bar-code is used [41]. The carried information consists of passenger details and destination of the piece of luggage. Within the system an automated bar-code scanner is used to scan the tag. In case it is not possible to read the tag then it is transported onwards for manual identification.

Screen

After successfully identifying a piece of luggage, it is transported onwards for screening where it is checked for explosives and other illegal substances or objects.

At first stage screening a machine able to create an image of the luggage is used. The created image is then evaluated by an employee. If for any reason luggage fails first level screening it is taken out of the system and checked manually, if no illegal objects or substances are found luggage is again putted into the system.

Figure 2-6: Screening machine [10]

Transport and sort

The luggage my be transported within the system by making use of conveyor belt or twin belt in combination with a tote (Figure 2-7a & Figure 2-7b). In case of transportation by a conveyor belt each piece of luggage is loaded onto the belt loosely. While, luggage loaded into a tub when making use of twin belt conveyors with the advantage that the achievable conveying speed increases. In addition, there are also types of equipment which are able to

(a) Conveyor belt [42] **(b)** Tub [43]

Figure 2-7: Transportation equipment in baggage handling [40]

perform both transportation and sorting of luggage: Cross belts; carts or Destination Coded Vehicles (DCVs) and tilt-trays (Figure 2-8a & Figure 2-8b & Figure 2-8c). When making use of Destination Coded Vehicle (DCV) or cart which is mounted onto a frame and sorting is performed by tilting the cart. As for the cross belt a conveyor performs sorting of luggage. An advantage of both systems is found in the the possibility to decouple the cart or cross belt from the rail in case of equipment failure.

Another option is to make use of a tilt-tray sorter system which carries luggage on trays which are mounted onto a chain or rail with a fixed distance between trays. Sorting of luggage is achieved by tilting the tray vertically. However, a drawback of the system is found in the fact that an entire sorter needs to run in order to sort out a sole piece of luggage.

(a) Cross belt [44] **(b)** Cart - DCV [45] **(c)** Tilt-tray [46]

Figure 2-8: Sorting equipment in baggage handling

As can be seen in Figure 2-9a & Figure 2-9b, when making use conveyor belts, decoupling of equipment and luggage in horizontal direction direction is performed by making use of a pusher. In case vertical sorting is needed luggage is transported up-or downwards by a special conveyor, depending on the destination of arriving luggage. While, in case of transportation by a tub or tote, the tub is tilted vertically to decouple it from the luggage.

(a) Pusher **(b)** Vertiical sorting

Figure 2-9: Sorting equipment in baggage handling

Store

The pieces of luggage which arrive early are stored in an Early Bag Storage (EBS) which may be either lane based or rack based.

In case of a lane based storage luggage is buffered on accumulating conveyors. Oppossing to this, the luggage is individually stored in racks when a a rack-based system is used. A Lane based storage needs more ground area since vertical storage possibilities are limited in comparison to the rack based solution where luggage is stored in racks which are located on top of one another (Figure 2-10a & Figure 2-10b).

(a) Rack based storage **(b)** Lane based storage

Figure 2-10: Early baggage storage

Make-up

Finally, after the BHS has delivered luggage at its correct destination the luggage needs to loaded into a container prior to being loaded onto a airplane. It is possible to perform make-up either in an automated fashion or manually (Figure 2-11a & Figure 2-11b). When performed automatically, a robot is used to load the container. In case of manual loading of the container, an employee picks luggage from either a lateral, which is basically a straight accumulating belt, or a carousel, which is a belt which moves luggage around in a circle. Hereafter luggage is loaded into a container. If for some reason the process of reclaiming is too slow, blockages might occur, causing an blockages of luggage elsewhere in the system.

(a) Automated unloading **(b)** Manual unloading

Figure 2-11: Make up

Reclaim

Eventually, when the passenger and the bag arrive at the final destination the passengers and their hold luggage are reunite. This occurs at the reclaim area where the hold luggage is recirculating on carousels (Figure 2-12).

Figure 2-12: Reclaim belt

2-2 Performance assessment

Choosing the right KPI is a hard task and which ones are appropriate depends on the research purpose. Granberg, states that airport managers prefer indicators which are related to volume since this makes it easier to evaluate system performance in different situations [47]. According to Helm the KPIs as listed below are often used for evaluation of BHS performance [4]:

1. Sustainability
2. System Capacity
3. Reliability
4. Economics

Sustainability

As described before, the level of sustainability is of importance to airports. The level of sustainability of a system may described in different methods. Sustainability is in principle a vague definition since it may have different meanings. It may for example describe the emission on green-house gasses or the consumed energy.

Measurement of electrical energy consumption is often done in kilowatt-hour [kWh]. However, in order to compare performance on energy consumption in different scenarios it should be related to transport volume of luggage. Additionally, it possible to add the distinction between type of luggage by separating O&D and transferring luggage:

1. Emissions of CO_2 [kg] / piece of luggage
2. Energy consumption [kWh] / piece of luggage
3. Energy consumption / type of transport / piece of luggage

Another approach is to measure energy consumption from the perspective of used equipment. In this manner energy intense equipment can be identified and it is possible to identify the useful energy consumed per piece of equipment which may help to identify potential directions for achieving energy savings. Furthermore, peak energy consumption is of interest since to the user since this parameter influences the value of the utility bills.

1. Energy consumption / type of equipment
2. Energy consumption / piece of equipment
3. Useful energy consumption per equipment type
4. Peak energy consumption

Capacity
The system should be able to perform at its required capacity over a given period of time. According to Haneyah capacity is subdivided into throughput and the response time of the system to a sudden change of dynamic operational requirements caused by for instance the arrival of a batch of time critical luggage or breakdown of equipment [48].

The number of pieces of luggage to be handled by the BHS is dependent on the number of airplanes and their respective capacity, together with the baggage ratio per passenger. Capacity is measured may be measured in various manners:

1. Pieces of luggage / unit time
2. Number of airplanes / unit time

Another KPI is that of equipment utilization. It is related to capacity and according to Helm it provides insight in supply and demand of process stations (volume v.s. capacity) and it helps to monitor the efficiency of operation of processes [4]. In case they are not synchronized a mismatch occurs. When demand exceeds supply, waiting times rise and congestions may occur. If it is the other way around, demand is low while supply is large unnecessary high cost occur.

Reliability
The reliability of the system is of importance to the airport since mishandled luggage, which comes with increased cost might occur when equipment breaks down.

According to Helm a flight is considered as late if the delay exceeds 15 minutes. It is defined as the "left behind index", it represents the percentage of luggage which is left behind relative to departed baggage. Left behinds occurs when a piece of luggage does not make the flight due to disruptions in the BHS while the passenger does. It is measured by the percentage of flights which delayed due to disruptions in the BHS.

Then, downtime of the system comprises the fraction of time the BHS is out of operation due to breakdowns of equipment, power failures or other causes.

It is also possible to measure downtime of system segments, doing this helps in identifying the level or reliability of different system parts. How to measure each indicator is summarized below:

1. Delay

   % of flights which is delayed due to the BHS

2. System downtime

   % of time the BHS is down

3. Segment downtime

   % of time a segment of the system is down

4. Left behind index

   % of flights which is delayed due to the BHS relative to total

Monitoring the reliability over a longer period of time could help in exposing changes in trends and operational evaluation, while measurements on a short time interval helps to evaluate performance during operations.

Economics

Economics are are result of the operational performance of the system. As for this KPI the costs consist of three components:

1. Costs of mishandled bags

   €/ handled bag

2. Cost of energy consumption

   €/ handled bag

3. Maintenance costs

2-3 Energy consumption

2-3-1 Life cycle energy consumption

Energy consumption occurs during each phase in the life cycle of pieces of equipment. (Figure 2-13) shows the life cycle a resource. The first stage, "Production" comprises the energy needed to manufacture a piece of equipment, for instance a conveyor belt. The next step is that of "Transport"; it consists of the energy needed to get the finished product towards the location where it is going to be used. After putting it into place, the equipment enters the

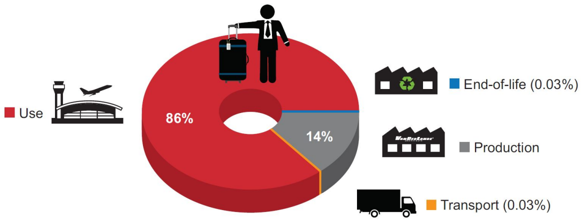


Figure 2-13: Lify cycle energy consumption of the blueveyor by VanderLande[49]

stage of main interest to this research, that of "Use". This is the stage where the piece of equipment is in operation and while doing so it consumes energy. Finally, equipment enters the last stage of its life cycle, that of the "End-of-life", completing its life cycle. Furthermore, it can be seen from the figure that the design stage investigated during this research ("Use"), has high impact on the total energy consumption of a piece of equipment, even in case of one of the most sustainable conveyor belts on the market it includes 86 % of the energy consumption during caused during the conveyor its life cycle.

2-3-2 Barriers towards sustainable operations

The next section is based on work from Alzawawi, who identified drivers and barriers towards increasing sustainability level of operations [23].

Internal barriers
Firstly, it is often the case that employees lack knowledge of the installed system. It is not exactly known how it works and in which manner it is controlled efficiently. By increasing knowledge of the system its lay-out, control and equipment,the capability of employees to identify potential to reduce energy consumption themselves.

Another factor which negatively influences the level of sustainability of the system is fear of the unknown. Employees feel familiar with the system as it is in its current state since it has proven to work for many years. As a result they do not feel the need to make changes to the system. Another factor is that people like to stay in control of processes themselves. They want to be the one who is in control off turning on or shutting down a system even though an automated control system performs control more energy efficient and consistent.

Secondly, other priorities, such as handling acute problems and keeping operations going often feel more urgent compared to looking for ways to improve system efficiency. Issues regarding the level of sustainability of resources and operations is not something which is solved when not actively pursuing it. As a consequence development of sustainable operations do not get the attention it requires.

The last internal barrier is found in the costs. As a matter of fact it is often unknown what are the financial benefits of executing projects on sustainability. As a consequence getting budget from higher management is a hard task. Often, projects are only carried out when they perform break even over a pre-set payback period.

It might for example be needed to install expensive measurement devices to gain insight in the current state of equipment being in operation. It is possible that it to function properly, however it might also emerge that resources need maintenance or have to be replaced entirely. Due to this uncertainty it is hard to asses the gains of a project in advance.

Table 2-1: Barriers for implementing sustainable solutions [50]

Barriers to sustainable operations	Internal	External
1.	Lack of knowledge	Volatility in energy prices
2.	Time	Competitors
3.	Cost	

External barriers

Competitors may both increase or decrease the willingness of a company to invest in sustainable solutions. When one company in a sector manages to perform operations cheaper by implementing new and more sustainable energy efficient technology, the rest has to follow.

On the other hand companies might be careful with implementing new technologies because they may not be proven to function correctly and may result in disruptions to operation or a temporarily decrease of product quality resulting in damage to the companies its reputation and customers to switch to competitors.

2-3-3 Drivers towards sustainable operations

Internal drivers

When insight in the possible gains of energy efficient operations become more evident without taking a lot of time, companies will implement measures on sustainable operations quicker since they are always actively looking for ways to reduce operational cost at low effort.

External drivers

The image of companies is important. Alzawawi states that the customers, stakeholders and society as a whole are becoming more aware of global warming, and other kinds of environmental depletion evolving. Customers are less willing to buy products from a company which they know is performing in a non sustainable manner. Another driver is found in the fact that employees desire a certain focus towards sustainable operations.

Governments are able to implement regulations on achieving greener operations. It also revealed that government regulation is often one of the major drivers towards green operations. Currently, examples of regulations are the Paris agreement, energy quota, subsidies for green energy initiatives such as start ups. Other measures are increasing taxes on fossil fuels or a law by the European Union which bans energy inefficient motors in industry [3]. Table 2-2 summarizes drivers for implementing sustainable operations.

2-4 Design stages

Design projects are generally organized in a similar manner. The detail level of the design gradually increases, uncertainties are reduced and attributes of the product are established [51].

Table 2-2: Drivers for implementing sustainable solutions [50]

Drivers to sustainable operations	Internal	External
1.	Cost reduction	Regulation
2.		Social
3.		Competitors

According to Jenkinson the freedom of choice decreases as a project proceeds [7]. This seems to be a valid statement. At first, during initiation of a project little or no work has been done and the nature of the work is highly conceptual. In other words, many choices have not yet been made. However, as the project proceeds choices are made and the detail level of the work increases. Therefore, it sounds reasonable that making changes in a later stage of the design comes with increased costs. It is expected that the same trend holds for the energy consumption.

Conceptual design According to Misra, the first stage in BHS design is that of the *conceptual design*. It serves as the foundation on which the life-cycle phases of the remaining stages of system design are based. In this stage the functional definition is created based on the requirements as specified by the customer and design criteria are established [52].

A set of conceptual designs for further development are created by performing research, creating a functional analysis of the system, a set of conceptual designs and testing if they fulfil design specifications.

Preliminary design The second stage, that of the *preliminary design* aims to develop the created conceptual systems into preliminary systems. At this stage the most promising ones are evaluated in more detail [52].

Furthermore, a subsystem functional analysis of the system is done. It is basically an iterative process and decomposes requirements from the system level to the subsystem level and if desired to the components level. Results from this phase support creating and evaluating a detailed design. The one conceptual design considered to perform best is taken into the next phase of design.

Detailed design The aim of this stage is to transform the chosen concept into a detailed design consisting of detailed drawings. also evaluation of interaction between subsystems and testing the system against the detailed design specifications is performed during this stage.

Manufacturing After the detailed design is complete the system is built according to design specifications during the manufacturing stage of the project.

Testing Finally, the manufactured BHS is tested. It is validated that the systems performs correctly and that operators.

Chapter 3

Energy consumption of a baggage handling system

In this chapter an analysis of the effect between design choices and its effect on energy consumption is discussed.

Reducing energy consumption of the BHS forms an oppurtunity to decrease operational costs of the system. For instance, according to a research by CASCADE which focussed on Malpensa airport energy consumption in the year 2010, during which the ATB consumed 128,967,400 . As for the BHS with a total conveying length of 20 km total energy consumption added up to 7,577,880 kWh (6 %) which equals to a cost of €757,788 at an energy price of 0,10 €/ kWh [53] on a yearly basis.

From a designer's perspective, it is very hard to estimate energy consumption at the preliminary design stage since it involves many dependent variables. Another reason is the fact that the system should be able to deal with dynamically changing demands. In fact, measures to obtain an energy efficient design may be implemented by either creating a system which uses energy efficiently, in other words, designing a system which consumes energy efficiently during operation, or by avoiding the necessity of use entirely, as displayed in Figure 3-1.

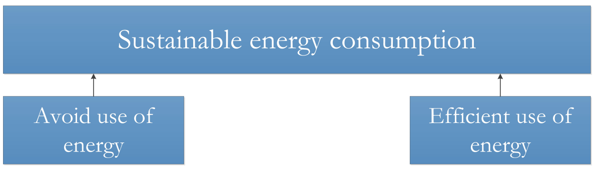


Figure 3-1: Ways to decrease system energy consumption

3-1 Introduction to system design analysis

Airports and thereby also BHSs come in different sizes resulting in a variance in the level and input profile of luggage. Bradley states that BHS sizes have been categorized by size and complexity according to the volume of baggage processed per hour [36]:

1. A, peak flow rate of luggage through the BHS is $< 1000 \frac{pieces\ of\ luggage}{peak\ hour}$
2. B, peak flow rate of luggage through the BHS is $>= 1000 \frac{pieces\ of\ luggage}{peak\ hour}$ and $<= 5000 \frac{pieces\ of\ luggage}{peak\ hour}$
3. C, peak flow rate of luggage through the BHS is $>= 5000 \frac{pieces\ of\ luggage}{peak\ hour}$

When a systems is classified in category A IATA advices a automatic or manual BHS. When an automated system is used the system should be able to process 50 % of the total baggage at all times. As for the back up system should be capable of processing a high proportion of the baggage through a redundancy system. This should at least consist of manual sortation being covered from the elements, safe to operate and secure.

When dealing with a category B airport IATA now recommends to sort handle and sort baggage automatically. In case of failure the redundant capacity should at least be 75 %.

In case the system is classified into category C; IATA advices to use a tilt-tray system or high end destination coded vehicles for sortation. The system is highly complex and the control mechanism needs to be very flexible. When the primary Category C baggage handling system fails it should be possible to process no less than 75 % of the peak baggage flow rate automatically at all times. Also the direction of luggage flow is important. Transfer luggage for instance is often time critical while OD luggage is less, the distribution of both exert implication on the design of the BHS.

In order to evaluate choices made during the design in a structured manner, the method by the name of "process chain model", as proposed by Blecker in "Innovative methods in logistics and supply chain management" is used. He has defined three categories; resources, structure and control. A visualization of the relations is found in Figure 3-2. As can be seen in the figure the input consists of incoming luggage and the output of handled pieces of luggage. They are delivered to the system its environment through the sink as a transformed object (handled luggage).

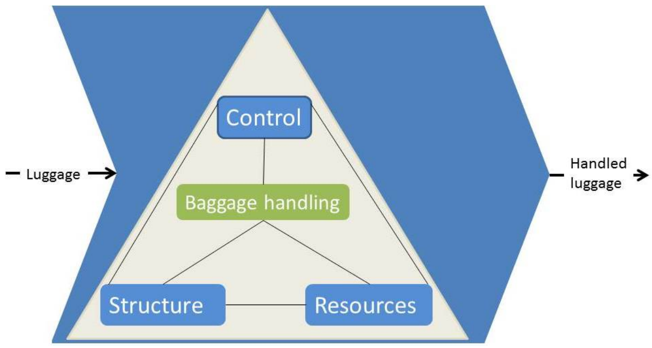


Figure 3-2: The three pillars determining energy consumption of a BHS [35]

The reasons for making use of the process chain model are multiple. Firstly, due to the fact that it has proven to be able to develop a holistic, process-oriented approach of complex logistics and production systems [35]. Secondly, the categories as defined in the process chain model match the BHS: resources match to the equipment used in baggage handling; the structure matches to the lay-out of the system; and lastly system control matches the the possibilities to control equipment present in the BHS under consideration.

Resources

The first category is defined as resources or equipment apparent in the sytem. In Figure 3-3 some conventional resources in baggage handling have been summarized. In most instances, after system installation, each resource is used for many consecutive years. As a matter of fact, the suppliers warrant the performance of a BHS over a period of about 15 years [36].

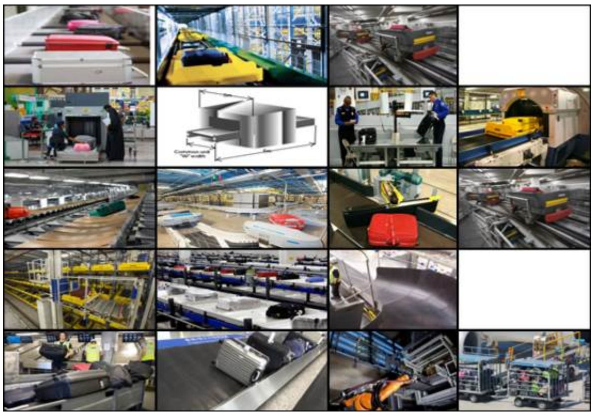


Figure 3-3: Conventional resources in baggage handling

Structure
By evaluating the connected resources the structure of the system is obtained. It is this category where concerns interactions between different parts of the system.

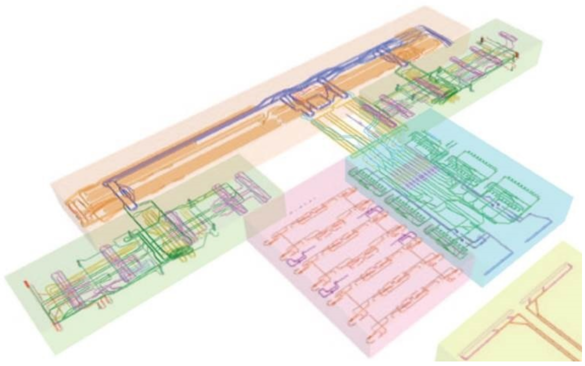


Figure 3-4: Structure of a BHS[54]

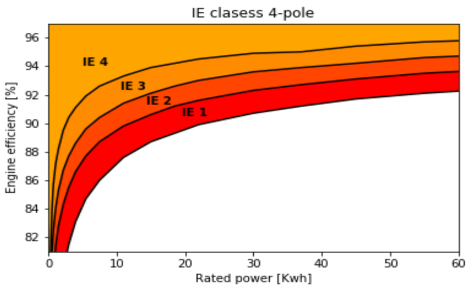
Control
Dependant on used resources and system structure a control policy may be implemented. Which control policies may be implemented depends on capabilities of installed pieces of equipment and the structure lay out of the system.

3-2 Design considerations regarding energy consumption

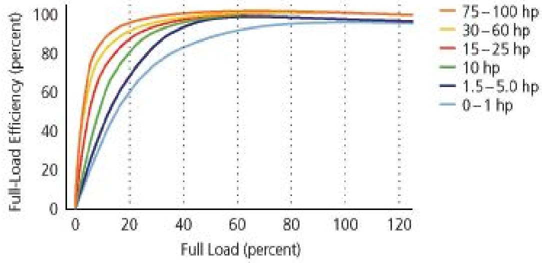
3-2-1 Resources

1. Equipment efficiency
The type of drive influences used to power a conveyor belt influences energy consumption. For instance, at Gatwick airport conveyors are powered by energy-efficient replaced old drive and obtained a reduction of energy consumption by about 50% in comparison to a conventional conveyor drive and gearbox [55]. During operation the efficiency of drives affect energy

consumption during operation. As can be seen in Figure 3-5a efficiency of drives decreases with decreasing size. Furthermore, efficiency drops when the experienced load decreases. The figure shows efficiency with load for efficiency ranges within 4 International Energy Efficiency Class (IE) classes: IE 1: Standard efficiency, IE 2: High efficiency, IE 3: Premium efficiency, IE 4: Super premium efficiency.



(a) Rated power vs engine efficiency, raw data from [56]



(b) Full load efficiency vs Full load percentage of premium motor [57]

Figure 3-5: Engine efficiency with rated power and varying load

Furthermore, the efficiency of a drive is dependant on the load experienced by the drive. As the load drops below 40 %, the efficiency does too. Figure C-4 in the appendix demonstrates the relation graphically.

Another method to reduce energy consumption is to equip drives with a Variable Frequency Drive (VFD), which provides the possibility to perform both soft starting of the conveyor in combination with operation at variable belt speeds [58]. However, using VFDs increases costs and they consume energy when in standby. The power factor is calculated by making use of equation (3-1), where P represents the active or in this case useful power absorbed by the drive and S denotes the apparent power.

$$\text{Power factor} = \frac{P}{S} \tag{3-1}$$

In order to accomplish transportation of luggage it is an ideal scenario when the active power equals the apparent power and supplied current and voltage are in phase. However, a shift in phase might cause a decrease of the active power and as a result the value of the power factor declines. A more detailed explanation of the power factor and its effect on energy consumption is found in Appendix C-1.

In addition, there is the soft starter which is able to increase performance on energy consumption during start up, however it is not able to change frequency. Instead it provides the possibility to increase voltage gradually, from initial to full voltage for example during start up.

Contrary to a soft starter a VFD is able to control frequency and thereby the speed of the motor. According to Eskom, the energy consumption during start differs per chosen solution [59] as summarized below:

1. Direct on-line starter 6-9 times full load current during start up

2. Soft starter 2-4 times full load current during start up

3. VFD 1.5 times full load current during start up

2. Equipment type
During operation conveyors have to fulfil requirements specified by the user on for instance speed, acceleration and stopping time. In case of conveyor belts, the chosen rubber cover material may reduce indentation resistance of a horizontal belt conveyor by as much as 30 % [60]. In addition, specifications on maximum load / meter influences energy consumption since belt weight increases in case an increased maximum load has to be overcome.

From the viewpoint of energy consumption it is an advantage that each cart can be driven separately by making use of linear induction motors [61]. The tilt tray system, used for sorting of luggage mostly runs at constant speed since one sorter consists of a train of trays. As a consequence start up takes longer and the flexibility of the system hereby decreases. Table 3-1 summarizes the characteristics of a DCV and tilt tray sorter.

Table 3-1: DCV vs tilt tray sorter

DCV	Tilt tray sorter
Higher operational speeds	Lower operational speed
Power factor issues	Load profile
Flexible capacity	Fixed capacity
Complex control	Simple control
Cart storage	Proven technology

As a result of performing inline screening a bottleneck within the system may occur since the speed of luggage has to be reduced during sreening [13]. Consequently, in order to handle peal loads parallel lines are generally installed. As a consequence the number of pieces equipment running at the same instance increases.

In addition, make up is either done by making use of a lateral, a carousel or chutes as a resource. The advantage of the carousel system is that it is easier to handle luggage destined for multiple flights. However a carousel is expected to consume more energy since it keeps on running even if only a few pieces of luggage are loaded onto it.

The life cycle energy consumption of different conveyor belts is shown in Table 3-3. Row one and two of the table show the results of found in the product declaration by VanderLande. The rows thereafter: CV-47 RA, BF-46 and BF-40 represent the results of actual measurements on the energy consumption of conveyors at Rotterdam airport. The last row of the table represents the calculation performed according to the DIN 22101 standard. The used formulas are found in Appendix C-3. In the calculation it is assumed that the conveyor experiences an average load of 17 kg, which according to the product declaration of vanderLande is the mean weight of luggage [49].

3. Equipment energy consumption
In the cost calculations of energy consumption it is assumed that the lifetime is 15 years, as stated in a research by Bradley [36]. Furthermore the cost of 1 kWh equals .1 €and it is assumed that equipment is operational for 8 hours per day (Table 3-3). During calculation of

Table 3-2: Operational characteristics destination coded vehicle

Conveyor	Lifetime [years]	[Euro/Kwh]	Average operational hours [hours / day]
Conveyor type	15	0.1	8

the 1.4 meter belts a constant efficiency of 0.84% has been assumed since this is the efficiency of a conveyor belt operating at a load of 60 % or higher in case of a premium motor according to Figure 3-5b. Furthermore,the belt weight is assumed to be 45 kg /meter.

Table 3-3: Energy consumption of conveyor belts

Conveyor	Electricity consumption [kWh]	Operating speed [m/sec]	Belt length [m]	Energy consumption [kWh]	Energy costs [Euro]
Greenveyor [49]	0.11	.5	1.3	4,818	482
Blueveyor [49]	0.33	.5	1.3	14,600	1,460
CV-47 RA [60]	0.307	0.53	1.4	13,446	1,344
BF-46 [3]	0.29	0.53	1.4	12,702	1,270.2
BF-40 [3]	0.87	0.53	29		
DIN 22101	0.22	0.5	1.4	12,702	1,270

Twin belt conveyors

Twin belt conveyors are often used in combination with tubs. In comparison to the calculation of the conveyor belt the belt weight per meter decreases and weight of the tub is added to the load experienced by the conveyor. After luggage has been delivered at its destination the tub travels empty, towards either its storage location or to a place in the system where another piece of luggage has to be picked up. Table 3-4 shows the results of calculation. In the calculation it is assumed that the tub weighs 10 kg.

Table 3-4: Characteristics of the twin belt conveyor

Twin belt	Electricity consumption [kWh]	installed power [kWh]	Luggage weight [kg]	Operating speed [m/sec]	Belt length [m]	Energy consumption [kWh]	Energy costs [Euro]
	.13	.21	17	17	1.4	5,694.0	569.4

Tilt tray sorters The table below shows the energy consumption profile of different 200 meter sorters without increasing or decreasing heights. It is assumed that they operate at an operational speed of 2 m/sec with an average load per tray of 3 kg and a tote / cart length of 700 mm.

Table 3-5: Characteristics of tilt tray sorter

Sorter type	Electricity consumption [kWh]	Energy consumption [Mwh]	Energy costs [Euro]
Tilt-tray sorter (LIM)	10.3	451.14	€45,114
Tilt-tray sorter (LSM)	2.4	105.12	€10,512
Cross belt sorter (LIM)	11	481.8	€48,180
Cross belt sorter (LSM)	2.7	118.26	€11,826

Destination coded vehicles DCVs are driven by linear induction motors which provide the opportunity of propulsion without the need for physical contact between track and moving object. Table 3-6 summarizes the energy consumption profile of DCVs, the calculation method is based on a calculation by SEW Eurodrive [62]. It is assumed that a cart weighs 20 kg.

Table 3-6: Energy consumption per destination coded vehicle

DCV	Electricity consumption [kWh]	Luggage weight [kg]	Energy consumption [kWh]	Energy costs [Euro]
1.5 m/s - empty	0.33	-	14415	€1,442
3 m/s - empty	0.72	-	31656	€3,166
6 m/s - empty	1.77	-	77449	€7,744
1.5 m/s - loaded	0.36	17	15735	€1,574
3 m/s - loaded	0.80	17	34957	€3,496
6 m/s - loaded	1.99	17	87350	€8,735

Hold baggage screening From Table **??** it can be seen that one screening machine consumes 4.4 kWh while in operation [63]. However, one piece of screening equipment per many conveyors is generally installed within the BHS making the total amount of energy consumed by transportation equipment higher than that of screening equipment [3].

4. Equipment error rates

Automatic tag readers (ATR) are used to identify luggage by reading the tag and perform at a success rate of 75-90 % for checked in pieces of luggage. An alternative is found in radio frequency identification RFID) since it results in an operational accuracy of 95-99 %. As a consequence the volume of mishandled bags is reduced and the travelled distance per piece of luggage decreases, however in general increasingly accurate systems come with increased cost [13].

5. Equipment start-up time
Reduction of start-up times results in an increase of operational flexibility since the time it takes to put into operation parts of the system decreases. As a result of shutting down parts of the system the number of pieces being in operation at a moment in time decreases and hereby energy consumption may be reduced.

3-2-2 structure

1. Location and size of equipment
Equipment size influences the level of flexibility of the system. As for sorters for instance, choosing for 1 large or 2 small sorters may result in an equal peak capacity of the system while energy profile and need of equipment to feed luggage into the sorter differs. The same holds for carousels,laterals, collector belts and HBS equipment. In each case there is a choice between installing larger conveyors or multiple small ones instead. The decision does not affect peak capacity but does have impactions on the possibilities of controlling separate parts of equipment, the system and ultimately the possibilities to take measures to decrease system energy consumption.

2. Cross connections
When luggage has to be transported over large distances implementing cross connections into the system increase system flexibility and energy performance by allowing for changing between conveyor lines at times when capacity allows.

3. Equipment interaction
When making use of conveyor belts to complete transportation the designer has to choose the dimensions of separate belts. When installing larger ones; rated power per drive is higher (larger motors) and the number of engines per meter is lower, also start up times are longer.

Each motor loses a fraction of energy due to inefficiencies, so a smaller number of drives per meter increases efficiency at constant operation. However in baggage handling, demanded capacity of the system varies throughout the day and even in parts of the system. As a consequence it is possible that longer belts are more efficient in one part of the system, while shorter ones are preferred in others.

In Figure 3-6, situation A describes the case for with one conveyor belt of 10 meter of belt runs to perform transport of 2 pieces of luggage. However in situation B, only 4 meter of belt is actively transporting luggage. However, the number of short belts needed to transport a piece of luggage over the same distance is higher. In fact, smaller engines operate at lower efficiency so the energy needed to continuously operate for one hour is compared to longer conveyors. However in case the distance between pieces of luggage is large the total operation time of the smaller belt is lower compared to the large conveyor and energy might be saved, Table 3-7 summarizes the results.

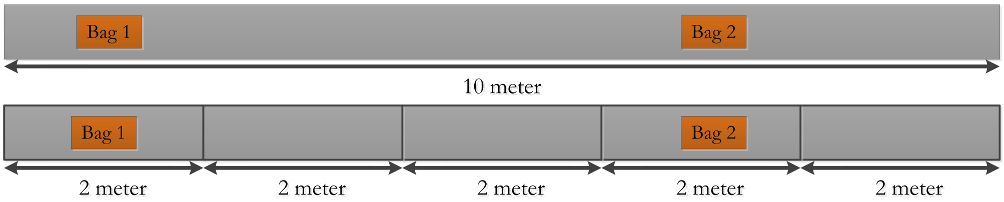


Figure 3-6: Static power of a belt conveyor with increasing length, situation A and B

Table 3-7: Short vs long conveyor belts

Short conveyor belt	Long conveyor belt
Short start up time	Start-up takes long
Small drives	Large drives
Many drives	Few drives
Short run time / bag Lower drive efficiency	Long run time / bag Higher drive efficiency

3-2-3 Control

1. Equipment control

According to Halepot it is the case that conveyor belts left running while under no load, consume 40 % of the full load power [64]. In his research he proposes to create an optimal belt speed control mechanism by smartly sensing the object weight and optimally adjusting the belt speed. The proposed system optimally switches the conveyor system to on/idle/off status to minimize the energy consumption of conveyor belts.

In addition Lodewijks performed research on reducing the velocity of a conveyor belt when in idle state and he also investigated the effect of switching the conveyor belt off after having been for a certain period of time when no luggage arrives. This procedure is for instance used in escalators and moving walks and is defined as energy saving mode [60].

In another research P. Vogel managed to decrease energy consumption of a conveyor belt based baggage handling system by 30 % by reducing run times of equipment [3].

Another reason for looking into equipment control policy is that only 5 % of luggage handled by the BHS is time-critical [65]. Making a clear separation of the two flows and designing processes that are able to achieve both speed and timeliness, depending on the requirements, can help raise quality and reduce costs and energy consumption. In case a piece of luggage is handled much faster than required by the customer, the system is over-processing.

Due to the demand for increased productivity and a growing automatisation in baggage handling, the amount of electrical equipment operating simultaniously has increased. As a consequence the demand for electricity has risen as well. In a research on container terminal operations performed by Robert Heij, it is investigated what the effect is of decreasing peak of energy consumption is on throughput and the utility bill [66]. The first aspect is the payment for actual energy demand (€/kWh/year). The second aspect concern transmission capacity costs. On forehand, container terminals need to present the height of their power demand, the so called contracted transmission capacity. In case the predetermined contracted demand differs too much from the average actual demand, the electricity supplier will charge extra. The third aspect is then the charge for peak demand. The container terminals are charged for the highest peak demand that is observed over a year even while this maximum is only achieved during a fraction of a second.

From the point of view of controls, DCV have the advantage that it is possible to drive each cart separately. However, a drawback is found in the increased complexity of control. Contrary, in case of the tilt tray sorter the opposite holds, per sorter each tray is connected to another, resulting in less control complexity and the need for an entire sorter to run when one piece of luggage has to be transported and sorted out. The DCVs are able to obtain speeds up to 10 m/s while the tilt tray sorting system typically runs at 2 m/s.

Another solution might be to allocate check in desks smartly with the purpose to reduce the travel distance of luggage. In another research P. Vogel investigated the effect of minimizing travel distance of luggage by re-allocation of check in desks and found out that energy consumption did not significantly change by doing so [3].

2. Routing policy

The routing policy influences the energy consumption of the system; for instance at Southwest Florida International airport re-routing of bags during times of low capacity demand saves 790,000 kWh compared to the old situation [67]. In case the predicted baggage flow is lower than a specified number per day and peak capacity is also not higher than a specified value per 2 hours the baggage is re-routed so that a part of the conveyors, check in desks and screening machines is shut down and energy is saved.

Reducing run time of equipment is a promising method to obtain a reduction in energy consumption. In an earlier study on an existing BHS savings of 30 % has been obtained by adapting the control policy so that run times decrease [3].

In the current situation peak loads are of main interest in system design. As a consequence more energy may be used than required. In combination with the fact that conveyors lines often run in parallel for reasons of system capacity and redundancy there is an opportunity to shut down parts of the system at times of low capacity.

3. Batching policy

Batching has been proposed as an promising solution for decreasing energy consumption BHSs [3]. A visualization of the effect of batching is found in Figure 3-7. For instance, when conveyors run at 1 m/s and stop when no piece of luggage arrives for the next 2 seconds, in the top case the figure demonstrates that conveyor 1, 2, 4 and 5 are running while only belt 1,2 and 3 run in the lower example (it is assumed that the conveyor needs 2 meter to obtain synchronized speed).

4. Storage policy

The control policy on when and how to perform storage affects energy consumption as it influences the location where a piece of luggage is buffered. Furthermore, it affects the required storing capacity and the routing of luggage.

The decision on whether to store a piece of luggage or to send it directly towards make up is an important one. Reasons for performing storage may be motivated either by security ,

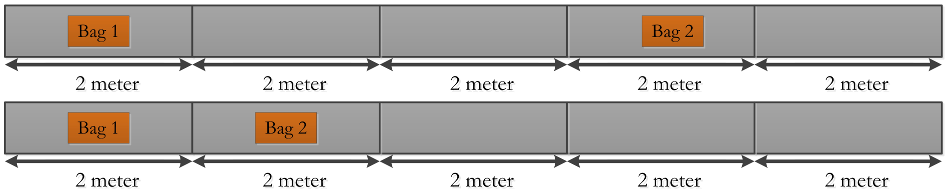


Figure 3-7: Efficiency of engines with rated power

system size or due to early arrival of luggage. If it is determined that storage of a piece of luggage is required then the next step is to choose its storage location. Table 3-8 displays possible storage policies.

Table 3-8: Choice of storage location

Policy on choice of storage location
Time to departure of flight
Time to departure time slot
Arrival time of luggage

Chapter 4

Introduction towards research case

In the previous chapters the BHS itself and its energy consumption have been analysed from a designer's perspective. In this chapter conclusions are drawn from the previous work and an outline of the remainder of the research is given.

4-1 Detailed research context

The first stage in BHS design is that of the conceptual design stage, in which a set of conceptual designs for further development are created. During the next phase, that of the preliminary design stage the most promising ones are evaluated in more detail. Nowadays this evaluation is mainly performed based on:

1. System peak load
2. Left behind index
3. Capital Expenditures (CAPEX) / Operational Expenditures (OPEX)
4. Redundancy

It is noted that the sustainability and energy consumption are becoming of increased importance to large buildings such as airports. While effect of design choices on energy consumption are mainly not concerned within BHS design, which is ashame since it is one of the main consumers of energy within the ATB [6].

CASCADE performed measurements on the energy consumption of the BHS at Malpensa airport for a period of one week; the results are found in Table 4-1. During one week, the price of keeping the baggage handling system in operation adds up to €16,000, in case this is an average week annually energy costs add up to about €830,000. Another system, that implemented at Dubai airport is much larger, the conveyor lines total to a distance of 90 km and keeping the system in operation requires 10,702 separate drives. The system is capable of processing 15,000 bags per hour during times of peak load [54]. It can be imagined that energy consumption of this system is even higher.

According to Jenkinson the costs of making changes increases as the project proceeds, it is expected that the same trend holds for the energy consumption. It is in the preliminary design stage that choices in equipment type and lay out are made and that conceptual designs are compared. From the perspective of a designer it is very hard to estimate energy consumption at this stage since it involves so many dependent variables. Another reason is the fact that the system should be able to deal with dynamically changing demands. This necessitates the use of dynamical models [5].

Within this research it is proposed to create a generic discrete event simulation model to investigate energy consumption in the preliminary design stage. The choice has been made to

Table 4-1: Energy consumption BHS Malpensa airport, januari 2011 - terminal 1

Day	Saturday	Sunday	Monday	Tuesday
Energy use	18,926.75	21,931.15	21,847.82	20,491.17
Nr. of bags	25,609	48,313	46,774	35,458
kWh / bag	.74	.54	.47	.58
Day	Wednsday	Thursday	Friday	Average
Energy use	19,404.82	19,413.	19,117.84	20,611.99
Nr. of bags	35,319	34,798	34,873	30,624.28
kWh/ bag	.55	.56	.55	.71

not investigate system peak loads during this research however, performance is measured by monitoring the Left Behind Index, which is defined as the number of pieces of luggage which do not make it into the plane due to disruptions in the baggage handling process. Furthermore, CAPEX is not taken into account since the purpose of this research is to contribute to increasing the level of sustainable of BHS operations.

The model is generic since it is able to evaluate performance on energy consumption while monitoring selected requirements on logistic performance quickly. To be able to compare energy consumption per piece of luggage for different systems the simulation model will compare multiple concept designs consisting of different types of transportation equipment.

Chapter 5

Model design

In this chapter the working of the model is described in a qualitative manner by determination of the purpose of the model. In addition, the performance indicators and the different processes occurring within the simulation model are discussed.

5-1 Model objective

This study is to aid in the creation of insight in the performance on energy consumption of BHS during the preliminary design stage. Designers of BHSs are faced with the task to choose between conceptual designs. Their task is to choose the one which in their opinion functions best.

Goal: "To create a model that determines the energy consumption resulting from baggage handling operations of different design concepts quickly. The energy / piece of luggage is particularly important."

5-2 Model output and performance indicators

As can be seen in Figure 5-1, within this research energy consumption per piece of luggage is used to evaluate the results obtained from the conducted experiments:

- Energy consumption [kWh] / piece of luggage.

As a consequence of evaluating this variable it becomes possible to compare performance in case of different input profiles of luggage and also to investigate system performance in combination with different control methods and equipment types.

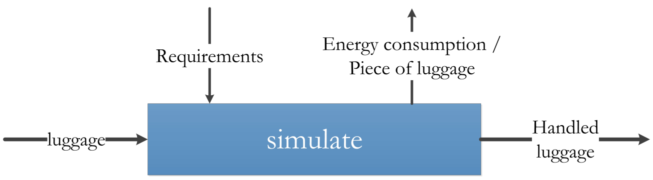


Figure 5-1: Black box of the simulation model

Besides the performance on energy consumption certain system requirements should be fulfilled. Within this research the LBI is monitored since this evaluation of this value gives insight in the number of pieces of luggage which do not make it onto the airplane due to disruptions in the BHS.

- Left Behind Index, % of handled luggage which is late due to disruptions in the BHS

Mishandled luggage results in a fee to the baggage handler. In the year 2014 on average 6.96 per thousand passengers where not reunited with their luggage [68].

In more detail, the following variables have to be measured:

1. Luggage travel:
   (a) In-system time
   (b) Ultimate departure time
   (c) Realized departure time
2. Luggage transport via conveyor belt:
   (a) Stop time
   (b) Start time
   (c) Speed
   (d) Load
3. Luggage transport via DCV:
   (a) Start time of travel
   (b) End time of travel
   (c) Speed
   (d) Monitor if cart is empty or loaded

5-3 Model scope

Passenger behaviour is beyond the scope of this research. The reason is found in the fact that they do only affect energy consumption by choice of check-in desk. Earlier research by P. Vogel demonstrated that the effect of check-in desk choice on energy consumption is not significant [3].

Also, transportation of luggage between the airplane and make up, as well as loading and unloading of airplanes are not taken into account due to the fact that this function is not performed by transportation equipment of the BHS. Furthermore, misread percentage are not taken into account (around 3 % [69]) and therefore the effect on energy consumption of the system is minimal in comparison to, for instance screening which is characterized by a rejection rate of 30 % [36].

Another limitation to the scope is that the system is not subjected to transferring flights since this adds to the level of complexity and due to the fact that transferring luggage is partly transported directly from airplane to airplane. Furthermore, in case of focussing on small airports only a small fraction of handled luggage is destined for a transferring flight. Lastly, OOG luggage is considered to not be handled by the simulated BHS.

5-4 Conceptual model

The model should be able to simulate the behaviour of a BHS which is subjected to a specified luggage input profile. This input profile is related to a flight-schedule and these bags are, by that, linked to a certain airplane where these are needed to be transported to. The bags arrive starting from a specified time in advance of the flight. As can be seen in Figure 5-2 the arrival of luggage takes place at the check-in After completion of the check-in process

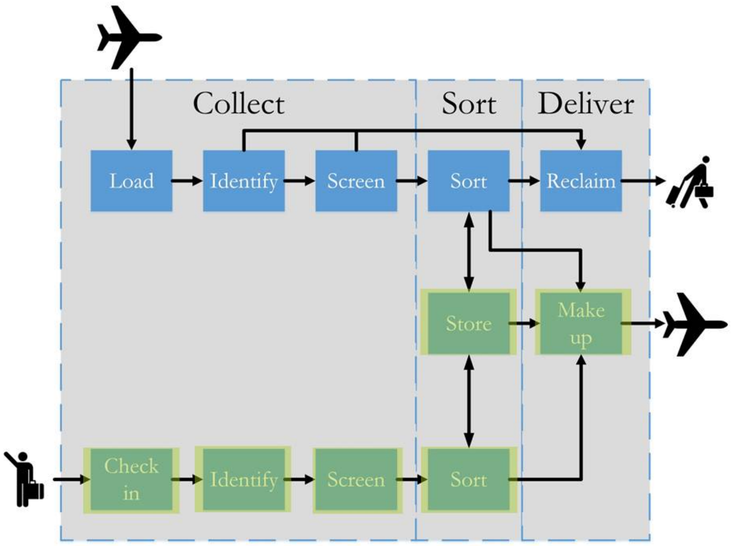


Figure 5-2: Processes in baggage handling [9]

luggage has to be screened for security reasons. The next step is to sort out the luggage and transport it towards storage in case it has arrived early or directly towards make up if the airplane departs shortly.

5-5 Model assumptions

1. The input of the model consists of luggage entering check-in. In case a queue of 10 pieces of luggage occurs in front of a check-in desk, a next one is opened.
2. Airplane and luggage arrival are modelled by making use of a scheduled input distribution
3. Luggage may arrive up to three hours prior to departure and it never arrives at the wrong check-in desk [70]
4. The weight of each piece of luggage is constant equal to 17 kg [49], motivation in appendix F
5. The modelled airport is a point to point airport
6. The occupancy rate of airplanes is equal to 85 % [71]

7. As for the equipment used; it is assumed that each same piece of equipment operates at a similar speed and performs acceleration and deceleration at the same rate
8. Screening of luggage takes 10 seconds
9. Check-in takes 30 seconds per piece of luggage [72]
10. No reads are not taken into account since this percentage is, the percentage is about (about 3 %) [69]
11. Luggage is considered late when it exits BHS less than 45 minutes prior to airplane departure [30]
12. The security rejection rate is a constant percentage of handled luggage of 30 % [36]
13. Breakdowns of equipment are not taken into account
14. Empty DCVs enter the system when required on a fixed position
15. No warm up time is needed since the BHS starts empty and at the end of the day is again empty
16. Each piece of luggage is cleared after screening
17. The distance between each piece of luggage is at least 1 meter

Energy consumption

1. Energy consumed during start up is a constant per piece of equipment. Each start comes with an energy consumption of 1 second of constant operation [3]
2. In case conveying is performed by a belt the amount of energy consumed is assumed to be constant and is dependent on the length of - and load on the belt
3. Each DCV uses a constant amount of energy during travelling, however a distinction is made between loaded and unloaded state
4. After delivery of luggage at the desired destination DCVs return to cart storage

5-6 Process description

5-6-1 Classes,attributes and queues

Table 5-5 lists the classes present in the simulation model. Those which have a process are highlighted with a red P. The simulation starts at simulation time zero and runs until the pre-set run time of the simulation time is reached.

Table 5-1: Classes and processes

Class	Association / Aggregation	Attribute name
Simulation time P	Has a	Model run time
Airplane generator P	processes an airplane	Arrival time distribution Capacity distribution
Airplane	has a/an	Arrival time Departure time Capacity
Luggage generator P	processes luggage	Arrival time distribution
Luggage	has a / an	Arrival time Departure time Weight
Route P	processes luggage	Next destination
Check-in P	processes luggage	Check-in time duration
Manual screening P	processes luggage	Screening time duration
Storage P	processes luggage	Storage time
Make up P	processes luggage	Make up time duration
Transport equipment P Twin belt conveyor Rail Conveyor belt	processes luggage	Speed Acceleration rate Deceleration rate Load Length

After creation of the airplane and luggage element with their respective attributes luggage enters the via a check-in queue (Table 5-2).

Table 5-2: Classes and processes

Queue	Explanation
CheckInQueue	Luggage waiting to enter system via check-in desk

5-6-2 Conceptual process description

Airplane generator

At the start of the simulation, the airplane generation initiates the creation of airplanes by making use of an input distribution. This includes the assignment of the airplane size which is related to the amount of luggage.

At airports it is common practice that the luggage they carry may arrive up to 3 hours prior to their designated departure time until 30 minutes prior to flight departure which is equal to the turn around time of a narrow body aircraft [30]. Table 5-3 represents the attributes belonging to each created airplane element.
On average, narrow bodies carry 170-200 passengers. The wide-body segment aircraft are able to transport 200 to 600 passengers per flight [73]. However, those do hardly fly to point to point airports.

Table 5-3: Airplane element

Element	Attribute name	Attribute value
Airplane	Arrival time	distribution
	Departure time	Fixed time after arrival
	Passenger capacity	distribution

Luggage generator

Table 5-4 shows the attributes of the luggage created in the model. Each piece of luggage is created at the instance its entry time is reached. The luggage is allowed to leave the system between 45 and 30 minutes prior to airplane departure [30]. Luggage is allowed to enter the system between 3 hours and 30 minutes prior to departure in the standard scenario and the peak of arrivals is expected to occur 60 minutes prior to airplane departure.

Table 5-4: Luggage element

Element	Attribute name	Attribute value
Luggage	Arrival time	distribution
	Departure time	Arrival time + 3 hours
	Airplane ID	Name description
	Weight	17 kg

Check-in
On arrival at a check-in luggage is first put into a check-in row until its designated check-in desk becomes available. In case the check-in desk is empty it is available to to process a next piece of luggage.

Transport by equipment
Transportation through the system is performed by transport equipment. The equipment waits until a piece of luggage arrives and is in need of onwards transport. It then performs transport at a speed specified in the model and again waits until a next piece of luggage arrives.

Screening
Each piece of luggage must be screened. In case it a "passes" screening luggage is transported onwards to either storage or make up area where it is held for some time. If luggage fails the test it is transported towards manual screening. Within the model screening of a piece of luggage is done in 15 seconds.

The luggage is dynamically routed towards a screening machine. If luggage is accumulating in front of a screening machine arriving pieces of luggage are re-routed towards another one.

Manual screening
Luggage is checked manually and is put into the system again. Within the model manual screening takes 90 seconds.

Storage
Luggage is stored when it enters the system more than one hour prior to its departure time. It is held until departure time is less then 45 minutes away.

Within the simulation model luggage is stored in lines and is able to enter a storage line either when it is empty or in case the departure time of the luggage is equal to that of the luggage already stored in the line and it is not yet full.

As can be seen in Figure 5-3, initially (1) storage is empty . Then, (2) after a few pieces of luggage have arrived, a storage line accumulates the luggage on the belt. Finally (3) at the moment the first accumulating belt is completely filled, the luggage is sent onwards to the next one and the first accumulating belt is again filled.

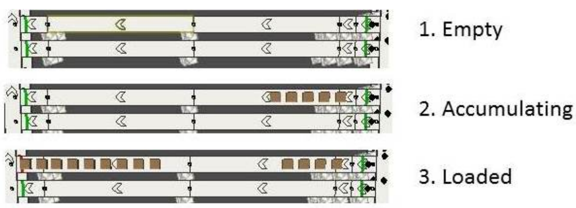


Figure 5-3: Storage policy

Make up
Finally, luggage is put into a container during the make up process, taking 30 seconds per piece. On completion of the process luggage is considered as handled and leaves the simulation model.

Routing

During simulation the Dijkstra A-star algorithm is used for automatically routing luggage through the system. At the moment a piece of luggage arrives at a junction the optimal route towards the final destination is calculated (Figure 5-4). The information on path lay out is obtained from a table which for each conveyor consists of each predictive and successive conveyor.

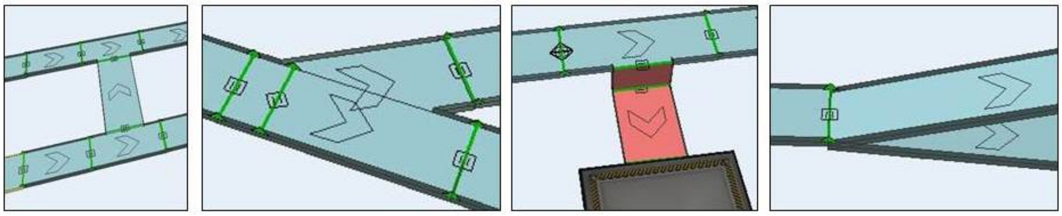


Figure 5-4: Types of junctions in the simulation model

The algorithm makes use of the cost function as displayed by equation (5-1), where $g(v)$ denotes the cost so far and $h(v)$ represents the cost from the current position towards the final destination.

$$f(v) = g(v) + h(v) \tag{5-1}$$

The algorithm in its standard form relies on the value of a cost function, which in the basic scenario depends on the summation of the distance travelled so far and the travel distance until the destination.

However, it is possible to extend the function in order to fulfil simulation requirements. Within the model, at each moment where luggage arrives at a junction the model calculates the optimal route.

5-6-3 Classes and attributes

Table 5-5: Classes and processes

Process	Description
Simulation time P	Wait until runTime is reached -Create model output -Stop simulation
Airplane generator P	Repeat during runTime -Wait until the next Airplane should arrive -Create new Airplane with Capacity -Start the Airplane Process
Airplane P	Repeat during runTime -Hold during time until Departure -Initiate luggage generator -Delete Airplane element
Luggage generator P	Repeat during runTime -Wait until the next Luggage should arrive -Create a new Luggage -Put Luggage in the **CheckInRow** or **TransferInputRow**
Routing P	Repeat during runTime Wait until Luggage arrives -Compute Route by making use of Dijkstra A* algorithm -Send Luggage to next Destination
Check-in P	Repeat during runTime -Wait until next Luggage from checkInDeskQueue -Hold Luggage during checkInTime -Send Luggage to next Transport Equipment
Screening P	Repeat during runTime -Wait until Luggage arrives at Screening - Hold Luggage during screeningTime - Send Luggage to next destination
Manual screening P	Repeat during runTime -Wait until Luggage arrives at ManualScreening - Hold Luggage during ManualScreeningTime - Send Luggage to next destination
Storage P	Repeat during runTime -Wait until Luggage arrives at Storage -Hold during StorageTime -Send to Transport Equipment process
Make up P	Repeat during runTime -Wait until Luggage arrives at MakeUpArea -Hold Luggage for Make Up Time -Delete Luggage element
Transport equipment P	Repeat during runTime -Wait until Luggage arrives -Start Transport Equipment -Transport Luggage -ShutDown current Transport Equipment

5-6-4 Model control section

Creation of the model is done in two steps. Firstly, the structural lay out of the model is created. Then, the model is prepared to process luggage.

The createSystem process makes use of raw lay out data created in Excel to create the model lay-out in the simulation model. Table 5-6 describes the process in more detail.

Table 5-6: Functions to create the system lay out in the model

CreateLayOut.Process
MAIN Repeat(Read next row of InputData) if type=1: straightConveyor.Create else if type=2: InclineConveyor.Create else if type=3: MergeConveyor.Create else if type=4: CurveConveyor.Create else if type=5: CurveConveyor.Create else if type=6: DivertConveyor.Create else if type=7: DivertConveyor.Create else if type=8: VertiMerge.Create else if type=9: VertiMerge.Create else if type=10: VertiSortConveyor.Create else if type=11: XRay.Create else if type=12: straightConveyor.Create else if type=13: straightConveyor.Create Motor.Create

5-7 Used software

In order to perform a simulation of the BHS, the system can be represented within several software packages. A choice has been made after comparing Delphi, Python and Flexsim. During the time of this research each of the programs presented in the table were available for use and provide the opportunity to write own code. However, after comparison it has been decided to make use of Flexsim for creating the simulation model. The reasons for this choice is found in the fact that it has many standard objects built in, while one is still flexible to change their behaviour by adding own code. Furthermore, it was possible to contact their professional support in case of experiencing software errors. Another advantage of Flexsim is that it takes little time to visualize system behaviour and a separate module for performing experiments is available within the program.

Chapter 6

The simulation model

In order to create a model which has the ability to analyse different layouts a range of programs is used. Figure 6-1 demonstrates the step-by step creation of the model. At first the structural design is created in Revit. Then Dynamo has been used to convert system lay-out data into Excel which is then used to prepare and transfer the data to Flexsim. After loading the lay out data into Flexsim it is possible to implement model logic. Finally, Excel has been used for post-processing of simulation results.

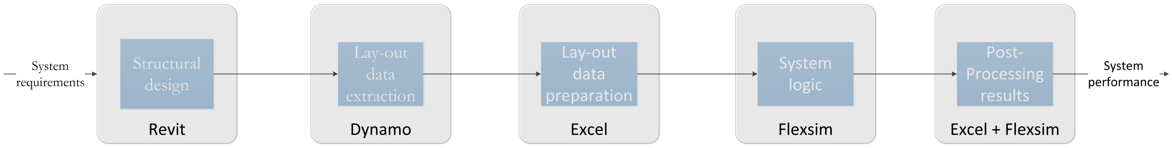


Figure 6-1: Model set up

6-1 Research case: Aruba airport

The research case should be a point to point airport and should be relatively small while the system must contain all functions which appear in larger systems. Another requirement is that the different concepts make use of different combinations of pieces of equipment.

The Aruba airport has been used as a research case since it fulfils the requirements listed above and due to the fact that lay out data of this airport is available. Two design concepts of the Aruba airport have been created in a simulated environment.

Concept 1: Conveyor based concept
Within the first conceptual design transportation is performed by making use of conveyor belts, accumulating conveyors for performing storage and carousels are used to perform make up. After check-in, luggage is loaded onto the collector belt. Then, conveyor belts are used for transportation through the system (Figure 6-2). Luggage which passes screening

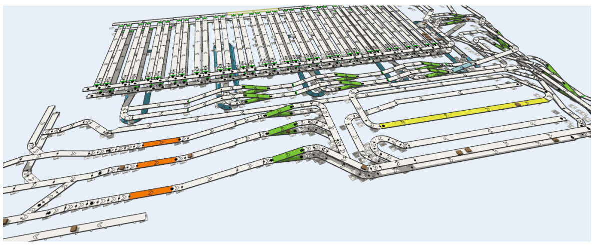


Figure 6-2: Impression of the conveyor based concept

is transported towards line storage if it has arrived early or onto the carousel if passengers have passed security. However, luggage failing to pass level 1 screening is directed towards a manual screening location before onwards transportation. For reasons of redundancy and capacity requirements the lane based storage consists of two levels. Finally, a conveyor belt loads luggage onto a carousel located at the make up area. Finally luggage is unloaded from the carousel.

Concept 2: Conveyor and cart based concept
After completing check-in luggage is received by a collector belt. Then, conveyors are used to transport luggage through HBS. Consequently luggage is loaded onto DCVs (carts) for onwards transportation and sorting (Figure 6-3). Line storage is performed at 2 levels for reasons of redundancy. Make up is performed by making use of chutes.

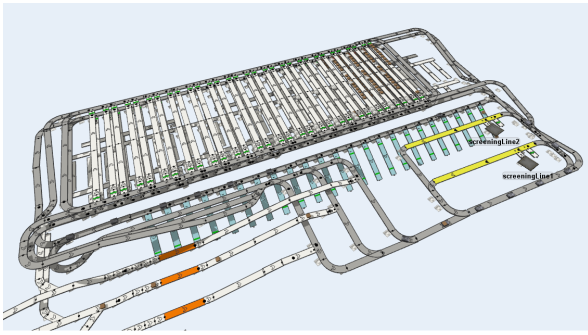


Figure 6-3: Impression of the conveyor and cart based concept

6-2 Input data set

The characteristics of the input data are summarized in Table 6-1. The gamma distribution has been used since it is flexible in creating different arrival patterns.

Table 6-1: Standard input values

Model parameter	Type	Standard setting
Run time of simulation	Fixed	24 hours
Number of airplane departures	Number value	Variable
Pieces of luggage per airplane	Fixed	180
Airplane arrival distribution	Gamma distribution	Scale 0,8700 shape 12,5000
Luggage arrival distribution	Gamma distribution	Scale 0,1330 shape 11,2500
Transport speed	Variable	
Check-in time	Fixed	30 seconds
Screening time	Fixed	15 seconds
Manual screening time	Fixed	30 seconds
Make up time	Fixed	30 minute

6-3 Verification

Before performance of experimental runs the results obtained by making use of the simulation model have been verified in order to determine if the model performs as it is supposed to:

1. **Event tracing:** During creation of the model in Flexsim behaviour of the model has been checked by observing travelling of luggage in the model in the 3-d environment. Furthermore, the characteristics of elements has been checked step by step in a process flow environment. Lastly, also event tracking has been performed during simulation.
2. **Testing seed dependency:** the dependency on used seeds is done in order to check the influence of changing picks from used distributions on model behaviour.
3. **Verification with analytical results** The results of the model obtained by, taking the mean value of each distribution and assuming that each piece of luggage is able to travel towards its final destination directly, are compared with hand calculations.

At first, it is verified if each piece of luggage putted into the model also comes out. As can be seen in Figure 6-4 where one airplane is to be loaded with 160 pieces of luggage, each piece of luggage put into the system also comes out. Furthermore, it is seen from the figure that

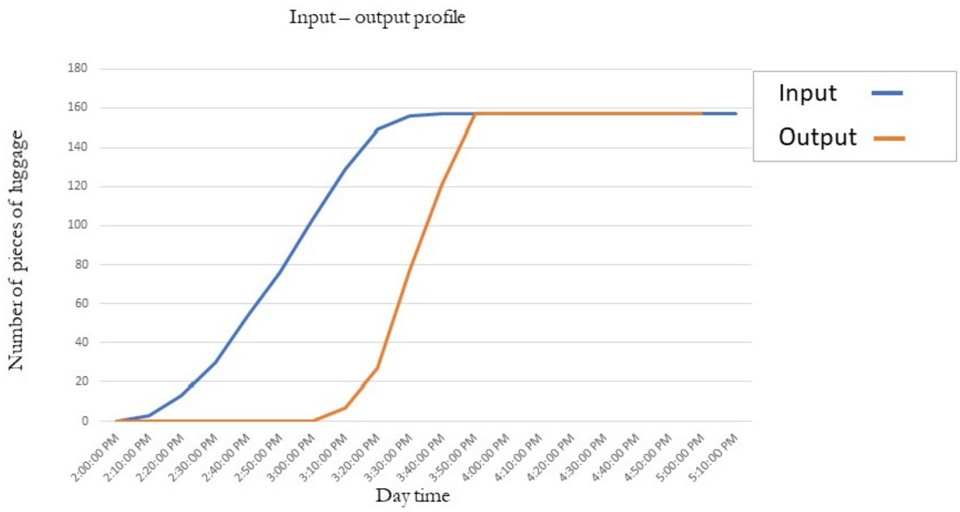


Figure 6-4: Types of junctions in the simulation model

arrival of luggage builds up gradually and the handled piece of luggage follow with a slight delay. The average in-system time has been measured at 41 minutes.

Energy calculations The next step if the verification has been performed to check if conveyor belts behave correctly. Figure 6-5 illustrates the path followed by one piece of luggage.

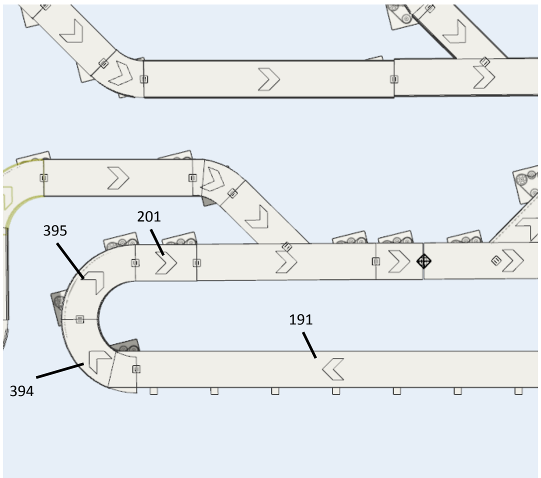


Figure 6-5: Model lay out

Firstly, the energy consumption is calculated in according to a basic calculation method. At first, the energy needed by a conveyor to travel empty during its entire run time is calculated by keeping track of empty travel time. The loaded run time is also measured by keeping track of the number of pieces of luggage handled by the conveyor. By combining the number of pieces of luggage with belt length and the conveyor speed the loaded run time is obtained. Finally, the empty and loaded added energy consumption are calculated according to the DIN 22101 standard and added to obtain the total energy consumption of each conveyor. The working principle of the basic calculation method is summarized in Table 6-2. Then,

Table 6-2: Basic calculation of energy consumption

ID	Nr of starts	Throughput	Length	Runtime		Speed	Empty kWh	Loaded kWh	Consumed energy [kWh]
190	1	1	25.3	48	0	0.5	1.066	0.183	0.0249
394	1	1	2.4	5	0	0.5	0.105	0.020	0.0002
395	1	1	2.4	10	0	0.5	0.105	0.020	0.0005
200	1	1	1.7	9	0	0.5	0.076	0.015	0.0002
								TOTAL	0.0238

the energy consumption is also calculated with a more complex calculation method in order to verify results from the basic calculation method. In this case the energy consumption is calculated based on state change of the conveyor:

1. Start, equal to one second of constant travel energy consumption
2. Conveying, calculated by making use of the DIN 22101 formula

Table 6-3 summarizes the calculation of energy consumption of the complex method. For each time interval the energy consumption is calculated depending on the conveyor its state.

Conveyor 191 for instance is stopped from time 0 to time 52700 seconds. After that its state changes and some energy is consumed to perform a start. Then, the conveyor is in the conveying state at the next time interval. it can be seen from the table that the conveyor transports one piece of luggage during conveying.

Furthermore, it can be seen from the table that conveyor 394 turns on and starts running empty when the simulation time is equal to 52748 seconds (the moment conveyor 191 start conveying). The conveyor starts conveying empty so that its speed is synchronized when the piece of luggage has arrived and needs to be transported.

Table 6-3: Complex energy calculation

ID	Start time	End time	State	Contents	Length	Speed	Energy [kWh]
191	0	52700	Stopped	0	25.3	0.5	0.0004
191	52700	52748	Conveying	1	25.3	0.5	0.0222
191	52748	86400	Stopped	0	25.3	0.5	0.0004
394	0	52748	Stopped	0	2.4	0.5	0.0000
394	52748	52748	Conveying	0	2.4	0.5	0.0000
394	52748	52753	Conveying	1	2.4	0.5	0.0002
394	52753	86400	Stopped	0	2.4	0.5	0.0000
395	0	52748	Stopped	0	2.4	0.5	0.0000
395	52748	52753	Conveying	0	2.4	0.5	0.0002
395	52753	52758	Conveying	1	2.4	0.5	0.0002
395	52758	86400	Stopped	0	2.4	0.5	0.0000
200	0	52778	Stopped	0	1.7	0.5	0.0000
200	52778	52783	Conveying	0	1.7	0.5	0.0001
200	52783	52787	Conveying	1	1.7	0.5	0.0001
200	52787	86400	Stopped	0	1.7	0.5	0.0000
						TOTAL	0.0278

The results obtained from the model by making use of both the basic - and complex calculation method have been compared to that of a hand calculation. During the performed simulation run, conveyors operate at a speed of 0.5 meters per second. The time to get from check-in towards storage has measured to be 405 seconds (about 5.5 minutes) at a travel distance of 202 meters. Travelling from storage to make up takes 225 seconds. From Table 6-4 it is concluded that the basic energy consumption results in a slightly lower energy consumption in comparison to the complex and hand calculation. Although the results obtained from the three calculations performed match in value. Therefore, the basic calculation is used in the remainder of this research. However its results will be checked by making use of the complex calculation method for selected experimental runs.

Table 6-4: Complex calculation of energy consumption

Variable	Check-in - storage	Storage - make up	Total travel distance	Basic energy consumption	Complex energy consumption	Hand calculation
Value	202 [m]	110 [m]	312 [m]	0,12 [kWh]	0,14 [kWh]	0,15 [kWh]

The same check has been performed on the runtime, travel distance and energy consumption of the conveyor and cart based concept. Table 6-5 summarizes the results. The energy needed to perform cart travelling is found in Table 3-6. It can be seen from the table that most of the energy consumption of the concept is due to operation of the carts. Furthermore it is seen that the empty travel distance exceeds that of loaded travel distance.

Table 6-5: Complex calculation of energy consumption

Conveyor belt	Transport time [Sec]	Transport distance [meter]			Energy consumption [kWh]
	188	94			0.035
Cart	Empty travel time [Sec]	Empty travel distance [meter]	Loaded travel time [Sec]	Loaded travel distance[meter]	Energy consumption [kWh]
	271	814 188	56	168	0.067
					Total energy consumption [kWh]
					.102

Figure 6-6 shows an image of the conveyor and cart based simulation model. In the figure it can be seen that a piece of luggage which has completed check-in has been transported by conveyors (white pieces of equipment) and is about to be combined with a cart. The cart travels on a rail (gray pieces of equipment). The coloured paths represent the followed path of the cart in either empty or loaded state. First, prior to picking up a piece of luggage the cart travels empty (Empty 1-red line). After pick up of a piece of luggage the cart travels towards storage (Loaded 1 - The line in dark blue) and after the piece of luggage has been stored the cart travels back empty (Empty 1 - red line). After some time the piece of luggage has to be picked up again from storage (Empty 2 - Orange line). The cart then takes the piece of luggage towards make up (Loaded 2 - Light blue line) and finally travels back towards storage empty (Empty 2 - Orange line).

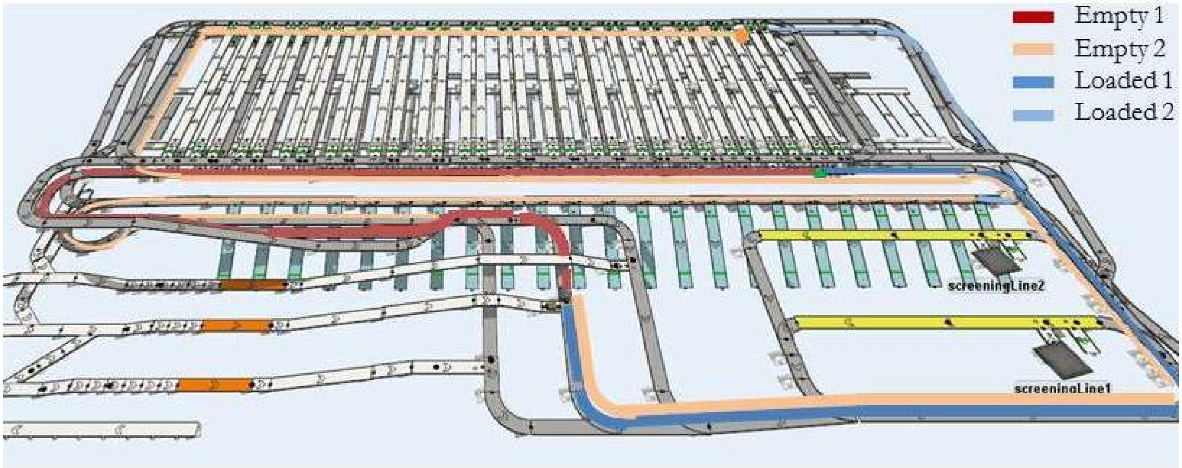


Figure 6-6: Image of the conveyor and cart based concept simulation model

6-4 Validation

In Figure 6-7 the energy consumption per passenger is summarized for different airports in Europe, total passenger numbers are found in Appendix G. It can be seen from the figure that the energy consumption per passenger ranges between 2 and 22 kWh per passenger for different airports. As for airports which handle less than 10 million passengers per year energy consumption per passenger is lower than 10 kWh / passenger.

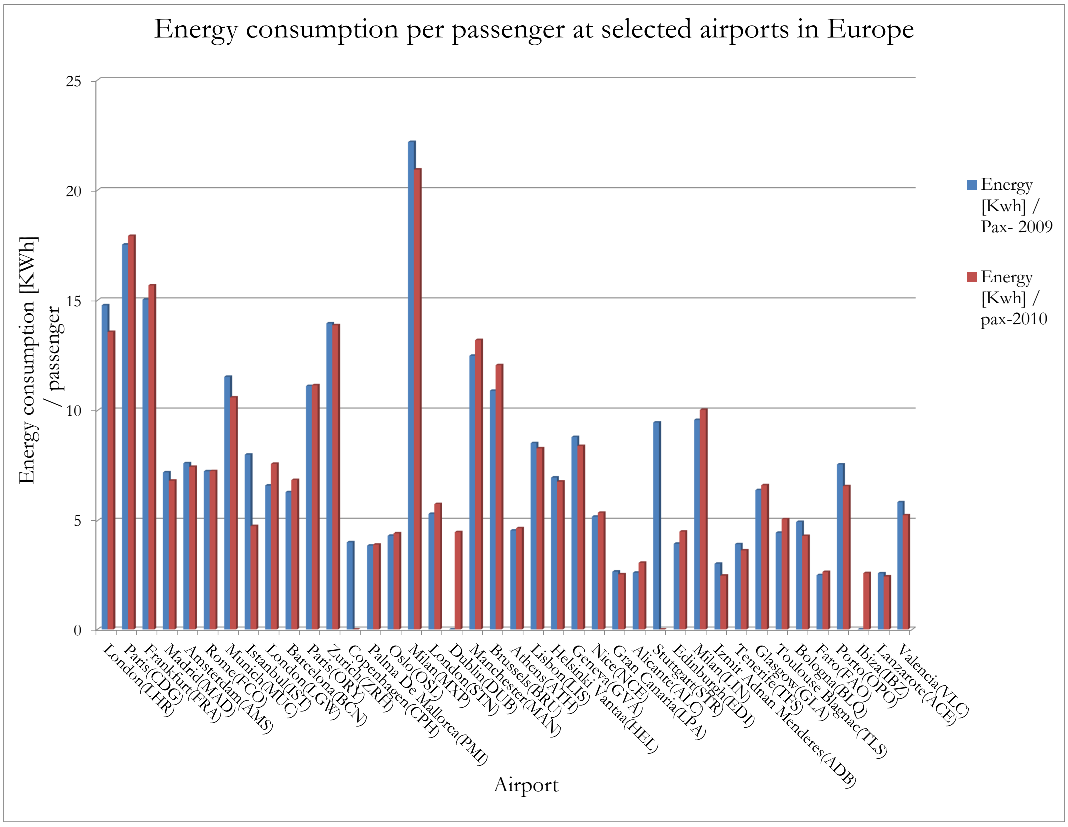


Figure 6-7: Energy consumption per passenger at selected airports in Europe [6]

Next, Table 6-6 summarizes the energy consumption per piece of luggage for two BHSs of different size. It can be seen from the table that energy consumption of the BHS increases with number of pieces of luggage handled. The research case evaluated later in this research handles a number of pieces of luggage which falls between Malpensa and Rotterdam airport, therefore it is expected that energy consumption per piece of the research case falls between the values displayed in the table.

Table 6-6: Energy consumption BHS Malpensa airport, januari 2011 - terminal 1

Aiport	Pieces of luggage / day	BHS energy consumption [kWh]	Energy / piece of luggage [kWh/luggage]
Malpensa	35,000	20,000	.57
Rotterdam	1,100	112	.08

From performing 20 replications at a throughput of 180 pieces of luggage it results that the energy consumption of the evaluated concept designs is equal to:

1. Concept 1: Conveyor based concept : 0,131 kWh / piece of luggage

2. Concept 2: Conveyor and cart based concept: 0,097 kWh / piece of luggage

Considering that in the current situation the BHS of Aruba airport handles about 7,000 pieces of luggage per day [74]. a number which is lower than that of Malpensa Airport but higher than that of Rotterdam airport it makes sense that the energy consumption of the Aruba falls between that of Rotterdam and Malpensa airport.

Chapter 7

Results

7-1 Experimental plan

Three scenarios are investigated during this research:

1. Variation of system load
2. Variation in arrival pattern of airplanes
3. Variation of the speed of equipment

These experiments are subjected to the two concepts which are examined within this research which are referenced to as:

- "Conveyor based concept"
- "Conveyor-cart based concept"

In the system analysis performed earlier in this research three categories have been defined: resources; structure; control. Since it is assumed that an existent lay out is the starting point of the model, changes in system structure are not investigated by the research cases under evaluation. Furthermore, since this research is a first step in taking into account energy consumption during concept design evaluation the choice is made evaluate designs at system level and to not investigate options to decrease energy consumption by variation of the control policy.

Each scenario has been 20 replications have been performed since differences in results between energy consumption are significant at this number of replications. At the same time duration of performing experimental runs remains at an acceptable level.

Scenario 1: Variation of system load
This scenario has been chosen to investigate system behaviour at different loads which corresponds to reality, since BHS operate under dynamic system loads:

- 180 pieces of luggage per day
- 900 pieces of luggage per day
- 1800 pieces of luggage per day
- 3600 pieces of luggage per day

In case of the conveyor based concept it is expected that the system its energy consumption per piece of luggage is relatively high. Since a small number of pieces of luggage is handled by the system the chance of a conveyor running to transport one piece of luggage. Furthermore, a smaller input results in a larger fraction of empty running of equipment since conveyor speeds need to be synchronized with its predecessor before a piece of luggage is transported by a conveyor.

Opposing to this, in case of the conveyor-cart based concept it is expected that energy consumption increases more linearly with an increase of load on the system. The reason is found in the fact that for each separate piece of luggage it is always the case that one cart is needed.

Scenario 2: Variation in arrival pattern of airplanes
By varying the peak load, the effect of arrival patterns during a day on energy consumption is investigated. Within this scenario three different input profiles are used. Figure 7-1 shows them graphically. It can be seen from the figure that luggage is able to arrive between 1 a.m. and 11 p.m. in case of the uniform distribution. As for the original distribution luggage is allowed to arrive between 7 a.m. and 8 p.m.. Lastly, the gamma distribution with increased peak, all of the airplanes arrive in about 5 hours time. On beforehand it is expected that

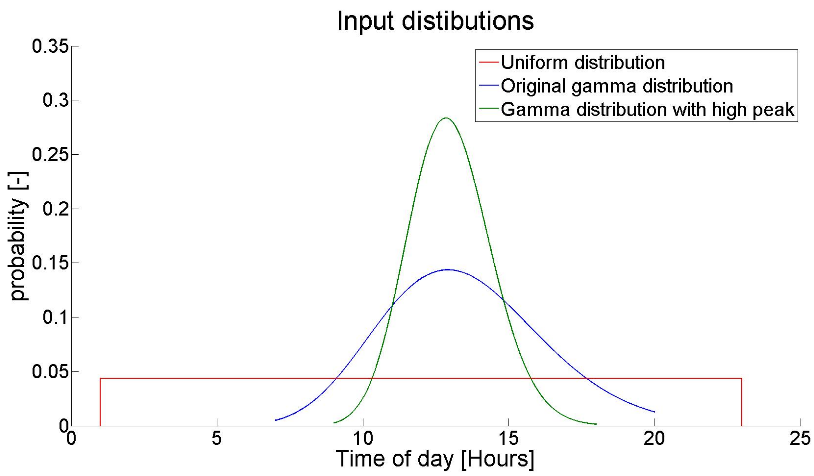


Figure 7-1: Input distributions - Variation in arrival pattern of airplanes

increasing peak load results in less energy consumption in comparison to a wider arrival pattern of luggage.

Scenario 3: Variation of the speed of equipment The third scenario investigates the effect of changing the transportation speed. Since running of equipment is the main cause of energy consumption of transport equipment the effect of varying equipment speed on energy consumption is investigated. Higher operational speeds decrease run times of equipment however energy consumption to perform a start up and to maintain constant operational speed increase. Three experimental cases have been defined in this scenario:

- Half the original speed
- Original speed

- Double Speed

At first, the operational speed is set to half the value of the original speed. After that the the original speed is investigated and finally, the original speed is doubled. On beforehand it is expected that energy consumption increases with speed. However, it is also expected that empty run times decrease since conveying speed is higher.

7-2 Model experiments

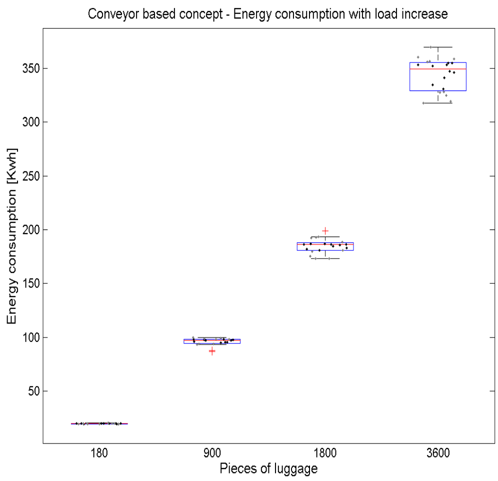
7-2-1 Variation of system load

Table 7-1 summarizes the settings used for each experiment performed within this scenario for both concept 1 and concept 2. From the table it can be seen that the number of airplanes has been varied per experiment.

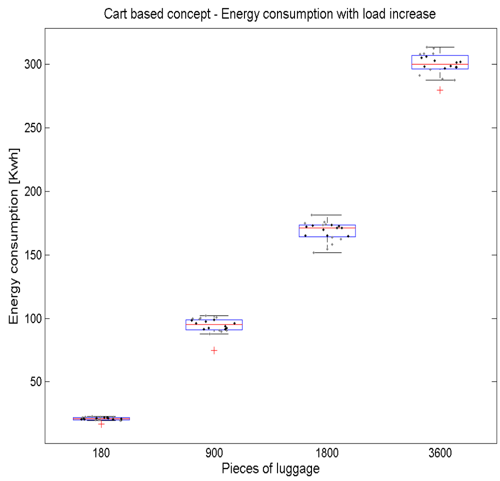
Table 7-1: Model input per experimental run - Variation of the number of airplanes

Conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	3600 pieces of luggage
Belt speed [m/sec]	0.5	0.5	0.5	0.5
Luggage per airplane	180	180	180	180
Cart and conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	3600 pieces of luggage
Belt speed [m/sec]	0.5	0.5	0.5	0.5
Luggage per airplane	180	180	180	180
Vehicle speed [m/sec]	3	3	3	3

Figure 7-2a and Figure 7-2b show the results per experimental run for both concepts. It can be seen from the figure that the variation in energy consumption increases with load, however at increased load the variation is smaller in case of the cart based concept. Furthermore, it can be seen from the figure that energy increases with an increase of the load. Furthermore, the difference in energy consumption between different concept has found to be significant after performing the student-t test, results are found in Appendix (Table G-2).



(a) Box plot of conveyor based concept - Load variation



(b) Box plot of cart and conveyor based concept - Load variation

Figure 7-2: Results from scenario 1, load increase

When looking into the replications per experiment in more detail it is noted that there is one replication where the amount of energy consumed is much smaller. As can be seen in Figure 7-3 where the number of pieces of luggage in the system over time is shown The reason for the low energy consumption of the one replication is found in the fact that all of the luggage has arrived in a short period of time. With an equal throughput, energy consumption differs 25 % between this replication and the average. The two replications displayed in the figure have also been evaluated by making use of the complex calculation method and the same trend is observed. The energy consumption obtained by making use of the complex calculation method has found to be 106 kWh compared to the 100 kWh found by application of the basic calculation method and 79 kWh instead of 75 kWh for the other replication, respectively.

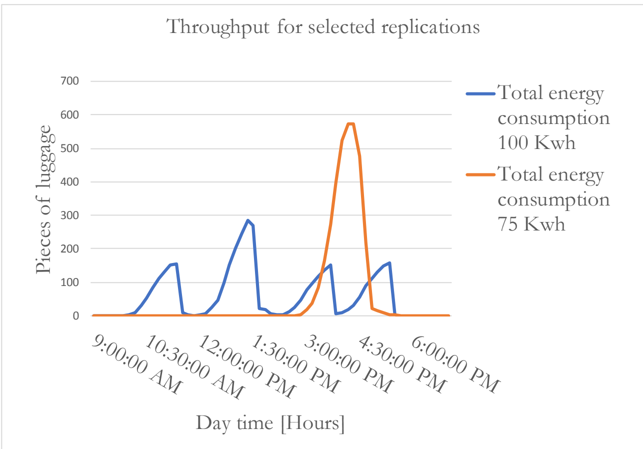


Figure 7-3: 2 selected replications - 900 pieces of luggage throughput

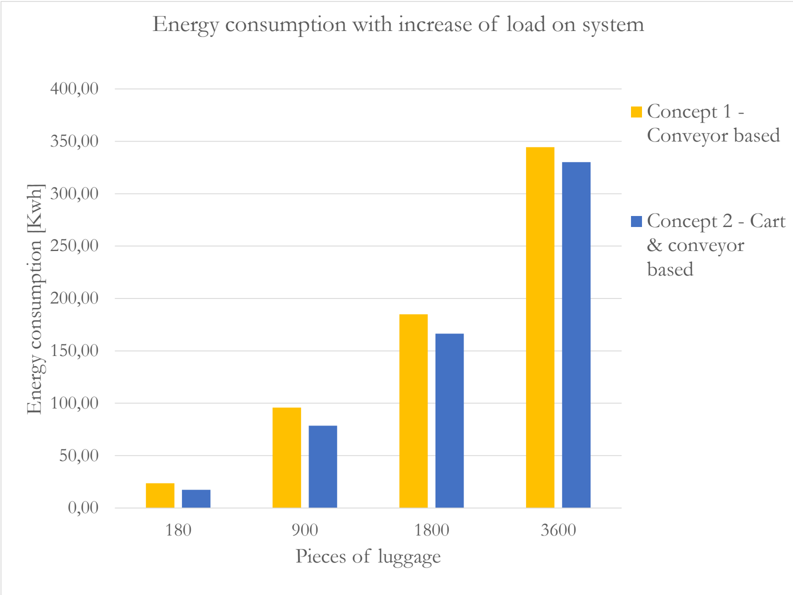


Figure 7-4: Energy consumption scenario 1 - Load variation

Comparison of concepts Figure 7-4 shows the energy consumption of the system with increasing load on the system in the form of a bar chart. From the figure it can be seen that the conveyor based concept consumes more energy at equal load, however the relative difference decreases as the number of pieces of luggage increases. The reason for this effect is found in the fact that a conveyor is turned on prior to the moment it has to transport luggage in order to synchronize their speeds. In case more pieces of luggage arrive shortly after each other, empty running decreases and thereby energy consumption per piece of luggage does too.

Next, Figure 7-5 displays performance of both concepts with an increase of system load, exact values can be found in Appendix K-1. From the figure it is concluded that for both concepts energy consumption per piece of luggage decreases with increasing system load. However it is observed decrease in energy consumption is larger in case of the conveyor based concept. The reason for this behaviour is found in the fact that each cart always transports one piece of luggage (supported by the data in K-1). Opposing to this, a conveyor belt starts empty to synchronize speed with its predecessor when a piece of luggage arrives. In case of higher system loads the chance that multiple pieces of luggage arrive shortly after each other increases and thereby empty run times decrease.

Furthermore, the figure shows that the LBI of the conveyor based concept is slightly higher than that of the cart based concept. Its value ranges between 0,85 and 1,22 %. Performing the F test showed that the difference in LBI is insignificant for the case where 1800 and 3600 pieces of luggage have been put into the system (Appendix J-1). In the other scenarios the difference is significant.

It is observed from the figure that the LBI decreases significantly when increase the load from 180 to 900 pieces of luggage. The reason for this behaviour is found in the fact that the number of planes arriving at the airport is small in case of these scenarios and that the number of mishandled pieces of luggage is small, its average value is 2, in case 180 pieces arrive. The number of replications performed is too low to obtain an insignificant difference between the LBI of the different loads.

It is tested and concluded that no blockages occur within the system. However it is seen that the cause of left behinds is due to pieces of luggage which have arrived late. Due to the fact that carts transport luggage at higher speed in comparison to conveyors they are able to handle an increased number of pieces of luggage on time.

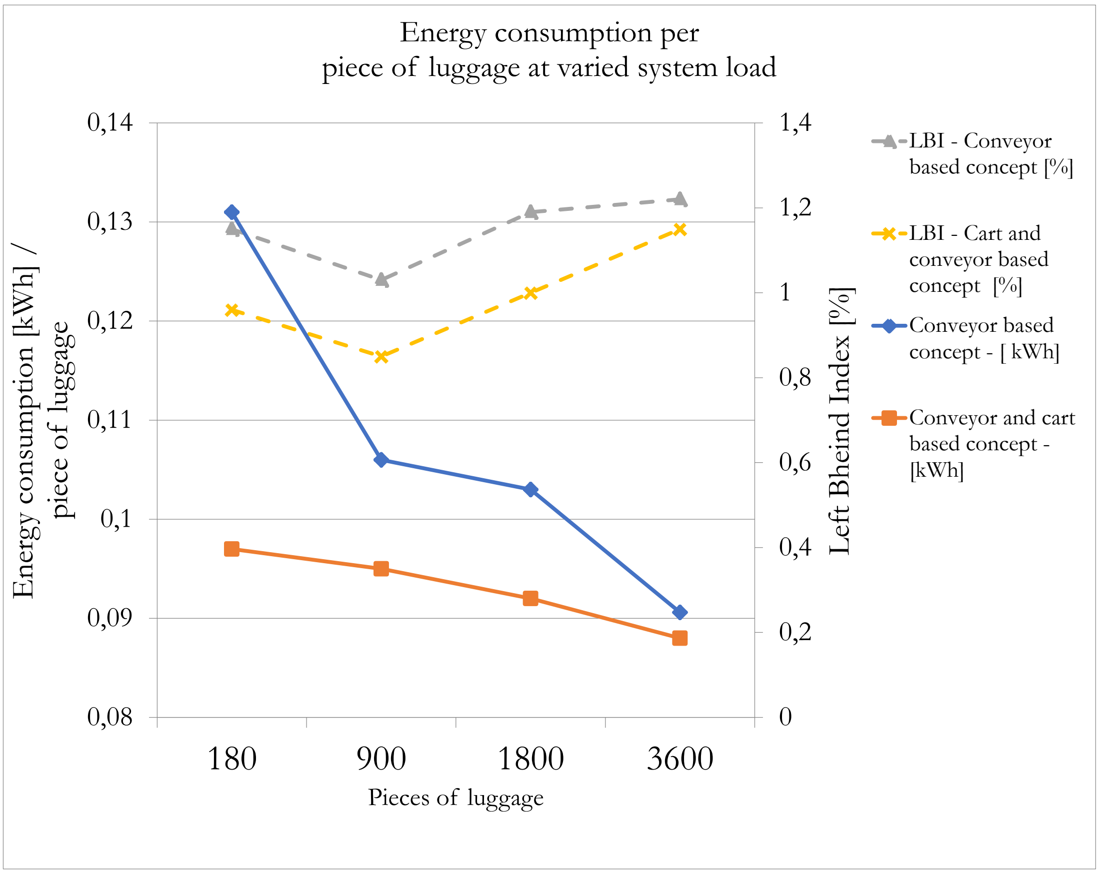


Figure 7-5: Energy consumption speed and capacity increase

7-2-2 Variation in arrival pattern of airplanes

Table 7-4 summarizes the input variables used during the investigation of this scenario. Within this scenario, the input distribution is changed per experimental case. After performing simulation runs the bar chart as seen in Figure 7-6 is obtained. A box plot showing the variation in energy consumption is stated in Appendix H. Furthermore, the difference in energy consumption between different concept has found to be significant after performing the student-t test, results are listed in appendix (Table H-2).

From the bar chart it can be seen that for both concepts energy consumption is the highest in case airplanes arrive according to a uniform distribution. Then, with the original distribution energy consumption decreases and lastly, in case of the highest peak energy consumption at same throughput decreases even more.

Table 7-2: Model input - Variation of the peak load on the system

Both concepts	Experiment 1	Experiment 2	Experiment 3
Belt speed	0.5 m/s	0.5 m/s	0.5 m/s
Luggage per airplane	180	180	180
Nr of airplanes	10	10	10
Airplane arrival distribution	Uniform distribution	Gamma distribution - original peak	Gamma distribution - steep peak

Furthermore, it is observed that the effect of a changing the input distribution affects the conveyor based concept more than the cart based one.

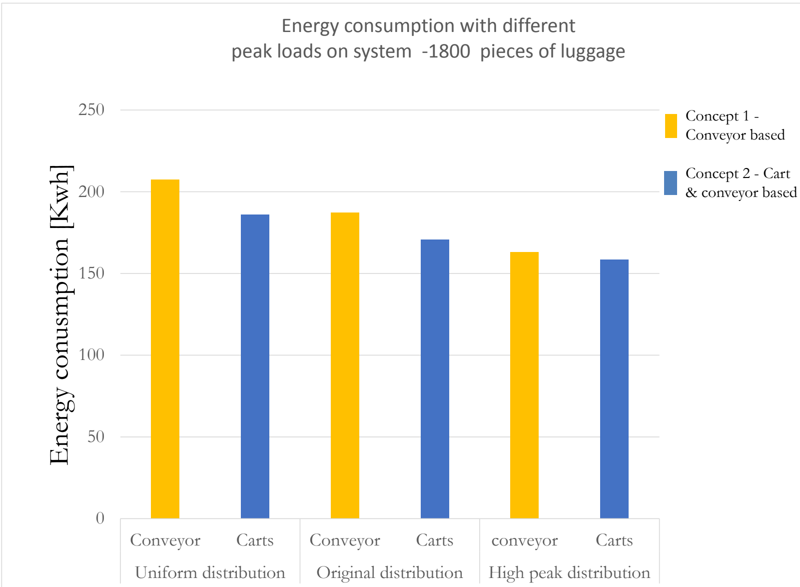


Figure 7-6: Decomposition of energy consumption cart- based concept

The cart based concept is less sensitive to different input profiles due to the fact that one cart always transports one piece of luggage at a time while one conveyor may transport multiple pieces of luggage at a time.

Figure 7-7 shows the energy consumption of the cart & conveyor based concept in more detail. It can be seen that the fluctuation in energy consumption is indeed mainly caused by the behaviour of the conveyors.

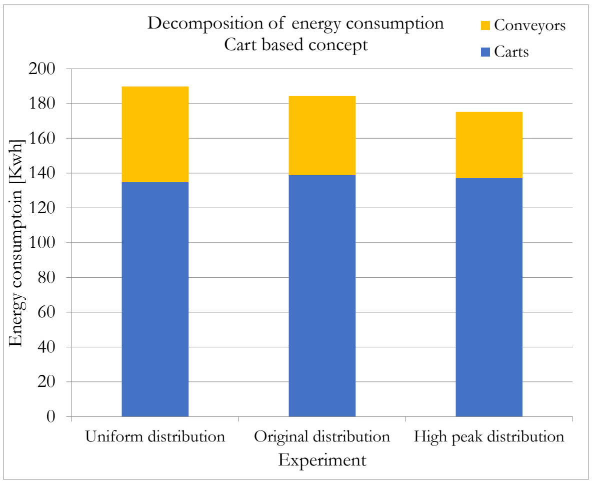


Figure 7-7: Energy consumption with peak variation

Table 7-3 shows the percentage of energy consumed for each input distribution. It can be seen from the table that the part of the energy consumed by the carts increases from 71 to 78 % of the total energy consumption as a result of a varied input profile.

Table 7-3: Model input - Variation of the peak load on the system

Conveyor and cart based concept	Carts	Conveyors
Uniform distribution	71 %	29%
Original distribution	75 %	25%
High peak distribution	78 %	22 %

Next, the performance of both concepts is compared in Figure 7-8, exact data values are listed in Appendix K-2. It can be seen from the figure that that the energy consumption per piece of luggage decreases with 21 % when comparing the uniform distribution with the one with the high peak. As for the conveyor and cart based concept the difference is 16 % and mainly caused the conveyor belts apparent in the design concept.

Furthermore, the difference between the high peak and original distribution in case of the conveyor based concept is found to be 12.5 % while the difference is 10.5 % in case of the conveyor and cart based concept. The results on the LBI have been analysed by making use of the F test. After evaluation of the results is concluded that the difference in LBI is insignificant (Appendix J-1)

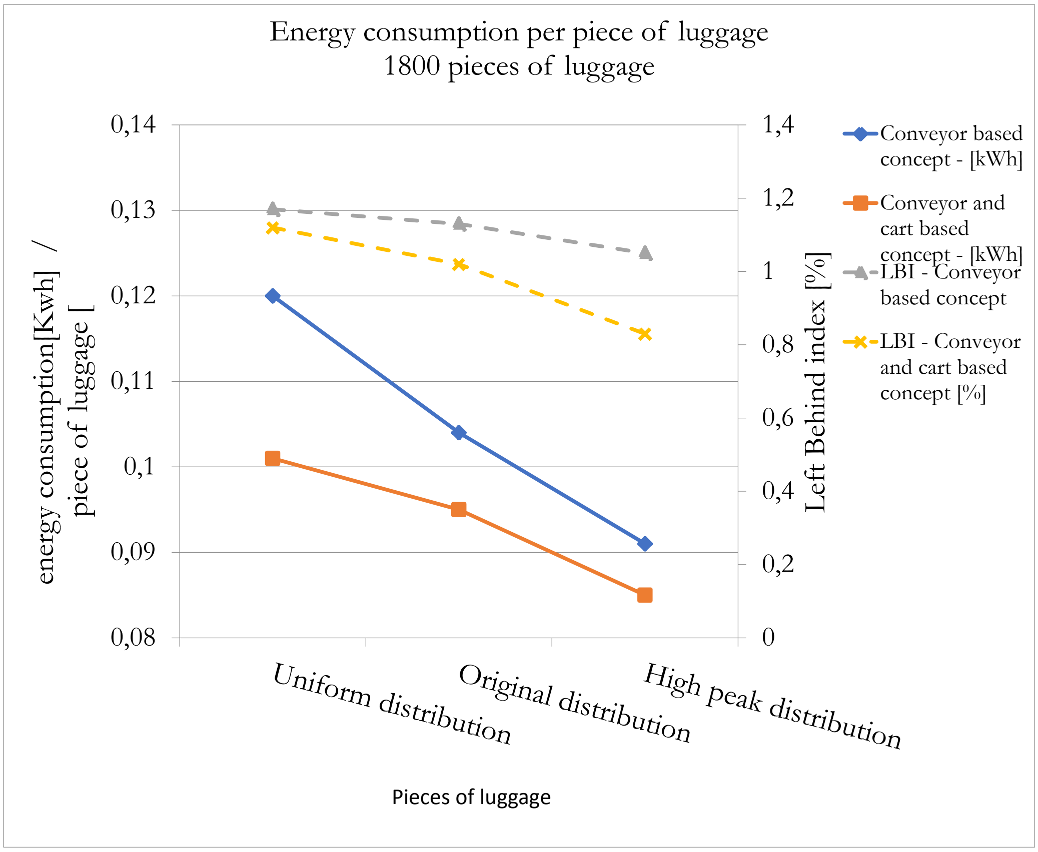


Figure 7-8: Energy consumption speed and capacity increase

7-2-3 Variation of the speed of equipment

Table 7-4 summarizes the input data for this scenario.

Table 7-4: Model input - Speed variation

Conveyor based concept	180	900	1800	2400
Speed [m/sec]	0.25 - 0.5 - 1	0.25 - 0.5 - 1	0.25 - 0.5 - 1	0.25 - 0.5 - 1
Luggage per airplane	180	180	180	180
Nr of airplanes	1	5	10	15
Cart based concept	180	900	1800	2400
Cart speed [m/sec]	1.5 - 3 - 6	1.5 - 3 - 6	1.5 - 3 - 6	1.5 - 3 - 6
Conveyor speed [m/sec]	0.5 - 0.5 - 0.5	0.5 - 0.5 - 0.5	0.5 - 0.5 - 0.5	0.5 - 0.5 - 0.5
Luggage per airplane	180	180	180	180
Nr of airplanes	1	5	10	15

The bar chart below summarizes the results for the runs performed in this scenario, more detailed information on the variation of the results per replication is listed in Appendix I. Furthermore, the difference in energy consumption between different concept has found to be significant after performing the student-t test, results are found in the Appendix (Table I-2,Table I-3 ,Table I-4).

Firstly, it is observed that energy savings are obtained when decreasing operational speed of equipment. Decreasing operational speed may be a promising solution towards decreasing system energy consumption. Also it is seen that energy consumption less than doubles when increasing energy consumption. Furthermore, it is seen that the energy consumption of the conveyor based concept approaches that of the cart based one for increased speeds. It is expected that this is caused by a decrease of empty run time of equipment.

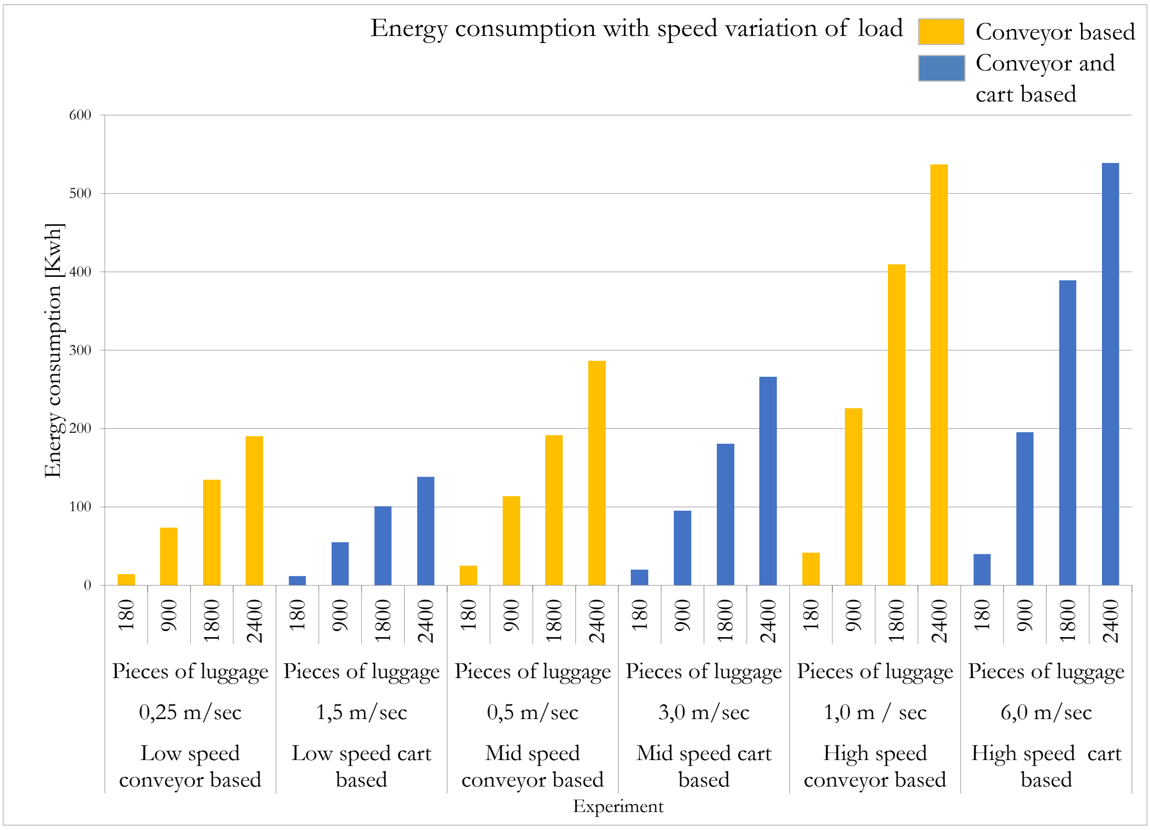


Figure 7-9: Energy consumption speed and capacity increase

Table 7-5 shows the reduction of energy consumption when speed is decreased from 0.5 to 0.25 seconds. It can be seen that the relative increase is lower for the conveyor based concept which is expected to be caused by a decrease of the empty run time of conveyor belts.

Table 7-5: Scenario 3: Speed variation - Relative energy savings

Conveyor based concept	180	900	1800	2700
0.5 to 0.25 m/sec energy savings	43 %	35 %	30 %	34 %
Cart based concept	180	900	1800	2700
0.5 to 0.25 m/sec energy savings	40 %	42 %	44 %	47 %

Table 7-6 summarizes the energy consumption per piece of luggage for each experimental case. When taking a look at the energy consumption of the conveyor based concept in more detail it is observed that energy consumption decreases with an increased load on the system. While in case of the conveyor and cart based concept the energy consumption per piece of luggage hardly changes. The reason for this behaviour is found in the fact that each carts transports one piece of luggage at once at all times, however the small decrease observed is caused by the conveyors operating in the system. In Appendix J-3 the F test has been performed on the resulting LBI values. From the table below it can be seen that the for the conveyor based concept the LBI is over five % at a speed of 0.25 m/sec, after evaluation of the results it has been found that the reason for the luggage to be late is due to the increased transport time between check-in and make up and that between storage and make up. The LBI results have been analysed in Appendix J-3. In case of the conveyor and cart based concept the LBI even exceeds 9 % for all scenarios. The reason that the LBI is higher for this concept is found in the fact that it takes extra time for a cart to get to the location where a piece of luggage is loaded onto it. The increased travelling time results in blockages in the system.

Table 7-6: Scenario 3: Speed variation - Comparison of concepts

Conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	2400 pieces of luggage
0.25 m/s Energy consumption [kWh] / piece of luggage	0.089	0.082	0.075	0.053
0.25 m/s LBI	5.639	6.261	5.472	7.515
0.5 m/s Energy consumption [kWh] / piece of luggage	0.143	0.126	0.116	0.082
0.5 m/s LBI	1.123	1.011	1.192	1.631
1 m/s Energy consumption [kWh] / piece of luggage	0.275	0.247	0.227	0.159
1 m/s LBI	0.833	0.533	1.142	0.881
Cart and conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	2400 pieces of luggage
1.5 m/s Energy consumption [kWh] per piece of luggage	0.066	0.034	0.034	0.024
1.5 m/s LBI	10.75	10.85	10.11	9.052
Energy consumption [kWh] per piece of luggage	0.109	0.106	0.100	0.098
3 m/s LBI	1.083	0.852	1.000	1.557
Energy consumption [kWh] per piece of luggage	0.222	0.217	0.216	0.210
6 m/s	0.667	0.833	0.542	0.963

Chapter 8

Conclusion

This research aims to answer the following main question: *"What is the impact of considering energy consumption in preliminary design stage of the design process of baggage handling systems on performance?"*
From the perspective of a designer it is very hard to estimate energy consumption in the *preliminary design stage*, where the designer(s) evaluate(s) potential conceptual designs and chooses the most promising one. It is a fact that it involves many dependent variables and that the system should be able to deal with dynamically changing demands. This necessitates the use of dynamical models [5]. The generic simulation model created during this research is a promising first step towards taking into account energy consumption during preliminary stage of the design. The model has been applied to two concept designs: (1) Conveyor based concept and (2) Conveyor & cart based concept.

From experiments in a simulated environment which are based on the performed system analysis it is concluded that carts operate at a lower energy consumption in comparison to the conveyor based concept, particularly in case of of low system loads. Furthermore, they are less sensitive to input variations. As for the conveyor based concept efficiency is lower at low loads and increases with increasing system load. It has been observed that the conveyor based concept operates almost equally efficient to the conveyor and cart based concept at higher system loads.

Furthermore, in case of the conveyor based concept a decrease in energy consumption of 25 % has been monitored for the case where all pieces arrive in about three hours in comparison to the situation where luggages arrives more evenly distributed along the day. As a consequence of this observation batching is believed to be an interesting measure to reduce energy consumption of a BHS.

Another observation is that a decrease of the number of pieces of luggage to be handled from 3600 to 180 per day results in an decrease of the carts their energy consumption of 10 % relative to that of the conveyors. The reason for this difference is found in the fact that each cart always transports one piece of luggage while a conveyor is able to transport one or more pieces of luggage at the same time.

Lastly, it is seen that decreasing conveyor speed is also a promising measure to reduce energy consumption of the system, however the effect of speed reduction on the left behind index has to be monitored closely, it increases for the conveyor and cart based concept at low speeds. In case of the conveyor based concept savings of 30 to 35 % are observed by decreasing speed from 0.5 to 0.25 m/sec, while in case of the cart based concept savings from 42 to 47 % are achieved.

Summarizing, during this research insight in energy consumption of conceptual designs is obtained. The energy consumption has been investigated at different load profiles. It is concluded that conveyor energy consumption per piece of luggage decreases with system load while the energy consumption per piece of luggage of carts is less sensitive to input changes.

From the research it is concluded that batching and variable speed control are promising topics for future research.

Chapter 9

Recommendations

9-1 Directions for further research on reducing BHS energy consumption

Within his research focus is on the behaviour of pieces of equipment used in different concept designs (resources). For future research it is firstly recommended to focus on the control policy. As a first recommendation batching poses an interesting topic for future research in case conveyors are used for luggage transport.

Secondly, it is recommended to investigate the effect of changing the structure of a concept design on energy consumption. As a first direction it is proposed to investigate the effect of adding cross connections to the system.

9-2 Test applicability in actual design process

By making use of this model during an actual design process it will become evident to evaluate its impact on a real life design process. It is expected that doing so results a design choice where energy consumption is taken into account.

9-3 Apply the model to evaluate energy consumption existing BHS

During this research conceptual designs have been evaluated which are not yet built. As a research case it is recommended to evaluate an load the lay out of an existing system into the model to demonstrate possibilities for reducing energy consumption and similarly obtain a more detailed validation of the model.

9-4 Benchmarking energy consumption of baggage handling systems

By benchmarking the energy consumption of more existing BHSs it will become possible to compare to obtain information on energy consumption of different BHSs, with a multitude of difference equipment types, loads faced by the system, differences in arrival patterns and conveying distances.

9-5 Extending the work within the scope of BHss

For future research it is recommended to investigate energy consumption of types of equipment not investigated within this research. Most recent developments in baggage handling concern the use of AGVs.

9-6 Application of the generic model in similar industries

This research focusses solely on baggage handling. As a next step for further research it is proposed to extend the scope of this work to other transportation systems. Particularly distribution, warehousing and manufacturing industry show similarities with baggage handling.

Appendix A

Research paper

Energy consumption of baggage handling systems

Impact assessment on the effect of taking into account energy consumption during preliminary design stage

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May 30, 2018

Abstract

*As a consequence of globalization and developing economies becoming more mature, airports face increasing passenger numbers [***IATA**, **2011***]. It is the case that large airports are energy intensive buildings with an electricity consumption ranging between 100 - 300 GWh anually [***CASCADE**, **2011***]. Within ATBs (Airport Terminal Buildings) the BHS (Baggage Handling System) is categorized as a high energy consuming system [***CASCADE**, **2012***]. As for the BHS, conveying equipment is the main consumer of energy (55% to 70%) [***Vogel**, **2009***]. From the perspective of a designer it is very hard to predict energy consumption in evaluation of conceptual designs and therefore energy consumption is often not given the attention it deserves at this stage of design due to the fact that baggage handling performance is dependent on many dependent variables and dynamically changing demands. As a consequence the use of dynamical models is necessary [***Zeinaly**, **2012***]. In this research a generic simulation model has been created to investigate energy consumption. The applicability of the model has been tested on two conceptual design lay outs.*

I. Introduction

Most passengers desire to take some sort of luggage onto their flight. If it qualifies as hand luggage the passenger is allowed to take it into the airplane himself. However, in case luggage does not qualify as hand luggage it has to be handed in at the check-in desk and is considered as hold luggage and is handled by the BHS.

A major factor that makes BHS an interesting topic of research is found in the highly dynamically changing loads, which is a consequence of the variation of the volume entering the BHS, the multitude of different aircraft capacities, changing flight schedules, lost luggage, barcode misreads, early luggage, late luggage and equipment downtime, what results is a highly stochastic and dynamic operational environment [**Johnstone**, **2010**].

The purpose of the BHS is to enable an increased comfort-level experienced by passengers during their travel due to the fact that they do not need to carry their hold luggage after check-in. When considered as a black box, as illustrated by figure 1, the function of the system is to transform incoming luggage (input) into handled luggage (output).

Figure 1: *Black box of BHS*

II. The baggage handling system

By further opening up the black box, figure 2 is obtained. It can be seen that the BHS performs 3 sub-functions in its environment. At first the system collects luggage which is then sorting and finally delivering at the correct destination while fulfilling requirements on system performance On entry luggage is first checked in, identified and screened (Collect). After that, luggage is sorted out (Sort) and finally delivered and is ready to be loaded onto an airplane (Deliver). After opening up the sub-functions, the processes as displayed in the figure below are obtained. Luggage which is transported

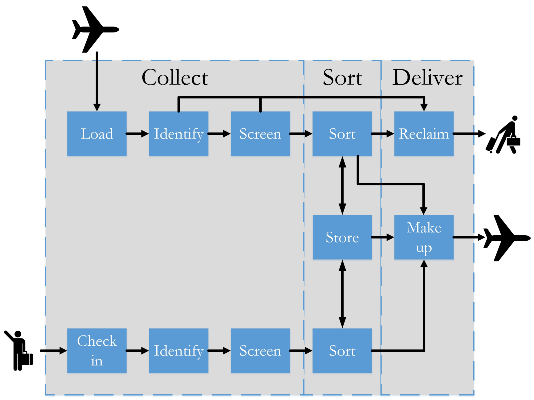

Figure 2: *Processes in baggage handling [**SEWEurordive**]*

between airplanes is defined as transferring luggage, while luggage travelling from check-in towards make up is defined as Check-in luggage and finally luggage travelling from an airplane towards reclaim is defined as Reclaim luggage. Those airports where check-in and reclaim luggage flows are dominant are defined as point to point or O& D (Origin and Destination) airports.
In case of a point to point airport luggage enters the BHS via either the "check-in" or "load" process. Two types of flows of luggage exist: (1) Transferring luggage flow, transportation between airplanes, (2) O& D luggage, luggage flows from check-in to make up or from load to reclaim. The next step is to identify each piece of luggage, so that it is known who owns it and what its destination is. Each piece of luggage having entered the system via check-in, passes screening. While in case luggage originates from an arriving airplane it not always needed to perform screening. However in some occasions is may be needed, for instance when a passenger behaves suspicious or when the airplane originates from high risk countries.

Subsequently, luggage is sorted out and is temporarily stored if it has arrived early. Finally, luggage is delivered to either a passenger via reclaim or to a departing flight via make up.

III. System energy consumption

The method by the name of "process chain model", as proposed by Blecker in "Innovative methods in logistics and supply chain management" has been used to evaluate the system its energy consumption. As can be seen in figure3 three pillars have been defined within the proposed model.

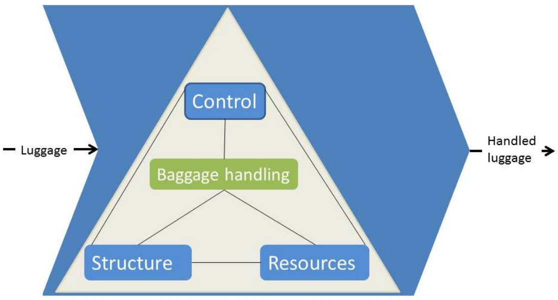

Figure 3: *The three pillars determining energy consumption of a BHS [**Blecker, 2014**]*

Resources During operation conveyors belts have to fulfil requirements on speed (typically 0,5 m/sec), acceleration and stopping time. In case of conveyor belts, the chosen rubber cover material may reduce indentation resistance of a horizontal belt conveyor by 30 % [**Lodewijks, 2012**]. Also, conveyor length, load and belt weight influence energy consumption. Calculation of conveyor energy consumption has been done according to the DIN 22101 standard.

Besides traditional conveying, tubs in combination with a twin belt are able to operate at an increased speed (3 m/sec). Another option is to make use of DCVs (Destination Coded Vehicles) or carts are to perform transporting and sorting of luggage. The advantage of the carts is found in the possibility of achieving even higher operational speeds (up to 10 m/sec) and the fact that maintenance of carts is straightforward since cart can be taken out of the system in case maintenance is required. From the viewpoint of energy consumption it is an advantage that each cart can be driven separately by making use of linear induction motors [**Tarau**, **2008**]. However a drawback of the system is found in the empty travelling of DCVs. After leaving storage a DCV has to travel towards the piece of luggage prior loading it onto a cart. It then transports a piece of luggage towards the desired destination and perform unloading. After that it needs to travel empty to find its next piece of luggage or to get back a storage location.

Structure By adding cross connections flexibility of the system increases. Furthermore, it becomes possible to re-route luggage with changing system loads. Another advantage is found in the fact that less energy is consumed due to shutting down parts of a line at times of low system load.

The interaction between processes within baggage handling due to the choice in equipment affects system behaviour and energy consumption. For instance, making use of a conveyor based system in combination with a line based storage results in different profile of energy consumption in comparison to making use of carts in combination with a racked storage.

Control In his research P. Vogel managed to decrease energy consumption of a BHS by 30 % by reducing run times of conveyors . Furthermore, he proposed the investigation of batching as an interesting topic for future research [**Vogel**, **2009**]. Another reason for looking into equipment control policy is that only 5 % of luggage handled by the BHS is time-critical [**Scholing**, **2014**]. Making a clear separation of the critical and non-critical flows and designing processes that are able to achieve both speed and timeliness can help raise quality and reduce costs and energy consumption.

IV. Model design

The created simulation model has been built by loading a system lay out into the model (created in Flexsim 18.1). An impression of the model is found in figure 4. On start of

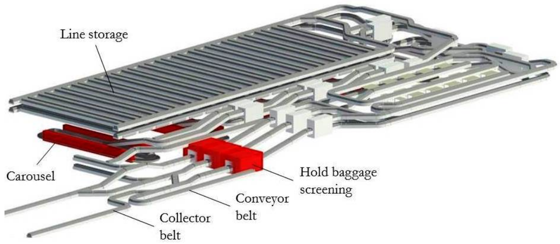

Figure 4: *Design lay out of simulation model*

simulation the simulation model is empty and is set to run for a time of 24 hours. Luggage arrive according to a gamma distribution and their arrivals are initiated by airplane arrivals, also arriving according to a gamma distribution. This distribution has been chosen since it provides the possibility to shift peaks and to change their magnitude by changing two parameters.

It is possible for luggage to arrive at airports between 3 hours and 45 minutes hours prior to scheduled airplane departure time. Table 1 summarizes the input variables used defined for running the simulation. Defining performance and requirements of the model with the right KPI (Key Performance Indicator) is a hard task and the ones which are appropriate depend on the research purpose. Granberg, as a first a definition states that KPIs should be related to volume since this makes it easier to evaluate system performance in different situations [**Granberg**, **2013**]. Within this research the performance level of the system is measured by measuring the performance on:

- Energy consumption [kWh] / piece of luggage .

Table 1: *Standard input values*

Model parameter	Type	Standard setting
Simulation run time	Fixed	24 hours
Nr of airplane departures	Number value	Variable
Pieces of luggage per airplane	Fixed	180
Airplane arrivals	Gamma distribution	
Luggage arrivals	Gamma distribution	
Transport speed	Variable	
Check-in time	Fixed	30 seconds
Screening time	Fixed	15 seconds
Manual screening time	Fixed	30 seconds
Make up time	Fixed	30 minute

while monitoring the (LBI) Left Behind Index, which represents the percentage of luggage not making it onto the airplane due to disruptions in the BHS and in-system times, defined as the time a piece of luggage remains within the BHS.

The model makes use of the Dijkstra-A-star algorithm, a shortest path algorithm, for routing of luggage. The reason for making use of this algorithm is found in the fact that it is possible to adapt the algorithm to the need of the designer by adding cost variables if desired. Furthermore, the model distributes load among installed screening machines in order to avoid blockages in the system. Within the research two conceptual designs have been created and compared:

Concept 1: Belt - carousel The first concept design has been defined as the "conveyor based concept" since transportation is performed by making use of conveyors. Furthermore a lane based storage and carousels are used to complete make up. After check-in, a piece of luggage is loaded onto the collector belt and is transported onwards for screening. In case luggage passes screening it is transported onwards, either towards line storage if it has arrived early or onto the carousel if the airplane departs shortly. However, luggage failing to pass screening is directed towards a manual screening station prior to onwards transportation. Within the conceptual design, the lane based storage consists of two levels for reasons of redundancy and capacity requirements. Finally, a conveyor belt loads luggage onto a carousel located at the make up area.

Concept 2 Conveyor-carts-chute The second concept is defined as the "conveyor & cart based concept". Initially luggage which has been checked-in is transported onwards by collector belts. Then, conveyors are used to transport luggage through screening. After completion of the screening process luggage is loaded onto carts for onwards transportation and sorting. Storage is performed in a lane based fashion and make up is performed by making use of chutes.

V. Results

Three scenarios have been investigated for both concepts and for each scenario 20 experimental runs have been performed per experimental case to decrease variation energy consumption / piece of luggage. First, the Anderson Darling test has been used to test for normality and after that the student t test has been performed to investigate significance of differences. The significance of variations have been found to be significant at a 95 % confidence interval.

Scenario 1: Load increase This scenario has been chosen to investigate system behaviour at different loads. Also, the variability of energy consumption is investigated by performing 20 runs per experimental case. In case of the conveyor based concept it is expected that the system its energy consumption per piece of luggage is relatively high at lower loads. Since handling a small number of pieces of luggage results in an increase of the chance that a conveyor runs to transport one or a few pieces of luggage at a time. Furthermore, running at lower loads results in empty running of equipment since conveyor speed needs to be synchronized with its predecessor before a piece of luggage is transported by a conveyor. While in case of the conveyor-cart based concept it is expected that energy consumption increases more linearly with system load since each separate piece of luggage is always transported by one cart.

Figure 5 shows the average energy consumption of the system with increasing load on the system in the form of a bar chart. It can be seen from the figure that the conveyor based concept consumes more energy at equal load in comparison to the cart based concept. However the relative difference decreases as the number of pieces of luggage increases. The reason for this effect is found in the fact that a conveyor is turned on prior to the moment it has to transport luggage in order to synchronize its speeds. In case more pieces of luggage arrive shortly after one another, empty run time decreases and thereby energy consumption per piece of luggage does too.

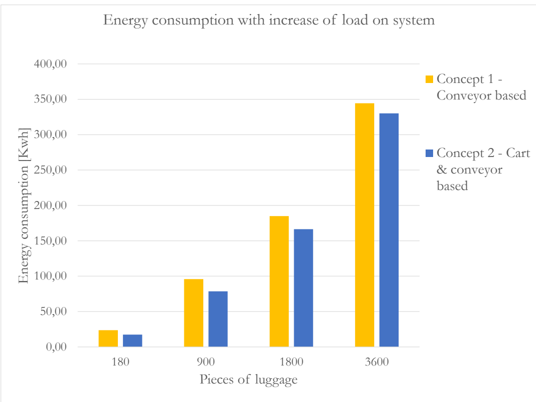

Figure 5: *Energy consumption scenario 1 - Load variation*

A decrease in energy consumption of 25 % has been monitored for the case where all pieces arrive in about three hours in comparison to the situation where luggages arrives more evenly distributed along the day (figure 6). As a consequence of this observation batching is believed to be an interesting measure to reduce energy consumption of a BHS.

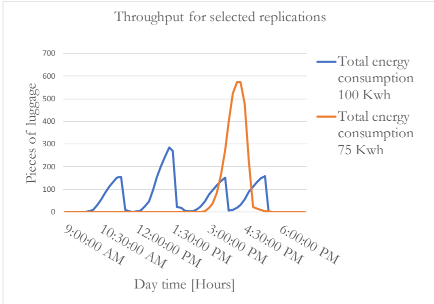

Figure 6: *Design lay out of simulation model*

Scenario 2: Varying peak arrival of airplanes By varying the peak load, the effect of arrival patterns during a day on energy consumption is investigated. Within this scenario three different input profiles are used. On beforehand it is expected that increasing peak load results in less energy consumption in comparison to a wider arrival pattern of luggage. The energy consumption has been investigated at a fixed level of 10 departing airplanes which are loaded with 180 pieces of luggage. The input distributions have been varied per experimental case, as can be seen in figure 7.

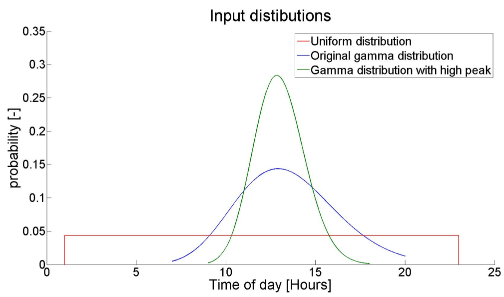

Figure 7: *Input distributions-Varying peak arrival of airplanes*

Figure 8 summarizes the results of energy consumption. it can be seen that energy consumption decreases as the peak in arriving airplanes increases. Another observation is that energy consumption of carts remains almost constant at a varied luggage input profiles.

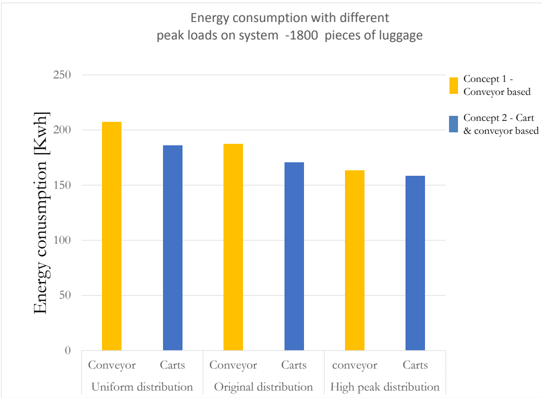

Figure 8: *Decomposition of energy consumption cart-based concept*

As can be seen in figure **??** the part of the energy consumed by the carts increases from 71 to 78 % as a result of a varied input profile.

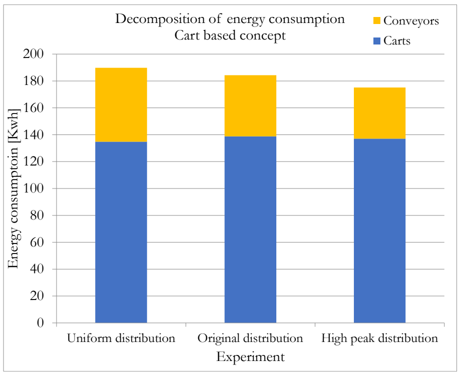

Figure 9: *Energy consumption with peak variation*

Scenario 3: Speed variation The third scenario investigates the effect of changing the transportation speed. By changing the operational speed, interactions between conveyors change as well since start up times increase, empty run times change and in-system time of luggage increases. At first, the operational speed is set to half the value of the original speed. After that the the original speed is investigated and finally, the original speed is doubled. On beforehand it is expected that energy consumption increases with speed. However, it is also expected that empty run times decrease since conveying speed is higher.

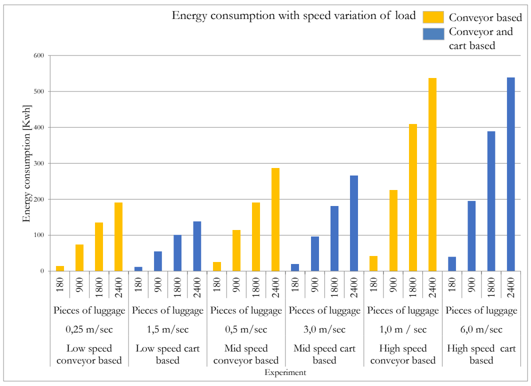

Figure 10: *Energy consumption speed and capacity increase*

Table 2 shows the reduction of energy consumption when speed is decreased from 0,5 to 0,25 m/sec. It can be seen that the relative increase of the conveyor based concept is smaller which is expected to be caused by a decrease of the empty run time of conveyor belts.

Table 2: *Scenario 3: Speed variation - Relative energy savings by reduction of speed*

Conveyor based concept	180	900	1800	2700
0,5 to 0,25 m/sec	43 %	35 %	30 %	34 %
Conveyot & Cart based concept	180	900	1800	2700
0,5 to 0,25 m/sec	40 %	42 %	44 %	47 %

VI. Discussion

From experiments in a simulated environment it is concluded that conveyors are becoming more efficient as the load on the system increases. Furthermore A decrease in energy consumption of 25 % has been monitored for the case where all pieces arrive in about three hours in comparison to the situation where luggages arrives more evenly distributed along the day. As a consequence of this observation batching is an interesting measure to reduce energy consumption of a BHS. Another observation is that carts consume less energy consumption in comparison to conveyor based system in case of low system loads, however conveyors operate almost equally efficient at higher system loads. A shift in peak arrival of airplanes results in a decrease of the carts their energy consumption of 10 % relative to that of the conveyors. The reason for this difference is found in the fact that each cart always transports one piece of luggage while the conveyor speed needs to be synchronized.

Figure 11 summarizes the energy consumption per piece of luggage with load increase. It can be seen that the conveyor based concept is much more dependent on a change in system load and approaches the energy consumption per piece of luggage of the cart and conveyor based concept at increased load.

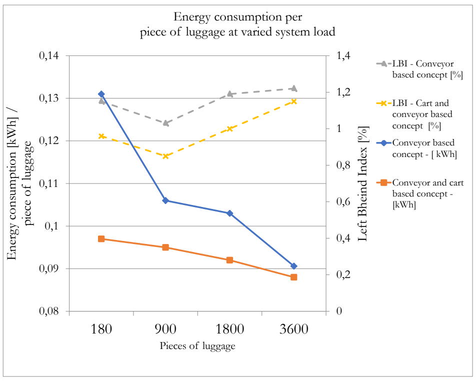

Figure 11: *Energy consumption speed and capacity increase*

Furthermore it is seen that there is a change in the LBI at 900 pieces of luggage. This drop is caused by the fact that the number of replications is not sufficient to obtain insignificant differences between results (180 & 1800) pieces of luggage. The random number of pieces of luggage which arrives late influences the value of the LBI. Next, figure 12 summarizes the energy consumption per piece of luggage for different arrival distributions. it can be seen that the conveyor based concept is much more dependent on a change in system load and approaches the energy consumption per piece of luggage of the cart and conveyor based concept at increased load. Furthermore, by making use of the F test the variation in LBI has found to be insignificant.

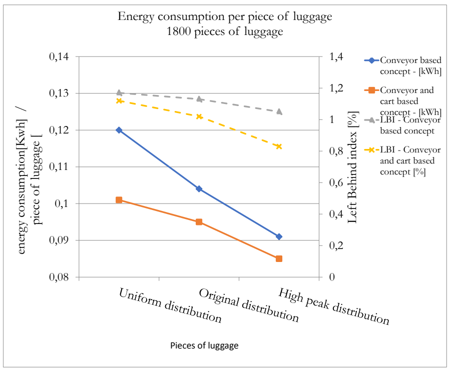

Figure 12: *Energy consumption speed and capacity increase*

Lastly, it is seen that decreasing conveyor speed is also a promising measure to reduce energy consumption of the system, however the effect of speed reduction on the left behind index has to be monitored closely. In case of the conveyor based concept savings of 30 to 35 % are observed while in case of the cart based concept savings from 42 to 47 % are achieved.

Summarizing, performing simulation during preliminary design stage is a good way to gain insight in energy consumption of conceptual designs under evaluation. The simulation model showed that there is a significant difference in energy consumption between different conceptual design concepts.

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Appendix B

Priority of baggage handling

SAM Breakdown of energy consumption systems in airports.	
Priority Systems – High energy consuming systems	Central Building Automation Systems
	HVAC
	Lighting controls and sensors
	Refrigeration systems
	Vertical transport
	Building Envelope
	Baggage handling systems (1)
	Information Technology systems (2)
Lower Priority Systems Low energy consuming systems	Emergency Power Generators and Automatic Transfer Switching
	Uninterruptible Power Supply systems
	Life Safety systems; Fire protection; Fire alarm; Egress pressurization
	Lighting Protection
	Domestic and Process water pumping and mixing systems
	Sound control systems
	Data and Communication systems

Figure B-1: Priorities in reducing energy consumption at airports

B-1 Specifications of research case

Table B-1: Evaluation of simulation scenarios

Concept 1	collector belts	check in desks	Screening machines	Line storage	Carousels
	4	60	3	32*2 levels	5
Concept 2	collector belts	check in desks	Screening machines	Line storage	Chute
	4	60	3	20 *2 levels	26
concept 3	collector belts	check in desks	Screening machines	Line storage	Chute
	4	60	3	20 *2 levels	26
Concept 4	collector belts	check in desks	Screening machines	Line storage	Chute
	4	60	3	20 *2 levels	26

Appendix C

Calculations

C-1 Power factor

P, represents the active power, which is the power used by the motor, while S denotes the apparent power.

For applications where objects need to be transported or moved, in an ideal situation the power factor equals 1, as in Figure C-1. In this situation current and voltage fluctuate in phase and the resulting power output as calculated in (**??**), where v represents the voltage and i denotes the current. In this case equal to that of a resistor, the power factor 100 per cent due to the fact that the apparent power and active power are equal to each other at every moment in time

$$P = v * i \tag{C-1}$$

While the power factor of an ideal coil is zero, because it does not consumes any power.

$$\text{Power factor} = \frac{P}{S} \tag{C-2}$$

As a consequence of the fact that voltage and current are in phase in the figure below, multiplication of voltage and current is either zero or positive at all times.

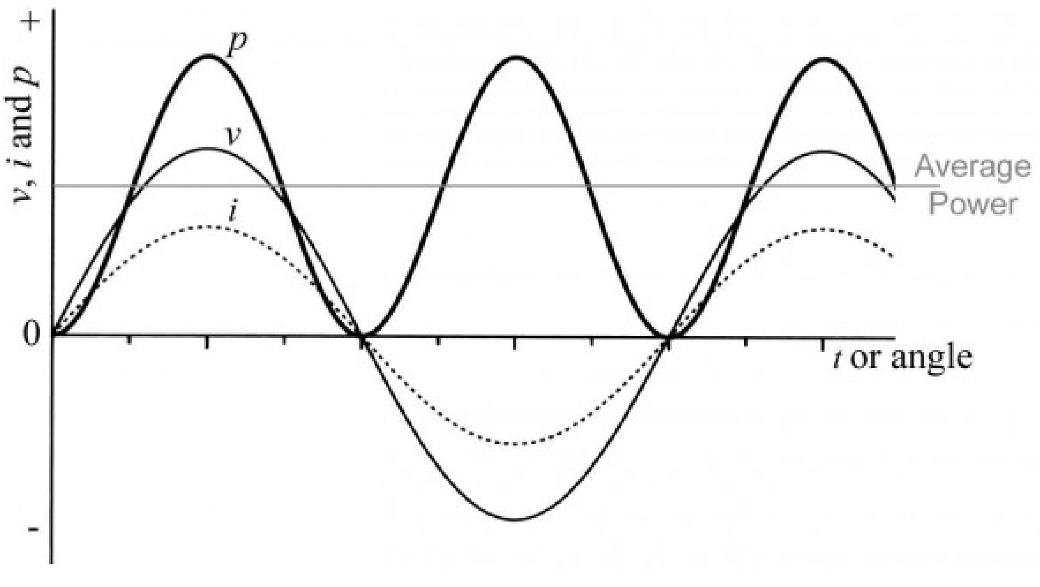

Figure C-1: Rated power vs engine efficiency [11]

All ac inductive devices such as magnets, transformers and induction motors absorb reactive

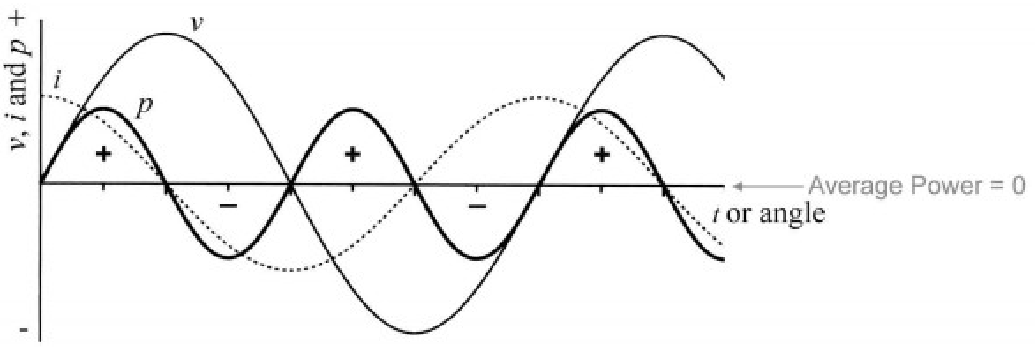

Figure C-2: Rated power vs engine efficiency [11]

power because one component of the current they draw lags 90 degrees behind the voltage. The reactive power is very important since it produces the magnetic field in these devices. Figure C-2 shows the case for which the voltage and current are 90 degrees out of phase. As a result, the average delivered power is equal to zero. During the first and third quarter-cycles the power is positive meaning that power is supplied by the circuit to charge the capacitor. In the second and fourth quarter-cycles the capacitor is discharging and thus supplies the energy stored in it (section 7.6) back to the circuit, thus p has a negative value. Although negative power may seem like an odd concept the minus or plus signs simply indicate the direction in which the power is flowing. Since this interchange of energy dissipates no average power no heating will occur and no power is lost (for a perfect capacitor, that experiences no current leakage, at least).

The reactive power is determined by the magnetizing current required to operate the device. This is non-working power. The magnetizing current is essentially constant, regardless of load placed on the motor.

The real power is the wattage used to drive the load on the motor. Because the voltage to the motor is essentially constant, regardless of load, a change in load requires a change in (non-reactive) current. Less load means less current.

When the load is highest, then the real power is highest, and the ratio of real power to reactive power is highest. As the load is diminished, the real power declines, and the ratio of real power to (essentially fixed) reactive power also declines.

In other words, the longer (real power) leg of the power triangle gets shorter, as the load is diminished. But the shorter (reactive power) leg is substantially unchanged. Hence, the phase angle changes. The phase angle becomes larger as the load declines, so the power factor of course declines also.

Draw yourself a picture of the power triangle at high load (which will have a small phase angle) and a picture of the power triangle and low load (which will have a larger phase angle).

C-2 Engine choice

C-2-1 Soft starter

As shown in Figure C-5, during start up, initially, the voltage to the motor is so low that it is only able to adjust to increase belt tension, rpm remain zero, avoiding jerks. Voltage and

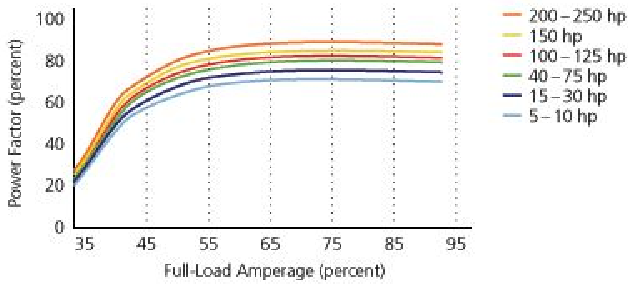

Figure C-3: Power factor vs Full load amperage of premium motor [57]

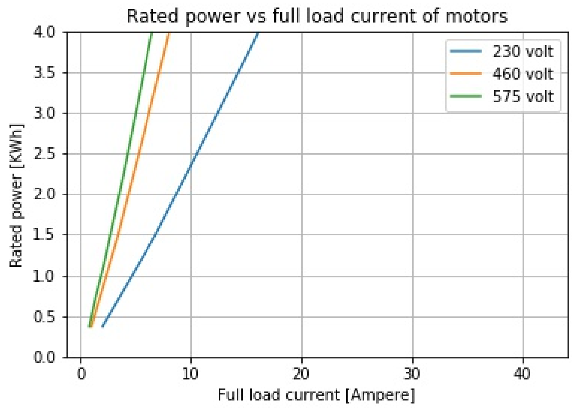

Figure C-4: Power factor vs Full load amperage of premium motor [57]

torque then increase gradually so that the belt starts to accelerate. The figure shows that less torque is needed when experiencing a lower load compared to the situation where a higher load is experienced.
Using a soft starter will reduce the starting current and thereby avoid voltage drops in the network. It will also reduce the starting torque and mechanical stress on the equipment, resulting in reduced need for service and maintenance. The soft starter is able perform a soft stop as well.

C-2-2 Variable frequency drive

It transforms incoming AC network frequency (50 Hz in Europe) into DC and after that again into AC, but now at the desired frequency. Figure Figure C-6 shows the working principle of the VFD. By varying the frequency, the torque curve is shifted. As a consequence of this shift, the motor is able to operate at its rated speed from start up and is able to deliver rated motor torque (T_n) at different operating speeds corresponding the the nominal current (I_n).

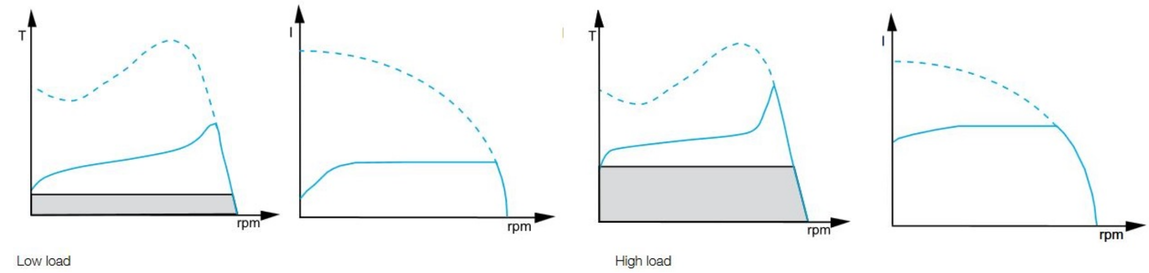

Figure C-5: Soft start at different load levels [58]

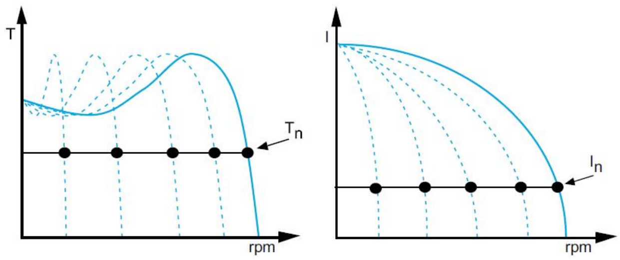

Figure C-6: Working principle of a variable frequency drive [58]

C-3 Calculation conveyor belts

Figure C-7 shows the increase of the needed static power with increasing load experienced by the drive. It can be seen that the static power almost doubles with increasing load. Often bags of maximally 25 kg are accepted to enter the system, typically clearance between bags is at least 1 meter. Since drives are dimensioned to handle a peak load of 50 [kg/m] they operate at half load or lower much of the operational time, which is a region where efficiency drops. Next, Figure C-8 shows the needed static power with increasing speed for a 2 meter conveyor

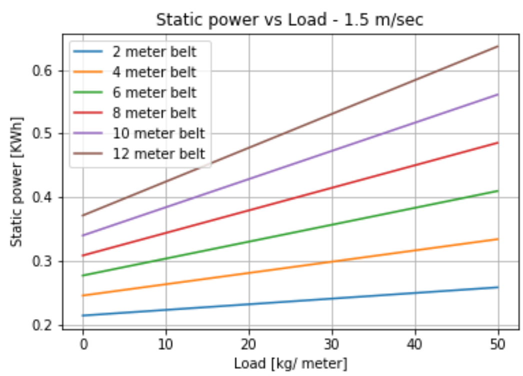

Figure C-7: Static power [KWh] of a belt conveyor with increasing load

which experiences full load at speeds ranging from 0.5-2.5 m/sec. During this research a conveyor is either loaded or unloaded, in the loaded scenario the conveyor transports a load it

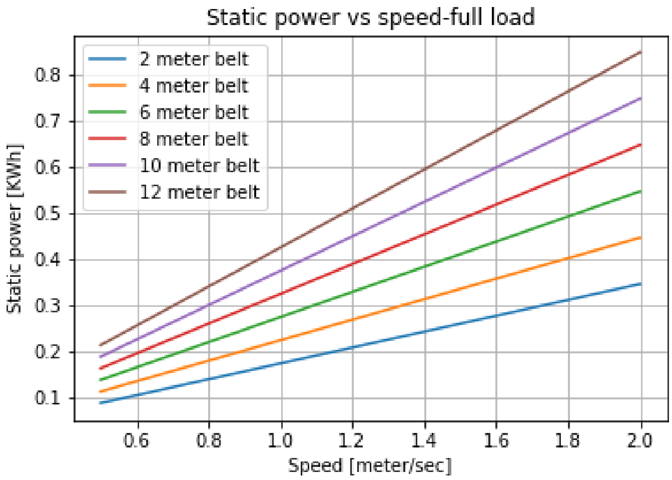

Figure C-8: Static power of a belt conveyor with increasing length

experiences a load which is about 25 kg per bag while it experiences zero load when travelling empty.

Table C-1: Conveyor belt energy consumption

Accelerate at .5 m/s^2	2 meter	4 meter	10 meter
-Empty travel [Kwh]			
-Full load travel [Kwh]			
-Maximal design load travel[Kwh]			
Constant speed -1.5 m/s			
-Empty travel [Kwh]			
-Full load travel [Kwh]			
-Maximal design load travel[Kwh]			

$$F_H = L * f * g * (\frac{m_R}{L} + (2 * m_g + m_L)\cos(\alpha)) \quad \text{(C-3)}$$

$$F_N = C * (1 + F_H) \quad \text{(C-4)}$$

$$F_{st} = L * g * m_L * \sin(\alpha) \quad \text{(C-5)}$$

$$P_{Static} = \frac{(F_H + F_N + F_{st} + F_s) * v}{\eta} \quad \text{(C-6)}$$

C-4 Chain driven

$$M_{Max} = (M_{Load} + M_{Tray} + M_{Frame}) * L_{sorter} \quad \text{(C-7)}$$
$$F_g = M_{Max} * g \quad \text{(C-8)}$$
$$F_{Constant} = F_g * \mu \quad \text{(C-9)}$$
$$P_{Constant} = F_{Constant} * speed \quad \text{(C-10)}$$
$$P_{Static} = P_{Constant} * \eta \quad \text{(C-11)}$$
(C-12)

C-5 Twin belt conveyor calculation

With a tub weight of 5 kg, Figure I-6 shows the needed static power for different belt lengths and load while assuming a smallest Inter Arrival time (IAT) of 2 second between bags.

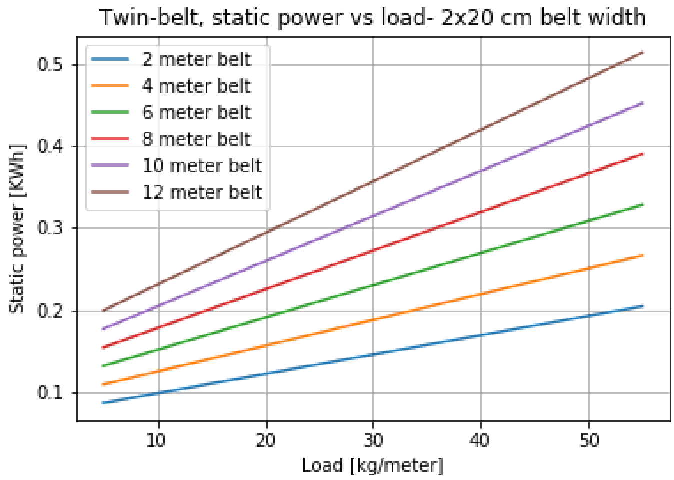

Figure C-9: Static power of a belt conveyor with increasing length and various speeds

C-6 Linear motors

First, the maximum required force F_{mMax} to be delivered by the motor is estimated by making use of (C-13) where M_{Load} represents the load, a_{max} represents the maximum acceleration,g the gravitational constant and α the angle of inclination. The power factor is obtained from [75].

$$F_{mMax} >= M_{Load} * (a_{max} + g(*1 - cos\alpha)) * 1.5 \quad \text{(C-13)}$$

Then the friction forces of the engine are calculated based on the friction coefficient of the bearing and the static forces which act upon it.

$$F_r = (F_g + F_D) * \mu_{Bearing} \quad \text{(C-14)}$$
$$F_g = (M_{Load} + M_{Primary}) * g * cos(\alpha) \quad \text{(C-15)}$$
$$F_A = (M_{Load} + M_{Primary}) * a \quad \text{(C-16)}$$
$$F_v = F_R + F_A + F_z \quad \text{(C-17)}$$

Then, the value of F_v should not exceed the maximum required thrust force calculated for the motor.

$$F_v \quad <= \quad F_{mMax} \tag{C-18}$$

After that it is checked whether the thermal load of the engine is not exceeded by filling out (**??**).

$$F_E = \sqrt{\Sigma \frac{F_i^2 * t_i}{t}} \tag{C-19}$$

Finally, the rated power of the engine is calculated by multiplying the the maximum thrust force by the speed and motor efficiency.

$$P_{Motor} = F_{thrust} moto * speed * \mu_{motor} \tag{C-20}$$

Appendix D

Stakeholders

Table D-1 gives the characteristics of the stakeholder "airport". The completion of the illustrated goals depend on the goals of the other stakeholders involved with the airport.

Table D-1: The definition and goals of the stakeholder "Airport"

	Definition	Goals			
Airport	"Management and staff, with responsibility for building and operating the airport"	Achieve high safety levels	Grow revenue and manage costs	Find new flight destinations	Drive economic growth
		Find new destinations and increase service frequency	Maximize customer satisfaction	Enhance competitive advantage	Achieve environmental sustainability
		Minimize noise	Develop employees	Grow passenger numbers	Increase service frequency

The completion of these goals depend on the behaviour and decisions of the other stakeholders involved with the airport. A selection is found in Table D-2.

Table D-2: Stakeholders in contact airport[40]

Stake holder	Definition	The Stakeholder Goals for the Airport
Passengers	O&D and transferring passengers	Move passengers quickly and conveniently Ensure on-time performance Provide access to low fares
Air carriers	Passenger and cargo carriers	Ensure on-time performance Ensure low cost of operations Ensure safety of operations
Investors and bond holders	Individuals / organizations holding bonds, and the credit ratings agencies	Maximize revenue Provide information on cash-flow in organization
Government	Bill-payer for infrastructure (AIP), operator of air traffic control and security, and system regulator	Maximize economic impact Maximize number of destinations served and frequency of those services Minimize noise and emissions
NGOs	Airport interest groups	Varies depending on the interest group
Employees	Employees of the airport organization and airport tenants	Provide secure jobs, wages, and benefits
Communities affected by airport	Residents in region, and in particular residents near the airport	Maximize economic impact Maximize number of destinations served and frequency of those services Minimize noise and emissions
Airport suppliers	Suppliers of contractor and consulting services and equipment	Maximize traffic volumes

Appendix E

Luggage weight

The luggage weight is fixed at an average weight of 17 kg, as is stated to be the average weight of luggage by info from VanderLande [49]. The reason for fixing the weight is that the load experienced per piece of luggage approaches the mean for large numbers of luggage. Furthermore, the variation in weight cause small deviations in energy consumption, as can be seen in Table E-1. The calculation performed on a small conveyor indicates that the variation of energy consumption is small with variation of the load experienced by the belt. In case conveyors get larger, weight of rollers and belt become even more dominant. As a consequence of the findings taking an average weight per piece of luggage is justified.

Table E-1: Energy consumption with variation of load (DIN 221012)

Energy consumption [Kwh]	Weight of load [kg]
0,20	0
0,21	5
0,22	17
0,23	25

Appendix F

Scenario 1: Load variation

Figure F-1 and Figure ?? demonstrate the variance in energy consumption of both concepts in boxplots.

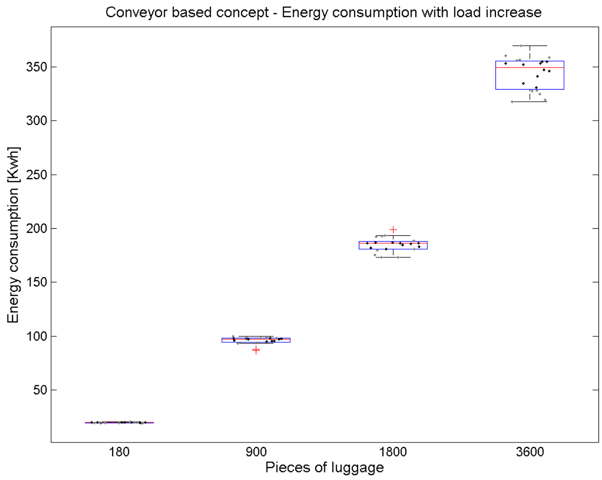

Figure F-1: Scenario 1: Increase system load - Conveyor based concept

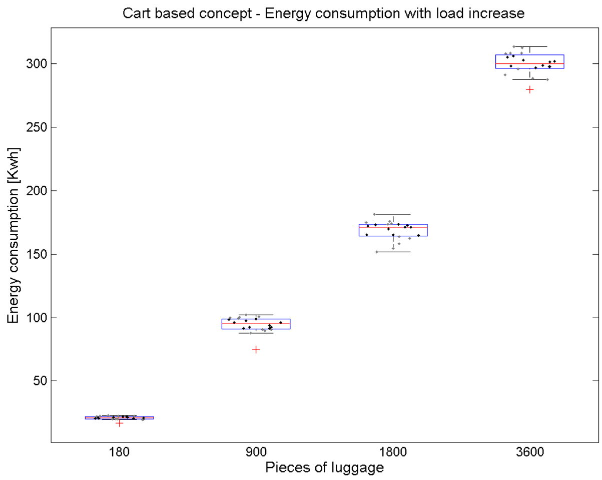

Figure F-2: Scenario 1: Increase system load - Conveyor and cart based concept

Appendix G

Passengers per airport

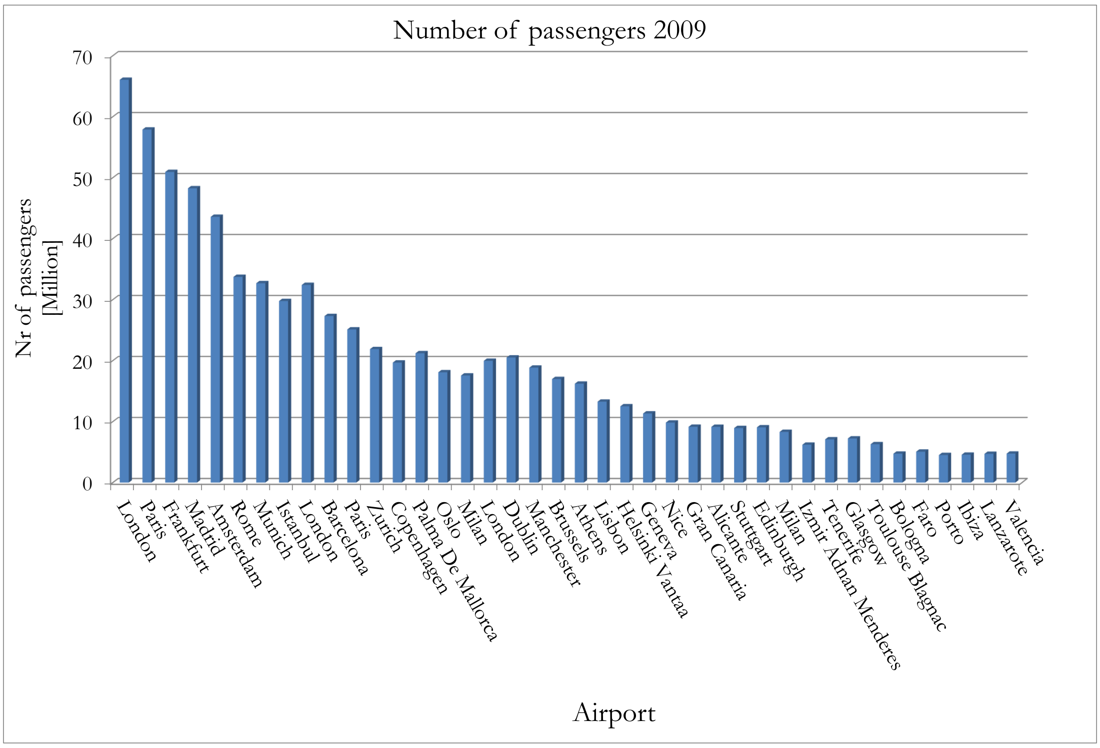

Figure G-1: Energy consumption per passenger at selected airports in Europe [6]

G-1 Significance of results, scenario 1: Load variation

The two-tail student-t test has been performed (inequality). Prior to performing the test it is first investigated if obtained results follow the normal distribution by making use of the Anderson Darling test. The null hypothesis is that the data are normally distributed; the alternative hypothesis is that the data are non-normal. The p ("probability") value represents the probability of getting a result that is not the null hypothesis. If the p value is low (e.g., $<=0.05$), it is concluded that the data does not follow the normal distribution. As can be seen from the results of the test displayed in Table G-1 it is found that all of the experimental scenarios follow the normal distribution.

Table G-1: Normality test of replications - scenario 1: Load increase

Conveyor based concept	p-value		**Cart based concept**	p-value
180 pieces of luggage	0,469		180 pieces of luggage	0,082
900 pieces of luggage	0,169		900 pieces of luggage	0,082
1800 pieces of luggage	0,519		1800 pieces of luggage	0,145
3600 pieces of luggage	0,057		3600 pieces of luggage	0,695

Then, the student-t test has been performed with the following hypothesis:

- Null hypothesis: The difference of the means is insignificant
- Alternative hypothesis: The difference of the means is significant

Since the resulting *t Stat* is not in the range of -*t* and *t critical* the null hypothesis is rejected. The observed difference between the sample means is convincing enough to say that the average energy consumption in the compared experimental cases is significant.

Table G-2: Significance of results - Scenario 1: Load increase

Scenario 1: Load increase 180	Cart - based	Conveyor - based		**Scenario 1: Load increase 900**	Cart based	Conveyor based
Mean	17,45	19,70		Mean	78,52	95,81
Variance	1,36	0,12		Variance	27,58	11,61
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,00	
t Stat P(T<=t) one-tail	-8,24 1,79E-08			t Stat P(T<=t) one-tail	-12,44 4,24E-14	
t Critical one-tail P(T<=t) two-tail	1,72 3,57E-08			t Critical one-tail P(T<=t) two-tail	1,69 8,49E-14	
t Critical two-tail	2,07			t Critical two-tail	2,04	
Scenario 1: Load increase 1800	Cart based	Conveyor based		**Scenario 1: Load increase 3600**	Cart based	Conveyor based
Mean	166,46	184,85		Mean	300,098	344,382
Variance	86,74	44,82		Variance	76,659	233,002
Observations	20,00	20,00		Observations	20,000	20,000
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,000	
t Stat	-7,17			t Stat	-11,254	
P(T<=t) one-tail	1,36-08			P(T<=t) one-tail	1,36E-12	
t Critical one-tail	1,69			t Critical one-tail	1,697	
P(T<=t) two-tail	2,73E-08			P(T<=t) two-tail	2,72E-12	
t Critical two-tail	2,03			t Critical two-tail	2,042	

Appendix H

Scenario 2: Variation of peak arrival of planes

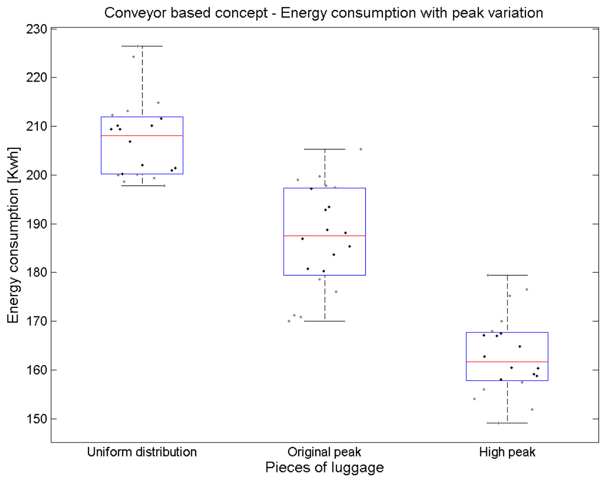

Figure H-1: Scenario 2: Peak variation - Conveyor based concept

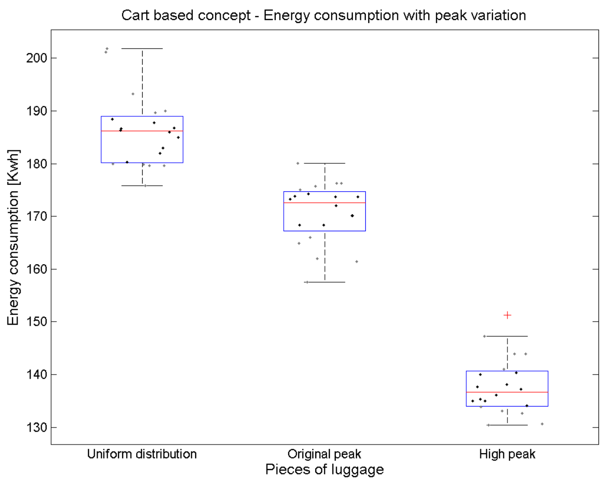

Figure H-2: Scenario 2: Peak variation - Conveyor and cart based concept

H-1 Significance of results, scenario 2: Peak variation

The two-tail student-t-test has been performed (inequality). Prior to performing the test it is first investigated if obtained results follow the normal distribution by making use of the Anderson Darling test. The null hypothesis is that the data are normally distributed; the alternative hypothesis is that the data are non-normal. The p ("probability") value represents the probability of getting a result that is not the null hypothesis. If the p value is low (e.g., <=0.05), it is concluded that the data does not follow the normal distribution. As can be seen from the results of the test displayed in Table H-1 it is found that all of the experimental scenarios follow the normal distribution.

Table H-1: Normality test of replications - scenario 2: Peak variation

Conveyor based concept	p-value		**Cart based concept**	p-value
Uniform distribution	0,556		Uniform distribution	0,155
Original distribution	0,770		Original distribution	0,271
High peak distribution	0,080		High peak distribution	0,097

Then, the student-t test has been performed with the following hypothesis:

- Null hypothesis: The difference of the means is insignificant
- Alternative hypothesis: The difference of the means is significant

Since the resulting *t Stat* is not in the range of -*t* and *t critical* the null hypothesis is rejected. The observed difference between the sample means is convincing enough to say that the average energy consumption in the compared experimental cases is significant.

Table H-2: Significance of results - Scenario 2: Peak variation

Scenario 2: Uniform distribution	Cart based	Conveyor based		**Scenario 2: Original distribution**	Cart based	Conveyor based
Mean	186,16	207,46		Mean	170,66	187,17
Variance	46,79	68,17		Variance	34,01	112,34
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,00	
t Stat	-8,89			t Stat	-6,10	
P(T<=t) one-tail	5,19E-11			P(T<=t) one-tail	5,21E-07	
t Critical one-tail	1,69			t Critical one-tail	1,70	
P(T<=t) two-tail	1,04E-10			P(T<=t) two-tail	1,04E-06	
t Critical two-tail	2,03			t Critical two-tail	2,04	
Scenario 2: High peak distribution	Cart based	Conveyor based				
Mean	137,85	163,99				
Variance	30,21	51,99				
Observations	20,00	20,00				
Hypothesized Mean Difference	0,00					
t Stat	-12,89					
P(T<=t) one-tail	2,34E-15					
t Critical one-tail	1,69					
P(T<=t) two-tail	4,68E-15					
t Critical two-tail	2,03					

Appendix I

Scenario 3: Speed variation

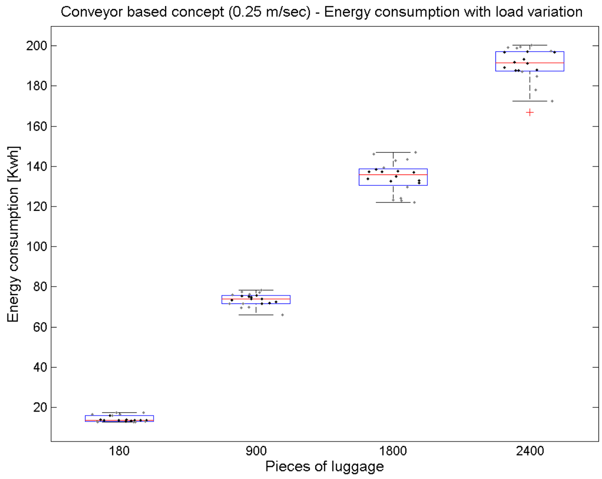

Figure I-1: Scenario 3: Speed variation - Conveyor based concept (0,25 m/sec)

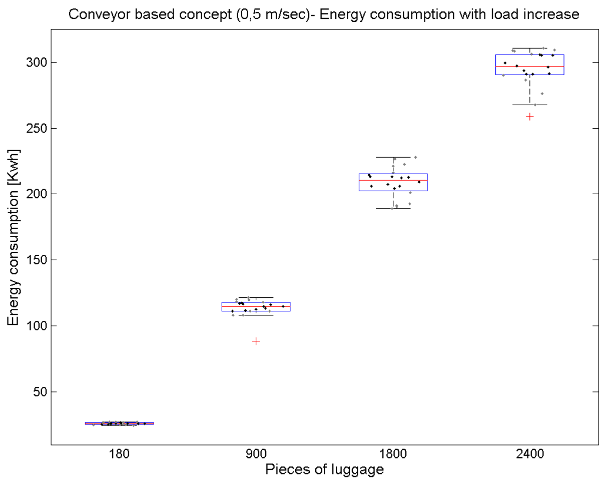

Figure I-2: Scenario 3: Speed variation - Conveyor based concept (0,5 m/sec)

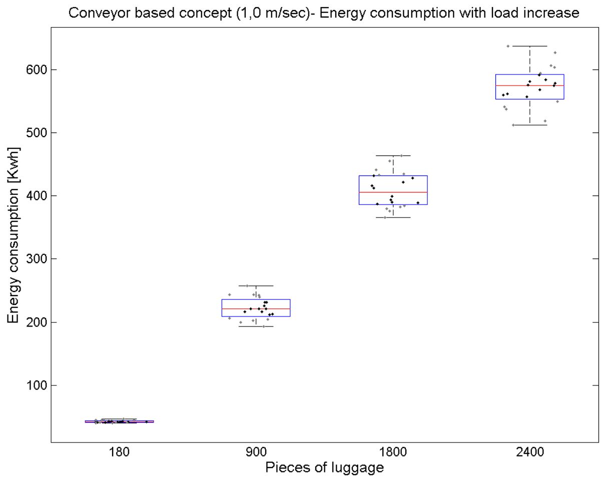

Figure I-3: Scenario 3: Speed variation - Conveyor based concept (1 m/sec)

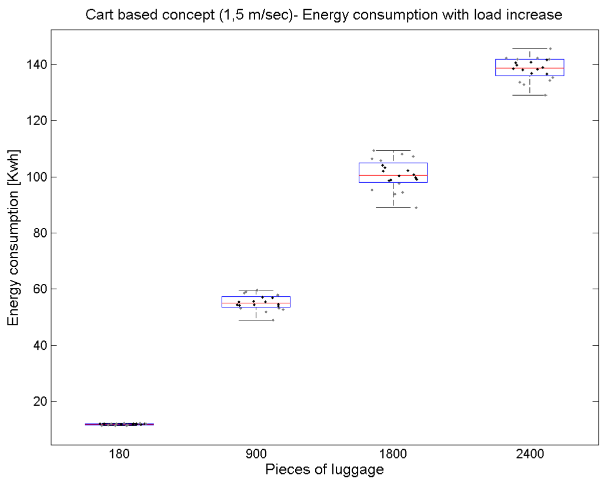

Figure I-4: Scenario 3: Speed variation - Conveyor and cart based concept (1,5 m/sec)

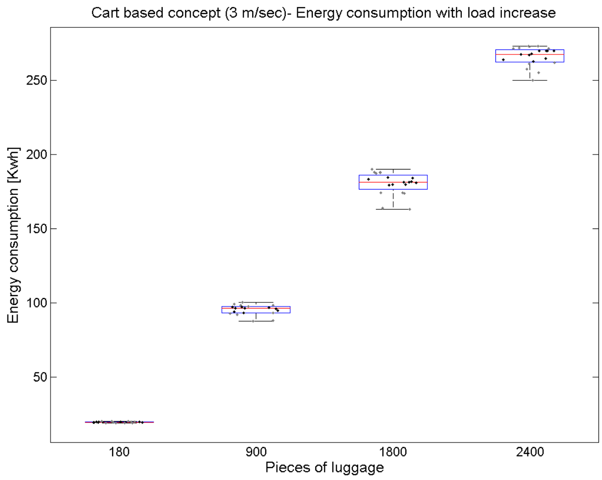

Figure I-5: Scenario 3: Speed variation - Conveyor and cart based concept (3 m/sec)

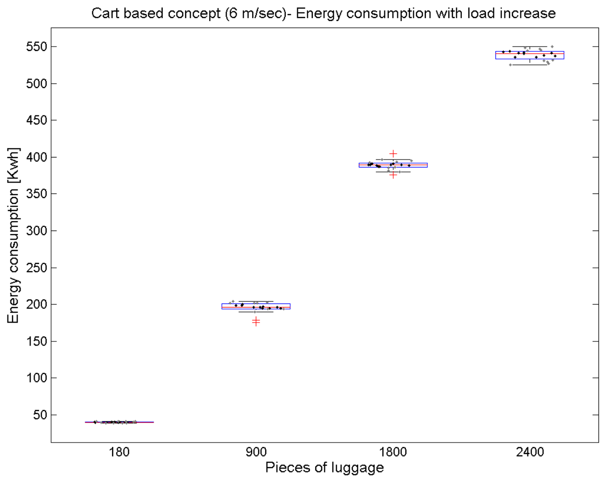

Figure I-6: Scenario 3: Speed variation - Conveyor and cart based concept (6 m/sec)

I-1 Significance of results, scenario 3: Speed variation

The two-tail student-t-test has been performed (inequality). Prior to performing the test it is first investigated if obtained results follow the normal distribution by making use of the Anderson Darling test. The null hypothesis is that the data are normally distributed; the alternative hypothesis is that the data are non-normal. The p ("probability") value represents the probability of getting a result that is not the null hypothesis. If the p value is low (e.g., <=0.05), it is concluded that the data does not follow the normal distribution. As can be seen from the results of the test displayed in Table I-1 it is found that all of the experimental scenarios follow the normal distribution.

Table I-1: Normality test of replications - scenario 3: Speed increase

Conveyor based concept	Speed level	p-value		**Cart based concept**	Speed	p-value
180 pieces of luggage	0,25	0,08		180 pieces of luggage	1,5	0,211
900 pieces of luggage	0,25	0,610		900 pieces of luggage	1,5	0,816
1800 pieces of luggage	0,25	0,414		1800 pieces of luggage	1,5	0,949
2700 pieces of luggage	0,25	0,155		2700 pieces of luggage	1,5	0,551
180 pieces of luggage	0,5	0,278		180 pieces of luggage	3	0,459
900 pieces of luggage	0,5	0,470		900 pieces of luggage	3	0,106
1800 pieces of luggage	0,5	0,414		1800 pieces of luggage	3	0,0561
3600 pieces of luggage	0,5	0,150		2700 pieces of luggage	3	0,0517
180 pieces of luggage	1	0,0526		180 pieces of luggage	6	0,582
900 pieces of luggage	1	0,753		900 pieces of luggage	6	0,572
1800 pieces of luggage	1	0,222		1800 pieces of luggage	6	0,195
2700 pieces of luggage	1	0,988		2700 pieces of luggage	6	0,546

The two-tail student-t test has been performed(inequality) with the following hypothesis:

- Null hypothesis: The difference of the means is insignificant
- Alternative hypothesis: The difference of the means is significant

Since the resulting *t Stat* is not in the range of -*t* and *t critical* the null hypothesis is rejected. The observed difference between the sample means is convincing enough to say that the average energy consumption in the compared experimental cases is significant.

Table I-2: Significance of results - scenario 3: Speed variation - Low speed

Scenario 3: Speed variation - 180	Conveyor based (,25 m/s)	Cart based (1,5 m/s)		**Scenario 3: Speed variation - 900**	Conveyor based (,25 m/s)	Cart based (1,5 m/s)
Mean	14,26	11,88		Mean	73,62	55,3
Variance	2,72	0,08		Variance	9,48	7,12
Observations	20	20		Observations	20	20
Hypothesized Mean Difference	0			Hypothesized Mean Difference	0	
t Stat	6,37			t Stat	20,11	
P(T<=t) one-tail	1,64E-06			P(T<=t) one-tail	8,17E-22	
t Critical one-tail	1,72			t Critical one-tail	1,69	
P(T<=t) two-tail	3,27E-06			P(T<=t) two-tail	1,63E-21	
t Critical two-tail	2,09			t Critical two-tail	2,03	
Scenario 3: Speed variation - 1800	Conveyor based (,25 m/s)	Cart based (1,5 m/s)		**Scenario 3: Speed variation - 3600**	Conveyor based (,25 m/s)	Cart based (1,5 m/s)
Mean	134,68	100,84		Mean	190,26	138,5
Variance	56,5	27,75		Variance	84,49	15,89
Observations	20	20		Observations	20	20
Hypothesized Mean Difference	0			Hypothesized Mean Difference	0	
t Stat	16,49			t Stat	23,11	
P(T<=t) one-tail	4,31E-18			P(T<=t) one-tail	3,70E-19	
t Critical one-tail	1,69			t Critical one-tail	1,71	
P(T<=t) two-tail	8,62E-18			P(T<=t) two-tail	7,40E-19	
t Critical two-tail	2,03			t Critical two-tail	2,06	

Table I-3: Significance of results - scenario 3: Speed variation - Mid speed

Scenario 3: Speed variation - 180	Conveyor based(0,5 m/s)	Cart based (3 m/s)		Scenario 3: Speed variation - 900	Conveyor based(0,5 m/s)	Cart based (3 m/s)
Mean	25,67	19,63		Mean	113,48	95,39
Variance	0,68	0,12		Variance	50,24	11,77
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,00	
t Stat	30,17			t Stat	10,27	
P(T<=t) one-tail	1,74E-21			P(T<=t) one-tail	3,98E-11	
t Critical one-tail	1,71			t Critical one-tail	1,70	
P(T<=t) two-tail	3,48E-21			P(T<=t) two-tail	7,96E-11	
t Critical two-tail	2,06			t Critical two-tail	2,05	
Scenario 3: Speed variation- 1800	Conveyor based(0,5 m/s)	Cart based (3 m/s)		Scenario 3: Speed variation- 3600	Conveyor based(0,5 m/s)	Cart based (3 m/s)
Mean	208,85	180,35		Mean	295,00	266,01
Variance	136,34	55,99		Variance	203,83	40,24
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,00	
t Stat	9,19			t Stat	8,30	
P(T<=t) one-tail	8,53E-11			P(T<=t) one-tail	4,41E-09	
t Critical one-tail	1,69			t Critical one-tail	1,71	
P(T<=t) two-tail	1,71E-10			P(T<=t) two-tail	8,82E-09	
t Critical two-tail	2,04			t Critical two-tail	2,06	

Table I-4: Significance of results - scenario 3: Speed variation - High speed

Scenario 3: Speed variation - 180	Conveyor based (1 m/s)	Cart based (6 m/s)		**Scenario 3: Speed variation - 900**	Conveyor based (1 m/s)	Cart based (6 m/s)
Mean	42,25	39,96		Mean	221,97	195,41
Variance	3,46	0,78		Variance	298,69	55,25
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00				Hypothesized Mean Difference	0,00
t Stat	4,97				t Stat	6,31
P(T<=t) one-tail	1,66E-05			P(T<=t) one-tail	5,50E-07	
t Critical one-tail	1,70			t Critical one-tail	1,71	
P(T<=t) two-tail	3,32E-05			P(T<=t) two-tail	1,10E-06	
t Critical two-tail	2,05			t Critical two-tail	2,06	
Scenario 3: Speed variation - 1800	Conveyor based (1 m/s)	Cart based (6 m/s)		**Scenario 3: Speed variation - 2400**	Conveyor based (1 m/s)	Cart based (6 m/s)
Mean	409,36	389,17		Mean	573,10	538,87
Variance	797,76	39,02		Variance	1067,86	51,48
Observations	20,00	20,00		Observations	20,00	20,00
Hypothesized Mean Difference	0,00			Hypothesized Mean Difference	0,00	
t Stat	3,12			t Stat	4,57	
P(T<=t) one-tail	2,59E-03			P(T<=t) one-tail	8,23E-05	
t Critical one-tail	1,72			t Critical one-tail	1,72	
P(T<=t) two-tail	5,17E-03			P(T<=t) two-tail	1,65E-04	
t Critical two-tail	2,08			t Critical two-tail	2,08	

Appendix J

Left behind index

J-1 Scenario 1: Load variation

Table J-1 summarizes the results of the test on normality of the LBI for the case of an increased load. It can be seen from the table that for each case but for the case where the conveyor based concept handles 180 pieces of luggage the LBI is normally distributed.

Table J-1: Normality check - left behind index - scenario 1: Load variation

Conveyor based concept	p-value		**Cart based concept**	p-value
180 pieces of luggage	0,069		180 pieces of luggage	0,525
900 pieces of luggage	0,087		900 pieces of luggage	0,525
1800 pieces of luggage	0,857		1800 pieces of luggage	0,661
3600 pieces of luggage	0,534		3600 pieces of luggage	0,157

From Table J-2 which summarizes the F test for the hypothesis tested as following:

1. H0: σ_1^2 is equal to σ_2^2
2. H1: σ_1^2 is not equal to σ_2^2

it can be seen that for the difference between variance of the LBI is insignificant for the case where 1800 and 3600 pieces of luggage have been handled.

Table J-2: F test - Left behind index - scenario 1: Load increase

Scenario 1:Load increase - F test	Cart based-p-value	Conveyor based p-value
900-1800	0,006	0,006
1800-3600	0,141	0,219
900-3600	0,004	0,001

J-2 Scenario 2: Peak variation

Table J-3 summarizes the normality of check of the LBI of the peak variation. It can be seen from the table that for each experimental case data is normally distributed.

Table J-3: Normality check - Left behind index - scenario 3: Speed variation

Conveyor based concept	Distribution	p-value		Cart based concept	Distribution	p-value
1800 pieces of luggage	Uniform distribution	0,794		1800 pieces of luggage	Uniform distribution	0,147
1800 pieces of luggage	Original distribution	0,879		1800 pieces of luggage	Original distribution	0,471
1800 pieces of luggage	High peak distribution	0,794		1800 pieces of luggage	High peak distribution	0,334

Table J-2 summarizes the results of the F test for the following hypothesis:

1. H0: σ_1^2 is equal to σ_2^2
2. H1: σ_1^2 is not equal to σ_2^2

From the table it is seen that the difference between variance of the LBI is insignificant for all if the investigated peaks.

Table J-4: F test - Left behind index - scenario 2: Peak variation

scenario 2: Peak variation - F test	Conveyor based p-value	F test - Peak variation	Cart based p-value
Uniform - high peak	0,500	Uniform - high peak	0,110
Uniform - original	0,347	Uniform - original	0,488
High peak - original	0,347	High peak - original	0,116

J-3 Scenario 3: Speed variation

Table J-3 summarizes the normality of check of the LBI of the speed variation. It can be seen from the table that data is normally distributed for each experimental case. Furthermore, it is concluded from the table that for each case data is normally distributed but for the case where 180 pieces of luggage are handled at 0,25 in the conveyor based concept and in the case where carts travel at 1,50 m/sec. The F test has therefore not been performed on the instance where the load is equal to 180 pieces of luggage.

Table J-5: Normality check - Left behind index - scenario 3: Speed variation

Conveyor based concept	Speed	p-value		**Cart based concept**	Speed	p-value
180 pieces of luggage	0,25	0,021		180 pieces of luggage	1,5	0,019
900 pieces of luggage	0,25	0,078		900 pieces of luggage	1,5	0,083
1800 pieces of luggage	0,25	0,531		1800 pieces of luggage	1,5	0,466
2700 pieces of luggage	0,25	0,069		2700 pieces of luggage	1,5	0,094
180 pieces of luggage	0,5	0,021		180 pieces of luggage	3	0,001
900 pieces of luggage	0,5	0,065		900 pieces of luggage	3	0,525
1800 pieces of luggage	0,5	0,065		1800 pieces of luggage	3	0,734
2700 pieces of luggage	0,5	0,534		2700 pieces of luggage	3	0,264
180 pieces of luggage	1	0,051		180 pieces of luggage	6	0,004
900 pieces of luggage	1	0,446		900 pieces of luggage	6	0,274
1800 pieces of luggage	1	0,139		1800 pieces of luggage	6	0,631
2700 pieces of luggage	1	0,681		2700 pieces of luggage	6	0,179

Table J-6 demonstrates the results of the performed F test for the following hypothesis:

1. H0: σ_1^2 is equal to σ_2^2
2. H1: σ_1^2 is not equal to σ_2^2

It can be seen from the table that

Table J-6: F test - Left behind index - scenario 3: Speed variation

Conveyor based concept				**Cart based concept**	
F test - 1,5 m / sec	p-value	F test - 3 m / sec	p-value	F test - 6 m /sec	p-value
180-900	1,66E-12	180-900	0,000	180-900	3,14E-04
180-1800	0,151	180-1800	0,000	180-1800	4,73E-05
180-3600	1,14E-09	180-3600	0,000	180-3600	1,13E-07
900-1800	0,000	900-1800	0,009	900-1800	0,283
900-2700	0,003	900-3600	0,132	900-2700	0,015
1800-2700	0,062	1800-3600	0,185	1800-2700	0,053
F test 0,25 m / sec	p-value	F test 0,5 m / sec	p-value	F test 1 m / sec	p-value
180-900	0,186	180-900	0,08	180-900	0,020
180-1800	2,85E-04	180-1800	0,000285337	180-1800	1,05E-07
180-3600	2,84E-08	180-3600	2,8383E-08	180-3600	2,19E-09
900-1800	0,004	900-1800	0,032419681	900-1800	2,00E-04
900-2700	1,25E-06	900-2700	0,002159394	900-2700	7,27E-06
1800-2700	0,008	1800-2700	0,140507379	1800-2700	0,168

Appendix K

Summary of values obtained from experiments

K-1 Scenario 1: Variation of system load

Table K-1: Scenario 1: Load increase - Comparison of concepts

Conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	3600 pieces of luggage
Energy consumption [kWh]	23.64	95.81	184.85	344.38
Energy consumption per piece of luggage	0.131	0.106	0.103	0.096
Left behind index	1.15	1.03	1.19	1.22
Cart and conveyor based concept	180 pieces of luggage	900 pieces of luggage	1800 pieces of luggage	3600 pieces of luggage
Energy consumption [kWh]	17.45	85.66	166.46	315.1
Percentage due to conveying	34.35	29.60	28.21	24.88
Percentage due to carts	65.65	70.40	71.79	75.12
Energy / piece of luggage	0.097	0.095	0.092	0.088
Left behind index	0.96	0.85	1.00	1.15

K-2 Scenario 2: Variation in airplane arrival pattern

Table K-2: Scenario 2: Peak variation - Comparison of concepts

Conveyor based concept	Uniform distribution	Original distribution	High peak distribution
Pieces of luggage	1800	1800	1800
Energy consumption [kWh]	207	187	163
Energy consumption [kWh] / piece of luggage	0.115	0.104	0.091
Left behind index [%]	1.17	1.13	1.05

Cart and conveyor based concept	Uniform distribution	Original distribution	High peak distribution
Pieces of luggage	1800	1800	1800
Energy consumption [kWh]	181	171	153
Energy consumption [kWh] per piece of luggage	0.101	0.095	0.085
Left behind index [%]	1.12	1.02	0.83

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Glossary

List of Acronyms

ATB	Airport Terminal Building
BHS	Baggage Handling System
BHSs	Baggage Handling Systems
CAPEX	Capital Expenditures
DCV	Destination Coded Vehicle
DCVs	Destination Coded Vehicles
EBS	Early Bag Storage
HBS	Hold Baggage Screening
IAT	Inter Arrival time
IE	International Energy Efficiency Class
KPIs	Key Performance Indicators
LEED	Leadership in Energy and Environmental Design
OD	Originating and Departing
OPEX	Operational Expenditures
VFD	Variable Frequency Drive