Estimating system-level energy consumption of airport baggage handling system configurations at an early stage of designing

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Estimating system-level energy consumption of airport baggage handling system configurations at an early stage of designing

by

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Preface

This thesis is the result of my graduation assignment at NACO. It marks the completion of my master's program in Transport, Infrastructure and Logistics at Delft University of Technology. During a five-month period, I developed a model for estimating the energy consumption of baggage handling systems at airports. While there are many interesting aspects to investigate with regard to energy consumption in baggage handling systems, my focus was on different system designs. Throughout the process, I improved my research skills and challenged my perseverance.

I wish to express my gratitude to NACO for giving me the opportunity for this project. Working on it allowed me to learn more about the aviation sector. I felt welcomed in the inclusive office environment. I wish to thank Pieter van den Berg for his help and commitment, especially when I faced difficulties. I also want to thank Michael Doughty for his support and thoughtful questions, and Taco Spoor for always being able to help when needed. Further, I would like to thank my TU Delft supervisors Yusong Pang, from the Mechanical Engineering department, and Alexei Sharpans'kykh, from the Aerospace Engineering department, for their feedback and critical view on the project. And of course, I cannot forget to thank my family and friends for their enduring support during this project.

I hope you enjoy your reading.

Marita van 't Klooster
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Abstract

The relationship between energy consumption and baggage handling systems (BHSs) has not been widely studied. In this study, this relationship is explored by considering BHS configurations - the designed arrangement of devices. The BHS consists of seven main processes: drop-off, transportation from drop-off to screening, hold baggage screening (HBS), transportation from screening to sortation, sortation, early baggage storage (EBS), and make-up. Transportation appears to cause a high share of the system's energy consumption, as it is a part of and connects several processes. An equation-based model is developed to estimate the energy consumption of BHSs with varying configurations. The model only contains parameters available at the BHS's conceptual design phase and is based on the BHS of a midsize airport in Scandinavia. It includes a series of formulas for each process, which depend on the structure of the process elements. The study proved a twofold effect of an airport's BHS configuration on the overall energy consumption. Firstly, more process elements structured in series result in bags travelling a longer distance on the conveyor within the BHS, thereby increasing energy usage. Secondly, the parameter values for transportation impact energy consumption notably. The research suggested that more process elements structured in series decrease the overlap of device usage, which in turn reduces energy consumption.

***Keywords* —** Baggage Handling System (BHS), energy consumption, configurations, conceptual design

Summary

The aviation sector is exploring ways to decrease the energy usage of airport baggage handling systems (BHS). A deep understanding of BHS energy consumption is crucial for mitigating an airport's environmental footprint. This knowledge aids in the selection of energy-saving designs for BHSs. This approach not only encourages the development of environmental sustainability but also supports operational efficiency and cost-effectiveness.

This project is initiated to find a way for NACO to estimate airport BHS energy consumption at an early stage of design. A model would allow them to compare different designs of airport BHS concerning energy consumption to make a well-substantiated choice for a design recommendation. Additionally, the research gap in understanding how BHS design impacts energy consumption is addressed. These BHS designs are defined to be designed arrangements of devices and are referred to as configurations. Several scenarios are set up that represent different configurations. The only variable factor is the structure of process elements. A process element is a subset of the devices in the BHS, often consisting of an entire process or a part of a process. Its structure describes whether the process element is designed to be in series or in parallel.

Based on a literature review, it is found that seven main processes can be distinguished in the BHS. In the drop-off process, the bags are inserted into the system. After a transportation process, the bags are screened in the hold baggage screening (HBS) process. This process includes four levels of screening. Still, a bag only needs to enter a higher level if it was not cleared at a lower level. Before entering the sortation process, another transportation process takes place. The sortation process is mainly aimed at guiding the bags towards their dedicated make-up location. However, the bags that need intermediate storage are diverted to the early baggage storage (EBS) process. In the make-up process, the bags are loaded into containers or carts to prepare them to be carried to the aircraft.

The bags have to undergo the seven main processes in the following order: drop-off, transportation to the HBS process, hold baggage screening, transportation to the sortation process, sortation, EBS, and return of trays. Still, some BHS may not have an EBS or employ a transportation technology that does not require the return of trays. Also, the bags generally return to the sortation process after having stayed in the EBS.

Further, it can be concluded from the literature review that the exact devices that contribute to the total energy consumption of BHS vary based on the technologies employed for each process. Independent of the design of the BHS, transportation accounts for a significant number of energy-consuming devices. Namely, it is present in many processes and in between some processes.

The BHS of a midsize airport in Scandinavia is used as a basis for the model. A MoSCoW prioritisation showed that equation-based modelling is an appropriate modelling method that fulfils the requirements. For each process, a set of formulas is set up to describe its energy consumption. The formulas depend on the structure of the process elements, such that the formulas can be customised for different BHS configurations. The model is proved to be internally consistent and to represent reality.

With the use of the model and seven scenarios for BHS configurations, a sensitivity analysis is performed. The sensitivity analysis results supported the hypothesis that the estimated energy consumption of the BHS depends on the total distance each bag needs to travel in the system. It is also found that the technique employed for the transportation of bags may have a significant impact on the system-level energy consumption. Additionally, an effect of the overlap of device usage is suggested, which is that the energy consumption is reduced because a device operates for multiple bags simultaneously.

The proven influence of an airport's BHS configuration on its estimated system-level energy consumption thus is twofold. Firstly, more process elements structured in series result in bags travelling a longer distance on the conveyor within the BHS, thereby increasing energy usage. Secondly, the parameter values for transportation impact energy consumption notably. The research suggested that more process elements structured in series increase the overlap of device usage, which in turn reduces energy consumption. To state it differently, an optimal configuration should cause the bags to travel a short distance, employ a transportation technique that involves a low energy consumption per meter, and cause maximum overlap.

Further research is recommended to explore the quantitative effects of BHS configurations on energy consumption to strengthen the conclusions. The model could be developed further by including the inbound and transfer baggage flow and revising the formulas representing the reduced energy consumption due to the overlap of device usage. Also, research could be done on the relationship between the operating strategy of the BHS and its energy consumption. The model presented in this research can serve as a basis for this exploration.

For NACO, the model can serve as a valuable aid during the conceptual design process, which enables testing various configurations on the impacts on energy consumption. Still, it is recommended to integrate the model with

the digital design tool to automate the estimation of the BHS's energy consumption in the conceptual design process.

Summary in Dutch

De luchtvaartsector onderzoekt manieren om het energieverbruik van bagageafhandelingssystemen op luchthavens (BHS) te verlagen. Een diepgaand inzicht in het energieverbruik van BHS is cruciaal voor het verkleinen van de ecologische voetafdruk van luchthavens. Deze kennis helpt bij de keuze van energiebesparende ontwerpen voor BHS's. De aanpak stimuleert niet alleen de ontwikkeling van duurzaamheid, maar ondersteunt ook de operationele efficiëntie en kosteneffectiviteit.

Dit project is opgezet om een manier te vinden waarop NACO het BHS-energieverbruik van luchthavens in een vroeg ontwerpstadium kan schatten. Een model zou hen in staat stellen om verschillende ontwerpen van een BHS met elkaar te vergelijken op het gebied van energieverbruik, zodat een goed onderbouwde keuze voor een ontwerpadvies kan worden gemaakt. Daarnaast wordt de onderzoekskloof in het begrijpen van de invloed van het BHS-ontwerp op het energieverbruik aangepakt. Deze BHS-ontwerpen worden gedefinieerd als ontworpen opstellingen van apparaten en worden configuraties genoemd. Er zijn verschillende scenario's opgesteld die verschillende configuraties representeren. De enige variabele factor is de structuur van proceselementen. Een proceselement is een subset van de apparaten in de BHS, vaak bestaande uit een geheel proces of een deel van een proces. De structuur beschrijft of het proceselement is ontworpen in serie of parallel.

Op basis van literatuuronderzoek blijkt dat er in de BHS zeven hoofdprocessen te onderscheiden zijn. In het afgifteproces wordt de ruimbagage in het systeem gedeponeerd. Na een transportproces worden de koffers gescreend in het ruimbagagescreeningproces (HBS). Dit proces omvat vier niveaus van screening. Een koffer behoeft alleen naar een hoger niveau te gaan als deze niet op een lager niveau veiligverklaard is. Voordat het het sorteerproces ingaat, vindt er nog een transportproces plaats. Het sorteerproces is vooral gericht op het leiden van de koffers naar de daarvoor bestemde laadlocatie. De bagage die tijdelijk moet worden opgeslagen, wordt naar het opslagproces voor vroege bagage (EBS) geleid. Tijdens het laadproces wordt de bagage in containers of karren geladen om ze klaar te maken voor vervoer naar het vliegtuig.

De bagagestukken moeten de zeven hoofdprocessen in de volgende volgorde ondergaan: afgifte, transport naar het HBS-proces, screening van ruimbagage, transport naar het sorteerproces, sortering, EBS en retourneren van trays. Sommige BHS's beschikken echter niet over een EBS of maken geen gebruik van een transporttechnologie waarbij trays moeten worden geretourneerd. De bagage komt doorgaans na verblijf in het EBS terug in het sorteerproces. Verder kan uit het literatuuronderzoek worden geconcludeerd dat de exacte apparaten die bijdragen aan het totale energieverbruik van BHS afhankelijk van de technologieën die voor elk proces worden gebruikt, variëren. Ongeacht het ontwerp van de BHS is transport verantwoordelijk voor een aanzienlijk aantal energieverbruikende apparaten. Het is namelijk aanwezig in veel processen en tussen sommige processen in.

De BHS van een middelgrote luchthaven in Scandinavië is gebruikt als basis voor het model. Een MoSCoW-prioritering toonde aan dat op vergelijkingen gebaseerde modellering een geschikte modelleringsmethode is die aan de vereisten voldoet. Voor elk proces is een reeks formules opgesteld om het energieverbruik ervan te beschrijven. De formules zijn afhankelijk van de structuur van de proceselementen, zodat de formules kunnen worden aangepast voor verschillende BHS-configuraties. Het is bewezen dat het model intern consistent is en de werkelijkheid representeert.

Met behulp van het model en zeven scenario's voor BHS-configuraties is een gevoeligheidsanalyse uitgevoerd. De resultaten van de gevoeligheidsanalyse ondersteunden de hypothese dat het geschatte energieverbruik van de BHS afhangt van de totale afstand die elk bagagestuk in het systeem moet afleggen. Het is ook gebleken dat de techniek die wordt gebruikt voor het transport van bagage een aanzienlijke impact kan hebben op het energieverbruik op systeemniveau. Bovendien is een effect van de overlap van apparaatgebruik gesuggereerd, namelijk dat het energieverbruik verminderd wordt omdat een apparaat voor meerdere bagagestukken tegelijk werkt.

De bewezen invloed van de BHS-configuratie van een luchthaven op het geschatte energieverbruik op systeemniveau is dus tweeledig. Ten eerste zorgen meer proceselementen die in serie zijn gestructureerd ervoor dat bagagestukken een langere afstand afleggen op de transportband binnen de BHS, waardoor het energieverbruik toeneemt. Ten tweede hebben de parameterwaarden voor transport een grote impact op het energieverbruik. Het onderzoek suggereerde dat meer proceselementen die in serie zijn gestructureerd de overlap van apparaatgebruik toe laat nemen, wat op zijn beurt het energieverbruik verlaagt. In andere woorden, in een optimale configuratie legt de bagage een korte afstand af, wordt een transporttechniek gebruikt die een laag energieverbruik per meter heeft en wordt maximale overlap veroorzaakt.

Om de conclusies te versterken wordt verder onderzoek aanbevolen naar de kwantitatieve effecten van BHS-configuraties op het energieverbruik. Het model zou verder ontwikkeld kunnen worden door de inkomende- en transferbagagestroom op te nemen en de formules te herzien die het verminderde energieverbruik weergeven als

gevolg van de overlap van apparaatgebruik. Verder zou onderzoek gedaan kunnen worden naar de relatie tussen de operatiestrategie van de BHS en het energieverbruik ervan. Het in dit onderzoek gepresenteerde model kan als basis dienen voor dit onderzoek.

Voor NACO kan het model dienen als een waardevol hulpmiddel tijdens het conceptuele ontwerpproces, waarmee verschillende configuraties kunnen worden getest op hun impact op het energieverbruik. Het wordt daarbij aanbevolen om het model te koppelen aan de digitale ontwerpprogramma om de schatting van het energieverbruik van de BHS in het conceptuele ontwerpproces te automatiseren.

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List of abbreviations

AGV	Automated Guided Vehicle
BHS	Baggage Handling System
CT	Computer Tomography
DCV	Destination-Coded Vehicle
EBS	Early Baggage Storage
EDS	Explosive Detection System
ETD	Explosive Trace Detection
HB(S)S	Hold Baggage (Security) Screening
HVAC	Heating, Ventilation, and Air Conditioning
ICS	Individual/Independent Carrier System
NACO	Netherlands Airport Consultants
OSR	On Screen Resolution
RFID	Radio Frequency Identification
ULD	Unit Load Device
V&V	Validation and verification

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1
Introduction

In the context of environmental sustainability, the aviation sector is exploring ways to decrease the energy usage of airport baggage handling systems (BHS). Research indicates that the contribution of the BHS to an airport's terminal energy consumption is up to 10%. This is contingent upon the type of airport and system design (Van Enter, 2018). A deep understanding of BHS energy consumption is crucial for mitigating an airport's environmental footprint. This knowledge aids in the selection of energy-saving designs, enables the incorporation of renewable energy and cooling systems customised to demand profiles and avoids system oversizing. This approach not only encourages the development of environmental sustainability but also supports operational efficiency and cost-effectiveness.

A company in the aviation industry that needs to take into account such sustainability considerations is Netherlands Airport Consultants (NACO). It has a wide expertise in providing design services for airport buildings. The projects NACO is engaged in are spread around the world. Recently finished projects comprise terminal extension and refurbishment of Aruba's Aeropuerto Internacional Reina Beatrix and increasing climate resilience at Changi Airport (NACO International Aviation Consultancy, 2024a, 2024b). NACO has several offices around the world and is headquartered in Den Haag, the Netherlands. The company is part of Royal HaskoningDHV, an engineering consultancy company, providing solutions in various contexts including infrastructure, maritime, buildings, and energy.

Among the various aspects of airport design, one area where NACO and similar firms can make a significant impact is the design of BHSs. Departing baggage has to be introduced to the system, screened, and prepared for boarding (Kalbarczyk et al., 2023; Malandri et al., 2018). Additionally, the bags need to be transported, sorted, and possibly stored intermediately (Yang et al., 2023). For each process, a technology is employed. To give an example for the case of transportation, the technologies refer to its type of infrastructure. This may vary from belts to Automated Guided Vehicles (AGV) (Barth et al., 2021; Fay et al., 2022; Shen et al., 2020; Srivastava et al., 2022; Yang et al., 2023). Bradley (2010), IATA (2016), Pisinger and Rude (2020), and Vijlbrief (2019) described the sequence of processes in the BHS for departing baggage being the following: drop-off, transportation from drop-off to screening, Hold Baggage Screening (HBS), transportation from screening to sortation, sortation, and make-up. From sortation, the bags may enter the Early Baggage Storage (EBS), when having arrived early. When time has passed and the bags can be processed further, the bags return to sortation. Transportation does not only exist as a process in the BHS but is incorporated in the remainder of processes, as well (Frey et al., 2017; IATA, 2016; Van Enter, 2018; Van Noort, 2018; Viswanadham et al., 2006). The design and size of the space for the BHS and the required capacity have an influence on the design of the BHS (Bradley, 2010). Airports are found to consume serious amounts of energy (Danjuma Mambo et al., 2015). The highest contributor is the heating, ventilation, and air conditioning (HVAC), which has been widely researched (Alba & Manana, 2016; Balaras et al., 2003). The BHS is another big contributor to airport energy consumption. In BHS, most energy is consumed by IT, HBS, and baggage transportation. However, Kierzkowski and Kisiel (2022) mentioned that little research is done on the topic of BHS energy consumption.

Much research has been done on the processes in the BHS. Guiding into the direction of energy consumption of airports, the scope of most studies entails HVAC. However, little research includes the link between energy consumption and BHS. Moreover, the research that has been done on this topic is limited to analysing historical data on a process level.

1.1. Problem

This project is initiated to find a way for NACO to estimate airport BHS energy consumption at an early stage of design. Currently, NACO estimates the BHS energy consumption at a very high level in the conceptual design phase. The estimation can be summarised as multiplying the installed power by a single simultaneity factor, oversizing factor, and utilisation factor. In the current way of estimating, the factors are not tailored to the considered BHS. To come to a more precise estimation, more details on the considered BHS should be taken into account. Also, this would allow them to compare different designs of airport BHS concerning energy consumption to make a well-substantiated choice for a design recommendation or make adjustments to the terminal design when this is still possible.

The identified scientific issue is the lack of understanding about how the energy consumption of a BHS is affected by its design. These BHS designs are defined to be designed arrangements of devices and will be referred to as configurations. As a consequence of this knowledge gap, the energy consumption of such systems cannot be accurately predicted or improved. Having acquired this knowledge would allow for more research on sustainability in BHS.

1.2. Research objective

The objective of the research can be defined as follows:

To gain insight into the relationship between configurations of baggage handling systems and the system's estimated energy consumption at the system level in an early stage of design.

1.3. Research questions

With the research objective in mind, the main research question is presented:

What influence does the configuration of an airport's baggage handling system have on its estimated system-level energy consumption?

The following sub-questions guide the research towards the intended result of answering the main research question:

1. *How can the main processes in baggage handling systems be described?*
2. *How do the main processes in baggage handling systems relate to each other?*
3. *Within the set of main processes, what are the devices that contribute to the total energy consumption of baggage handling systems?*
4. *How can the energy consumption of the energy-consuming devices within a baggage handling system be quantified regarding different configurations?*
5. *How does the energy consumption vary across different configurations of baggage handling systems?*

1.4. Scope

This research is focused on developing a model that estimates the operational energy usage of a BHS. This model is specifically designed to estimate system-level energy consumption during the conceptual design phase when many design details are yet to be determined. The model allows for the comparison of energy consumption associated with processing hold baggage across various system configurations. The energy consumption related to carry-on baggage handling is not included in this analysis. Also, the research concentrates on the outbound flow of baggage, thus excludes transfer and inbound baggage. Further, the focus is on the energy consumed by the BHS for processing baggage, excluding overhead energy such as lighting and HVAC, and ground handling energy consumption. The BHS of a midsize airport in Scandinavia serves as the basis for this model, because energy consumption data for this system is readily available, thereby facilitating model validation. In the analysis of the system configurations under consideration, the technologies employed for the processes and their parameters remain constant. The only variable factor is the structure of process elements. A process element is a subset of the devices in the BHS, often consisting of an entire process or a part of a process. However, a process element may include devices of two subsequent processes. The structure of a process element describes whether the process element is designed to be in series or in parallel. Still, the total amount of devices of a type remains constant throughout the scenarios. To give an example, if a configuration has a process element designed in series, a conveyor in that subsection of the process may consist of 20 devices. In another scenario, the configuration of the process element may be designed in parallel, meaning that there are x conveyors consisting of $\frac{20}{x}$ devices.

1.5. Stakeholders

To assess the impact of the research, the stakeholders should be identified. The stakeholders may have varied interests in the research which should be satisfied as much as possible. In the company, the departments involved in designing airport buildings, which includes BHS, and those involved in sustainability might be affected by the results of the project. This is because the project may suggest changes in the process of choosing an appropriate design for BHS taking into account the energy consumption.

Another stakeholder is the Greenbaggage Alliance. This partnership between NACO and BagsID aims to reduce the environmental impact of flying with baggage (Greenbaggage Alliance, n.d.). The alliance is highly interested in getting knowledge on the relationship between demand and energy consumption in the BHS, as this would help set up energy performance benchmarks and key performance indicators (KPIs), which are not yet in place. Further, the airports that are the subject of the projects NACO is involved in, could be seen as external stakeholders. Namely, the acquired knowledge may be exploited in making decisions on which designs to adopt. Considering energy use in airport BHSs matters to society, as well, because it leads to making air travel more sustainable. By using less energy, pollution is reduced, which is important for aviation's commitment to being environmentally friendly.

1.5.1. Deliverables

The model resulting from the research can be used by NACO to get more detailed estimations of the energy consumption of a BHS in its designs. This research aims to estimate energy consumption in more detail by making use of the information that is known about the BHS in the conceptual design stage.

For the scientific community, detailed insights into the energy consumption of BHS are expected to be found, especially with regard to system configurations. Those insights are based on a model and its configuration analysis. The description and results of the research are described in this report. Also, a paper summarising the study concisely is presented (see Appendix A).

1.6. Outline

This thesis report is outlined as follows. With a literature review, chapter 2 presents an overview of the main processes in BHSs and how these processes relate to one another. The technologies available for each process are highlighted. Additionally, the devices in the main processes of the BHS that are responsible for energy consumption are identified. In addressing the fourth sub-question, chapter 3 introduces a model for the estimation of energy consumption in the BHS. It is explained how the model is implemented, what the assumptions were, and how the model is calibrated, validated, and verified. A sensitivity analysis is applied in chapter 4. It shows scenarios that include either serial or parallel process elements, formulates a hypothesis, and provides the results of the analysis. Finally, the conclusion and discussion, including implications, limitations, and recommendations, are presented in chapter 5.

2

Main processes in the BHS

With the goal in mind of estimating the energy consumption of the BHS at airports, the first step is to examine the system's processes systematically. In this chapter, the processes are described and their various technologies are presented. At the end of this chapter, the first sub-question, *How can the main processes in baggage handling systems be described?*, is answered. Further, the sequence of processes the bags undergo and the role of transportation therein are described. This allows to answer the second sub-question: *How do the main processes in baggage handling systems relate to each other?* Lastly, the amount of energy consumed by the BHS is an aggregation of the energy consumption of all devices included in the system. To create a full understanding of this energy consumption, the devices present in each process are identified in this chapter. The result leads to the answer to the third sub-question: *Within the set of main processes, what are the devices that contribute to the total energy consumption of baggage handling systems?*

2.1. Baggage movements

Malandri et al. (2018) presented a high-level visual representation of the airport's baggage handling processes, which can be found in Figure 2.1. The process of handling outbound (departing) baggage starts at the baggage drop-off, where a bar code is normally attached to the baggage. The luggage is screened to ensure that no forbidden items are loaded onto the plane. In large airports, bags can typically be stored in early baggage storage (EBS) systems if it takes a considerable amount of time before the flight is planned to depart. After that, it is sorted, bundled in carts, transported to, and loaded into the aircraft's hold. When both the passengers and the luggage are on board, the aeroplane is ready for departure (Abdelghany et al., 2006).

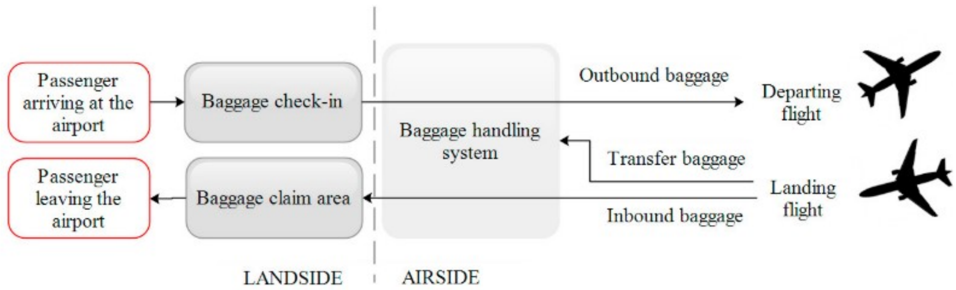


Figure 2.1: Baggage handling system (Malandri et al., 2018)

Upon landing at the destination airport, the process for inbound (arriving) baggage begins. The luggage is unloaded from the aircraft and transported to the off-loading area in the baggage hall. Here, the baggage is placed on a conveyor system that separates the transfer baggage from the inbound baggage. The inbound baggage is then transported to the baggage reclaim carousel. The transfer baggage, on the other hand, may be stored temporarily before being loaded onto another departing aircraft (Malandri et al., 2018; Pisinger & Rude, 2020; Saibabu et al., 2019).

2.2. Description of BHS processes

For each main process in the BHS, a detailed description and their available technologies are presented. Several terms are employed to describe the system and its processes. These terms are illustrated in the context of a sorting process in Figure 2.2. The BHS is characterised as a series of processes. The first process is the drop-off of baggage. The final process within the scope of the project is make-up. Intermediate processes are transportation, hold baggage screening (HBS), sortation, and early baggage storage (EBS). There are multiple technologies available to perform these processes. These technologies are implemented as devices, which are the actual installed machines. The used terminology is based on its prevalence in literature and is used by authors such as Bradley (2010), Kierzkowski and Kisiel (2022), Pisinger and Rude (2020), Romanenko et al. (2020), and Yang et al. (2023), among others.

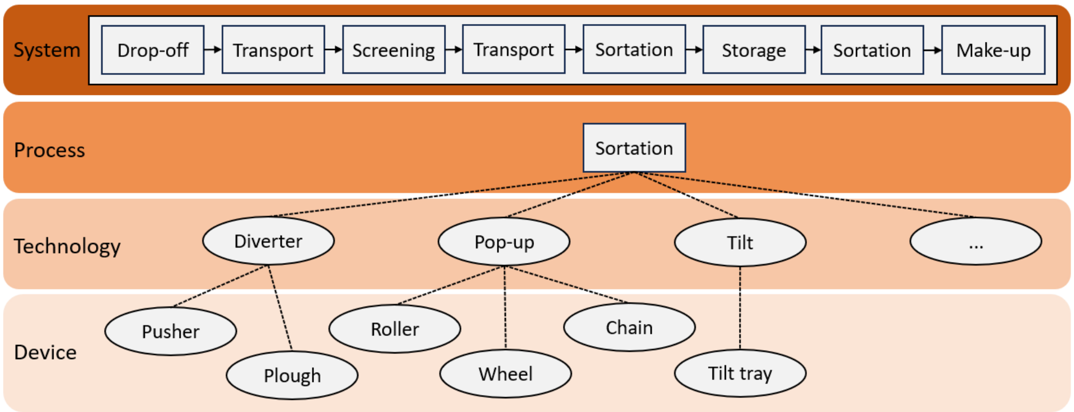


Figure 2.2: Terminology

2.2.1. Drop-off

The passenger takes his carry-on baggage with him but leaves the hold baggage at the baggage drop-off (Kalbarczyk et al., 2023; Malandri et al., 2018). At conventional drop-off desks, staff is present to facilitate the process. At some airports, passengers can drop off their baggage themselves (Kalbarczyk et al., 2023). In a hybrid option, the desk can easily be switched between a staffed counter and a self-service kiosk (Materna IPS GmbH, 2021). In all of those three cases, the luggage enters the BHS after being labelled. Figure 2.3 illustrates different baggage drop-off technologies.

(a) Conventional check-in and drop-off (Robson Handling Technology Ltd, 2024)

(b) Self-service drop-off (Farah, 2018)

(c) Hybrid drop-off (DCS aero, 2022)

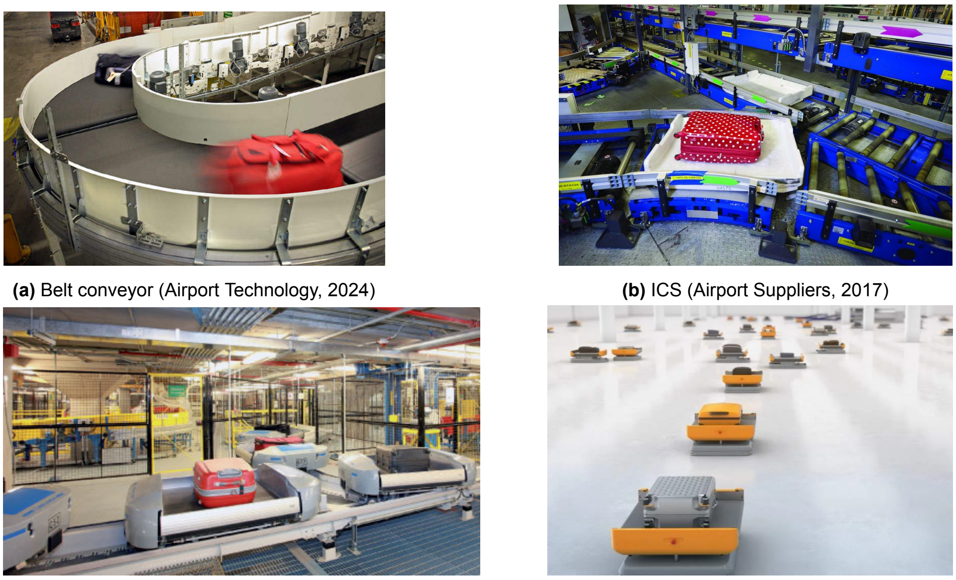
Figure 2.3: Drop-off technologies

Bradley (2010) described that the hold baggage screening (HBS) process typically occurs immediately after the baggage drop-off. At that stage, no distinction is made yet between the luggage of different flights. In other words, the baggage is transported to the HBS area without any sortation.

2.2.2. Transportation

Belt, track, and cart technologies can be used to transport luggage through the BHS (Yang et al., 2023). Currently, belt conveyors are used most frequently at airports (Barth et al., 2021). Although bags enter a conveyor device one by one, there could be multiple bags on the same belt device. This may cause difficulties for sorting and tracking purposes. Alternatively, each piece of baggage could be assigned a carrier such as a tote or tray, that moves around over a track. This technology is referred to as an individual/independent carrier system (ICS) (Brice et al., 2015; Sørensen et al., 2020). The baggage is generally loaded into a tote by a tray loader, which consists of a belt conveyor transporting the raw baggage above an ICS conveyor with empty totes/trays. The conveyors operate at the same speed, enabling a piece of raw baggage to drop into the tote/tray at the end of the belt conveyor

(Sørensen et al., 2020). Both belt and track technologies use a method to keep bags in order. They do this by giving each bag a specific space, often called a window. This window helps to keep a steady interdistance between bags or trays. In this manner, bags can be identified easier and collisions are prevented. Baggage may also be transported using destination-coded vehicles (DCVs), which consist of carts that choose their route over a fixed line network, such as rails (Sørensen et al., 2020; Tarău et al., 2009; Yang et al., 2023). Loading baggage into a DCV happens by a similar process as tray loading (Tarău et al., 2009). Automated guided vehicles (AGVs) are similar to DCVs, except that they do not require any sort of track. Instead, they can move around freely (Fay et al., 2022; Shen et al., 2020; Srivastava et al., 2022). The transportation technologies are illustrated in Figure 2.4.



(a) Belt conveyor (Airport Technology, 2024)

(b) ICS (Airport Suppliers, 2017)

(c) DCVs (ACI EUROPE Airport Business, 2009)

(d) AGVs (Airport Technology, 2017)

Figure 2.4: Transportation technologies

Transportation is present in the BHS in various forms. It does not only connect different processes, such as HBS and sortation, but it is also an essential part of these processes themselves. The following description of the BHS is a step-by-step representation of these processes from a transportation perspective. This depiction is based on the works of Frey et al. (2017), IATA (2016), Van Enter (2018), Van Noort (2018), and Viswanadham et al. (2006).

1. **Drop-off:** Each piece of luggage is placed on a conveyor at the drop-off station, which carries the luggage to the collector belt. The collector belt gathers the bags dropped off at all drop-off stations.
2. **Transportation:** There might be a transportation process between the drop-off process and the start of the HBS process. In an ICS or a DCV- or AGV-based system, this is the area where tray loader devices are installed.
3. **Hold baggage screening (HBS):** Luggage is transported through the HBS process using a conveyor. Horizontal diverting devices are placed throughout the process to separate cleared and uncleared baggage. Cleared baggage is guided towards the next transportation process, while uncleared baggage is transported to further screening before being directed to the transportation process.
4. **Transportation:** Another transportation process starts when the bags are cleared. It brings the baggage to the sortation area.
5. **Sortation:** In the sortation process, the bags travel along the junction where the bags can go to the EBS. Afterwards, they are transported along the discharge points leading to the make-up stations.
6. **Early baggage storage (EBS):** The EBS might not be directly connected to the sortation area. Therefore, some transportation may be present to bring the baggage from the sortation area to the EBS and back.
7. **Make-up:** The presence of an active form of transportation depends on the make-up technology applied. For instance, the carousel and lateral are types of conveyors, whereas the movement of luggage on a chute is driven by gravity.

In conclusion, transportation can be considered a standalone process when it only consists of a conveyor that connects two processes. Nevertheless, transportation is a part of a process if its goal is to facilitate the movement of luggage through the process.

2.2.3. Hold baggage screening

Regulations require that bags are screened for prohibited items before departure (European Union, 2010). Hold Baggage (Security) Screening (HBS or HBSS) consists of four steps, called levels. At each level, the bag may be cleared, meaning there is no suspicion of possible dangerous contents. When cleared, the bag does not need to be screened any further. Otherwise, the bag is screened again at a higher level of the HBS process. The screening levels are as follows (AlKheder et al., 2020; DeDonato et al., 2014; IATA, 2016; Price & Forrest, 2013):

1. The Explosive Detection System (EDS) checks luggage automatically on the presence of forbidden items with the use of an X-ray or a computer tomography (CT) scan.
2. The screening images are evaluated by a staff member. This On Screen Resolution (OSR) takes place in the screener room. However, the baggage does not need to travel along this room since the evaluation is executed remotely.
3. The bag's exterior and interior surfaces are swabbed manually with a special cloth. The cloth is tested by an Explosive Trace Detection (ETD) device on the presence of elements from explosive compounds.
4. The piece of baggage is opened and checked manually by a staff member in the presence of the passenger.

In case the luggage could still not be cleared after the manual inspection, it finds its destination in the bomb container. Most screening levels have one type of technology that is generally employed. However, for the first level, a 2D technology, using X-ray, and a 3D technology, using CT, can be distinguished (Hattenschwiler et al., 2018; Hättenschwiler et al., 2019; Merks et al., 2018). Currently, the 3D technology is widely applied.

Bradley (2010) outlined potential HBS structures for the future, including off-airport screening and pre-check-in screening. As these are not current practices, the focus of this study remains on the generally applied operations. The researcher also presented some typical HBS layouts for various airport sizes. The researcher acknowledges that the optimal configuration may vary depending on the required capacity. The author uses IATA's categorisation of airports for his study. Accordingly, airports are classified as small, medium, or large, based on the volume of baggage processed in peak hours. Specifically, small airports handle up to 999 pieces, medium airports handle between 1000 and 4999 pieces, and large airports handle at least 5000 pieces. For all airport sizes, decentral Level 1 screening may exist. There, the number of devices depends on the required capacity. For small airports, it is common to separate the cleared and rejected baggage immediately after Level 1 screening. Independent of the airport size, all baggage cleared in HBS Level 2 exits the HBS process. The rejected baggage is transported to a single Level 3 screening station. Contrarily, DeDonato et al. (2014) do not distinguish between airport sizes. The researcher depicts that the luggage exits the process immediately upon clearance.

2.2.4. Sortation

Immediately after leaving the HBS process, the baggage is transported to the sortation process. This process is unique because it does not merely transport luggage. Rather, it guides each bag to a pre-determined destination using diversion technologies. Sortation thus consists of conveyors and sorting devices that change the bags' direction. Before each junction, the system needs to identify each bag. This way, it knows whether and how to change the bag's direction. As per the study of Vijlbrief (2019), the bag's destinations could either be a make-up station or the EBS. This is conditional on the availability of the make-up station and the presence of an EBS. In numerous instances, the sortation process is facilitated by a sortation loop to which the EBS and make-up stations are connected.

Boysen et al. (2019), Bradley (2010), Briskorn et al. (2017), and Kay (2012) distinguished several sortation technologies. These can be applied in combination with a belt conveyor-based BHS. Firstly, horizontal diverters are arms that lead or push the object in a different direction. The pushing arm of the push diverter applies a physical force to the luggage for the object to reach a perpendicular conveyor or container (Chien et al., n.d.). Alternatively, the plough diverter is an arm that blocks the direction that the bag should not go, resulting in the bag moving to the right path. A plough diverter has a belt on the moving arm to guide the bag towards the right direction (Figure 2.5a). Secondly, devices that are by default hidden below the surface of the conveyor and pop up when a bag should change direction could be used as a sortation technology. The devices popping up are rollers, wheels, or chains. Thirdly, a tilting technology could be used for changing the baggage's direction with the use of elevation changes. This tilt tray sorter requires a special type of conveyor that consists of a sequence of trays that can tilt individually. The tilt results in discharging the bag (Figure 2.5b). It should be noted that the term 'tray' is used for both a wooden surface in the tilt tray sortation technology and as a synonym for tote in ICS transportation. Another sortation technology is cross-belt sortation. It requires a conveyor that is split up into equally sized pieces. Each piece is equipped with a small, perpendicularly directed belt conveyor able to move individually (Figure 2.5c). Lastly, turning a part of the conveyor up and down or tilting it could be used as a sortation technology. This is not discussed in the literature. However, the technology's devices are on the market. An example is the vertical sorter, which has two stacked belts on one side and a single belt on the other side. Baggage can be diverged by transporting it from the single conveyor to one of the two stacked conveyors. Alternatively, it can convert luggage by transporting it from the stacked conveyors to the single conveyor. The stacked conveyor can move up and down, such that it can pick up baggage from the single conveyor or drop baggage on the single conveyor, as shown in Figure 2.5d (Alstef Group, 2024a; Dimark, n.d.; Vanderlande Industries B.V., 2024e). A similar device is the vertical cross sorter, which has two stacked conveyors on both sides. Both sets of stacked conveyors can turn up and down. This means that the baggage from either conveyor on one side can reach either conveyor on the other side (Alstef Group, 2024a). Additionally, Siemens Logistics GmbH (2024) introduced a device that tilts the belt conveyor device itself to discharge luggage.

(a) Plough diverter (Yunnan KSEC International Trading Co. Ltd, 2020)

(b) Tilt tray sorter (Siemens Logistics GmbH, 2024)

(c) Cross-belt transfer device (AVIATIONPROS, 2022)

(d) Vertical sorter (Alstef Group, 2024a)

Figure 2.5: Sorting technologies

Most of the described sortation technologies can be applied in combination with an ICS, as well. However, tilt-tray sorters and cross-belt devices are not considered suitable for totes in the ICS. The sortation with a DCV-based system works differently than for a belt conveyor-based system. The DCVs run over a track which has switches installed at the junctions. Just before a junction, the vehicle is identified. Based on this information, it is decided whether or not the switch has to change the vehicle's direction (Tarău et al., 2009). AGVs move around independently, such that the sortation is integrated into the routing of the vehicles. No separate sortation technologies are required for an AGV-based BHS.

2.2.5. Early baggage storage

When a bag is ready to go to the make-up process and the make-up stations are not yet open, it is temporarily stored in the EBS. After storage, the bag re-enters the sortation process.

The simplest EBS technology is lane-based, in which conveyors are used as buffer space (Figure 2.6a). This could be employed in combination with belt conveyors or an ICS track. Typically, the baggage stored in a lane is filtered on departure time, flight, or class before entering the lane (Fay et al., 2022). Alternatively, baggage could be stored temporarily on vertical shelves with a racking and crane technology (Figure 2.6b). In this technology, cranes move in a 2D direction. Thereby, they insert luggage, together with their tote, into an empty storage position in a rack. It is highly suitable to integrate with an ICS system (Brice et al., 2015; Oftring, 2024; Vanderlande Industries B.V., 2024b). The shuttle-based technology is comparable to the crane-based technology. Instead of transporting the bags in a 2D direction by a crane, they are transported in a 1D direction by carts (Alstef Group, 2024b; Vanderlande Industries B.V., 2024a). The latter is portrayed in Figure 2.6c.

Pisinger and Rude (2020) described the possibility of a centralised or decentralised organisation of the EBS and make-up processes. In the central model, a 'baggage factory' is responsible for the storage and make-up of all luggage in the system. The decentral model includes multiple EBS and make-up facilities, each located near an aircraft parking position. Vijlbrief (2019) only described the central or decentral organisation of the make-up process. Thereby, the researcher implicitly suggests a central organisation for the EBS. A rationale for decentralising the EBS and make-up processes within the BHS is to have an independent system for every terminal at the airport.

2.2.6. Make-up

Baggage is transported to the aircraft in a container or cart. Filling the container or cart takes place in the make-up process.

Generally, baggage is loaded onto a carousel in the make-up area. One or several flights are assigned to

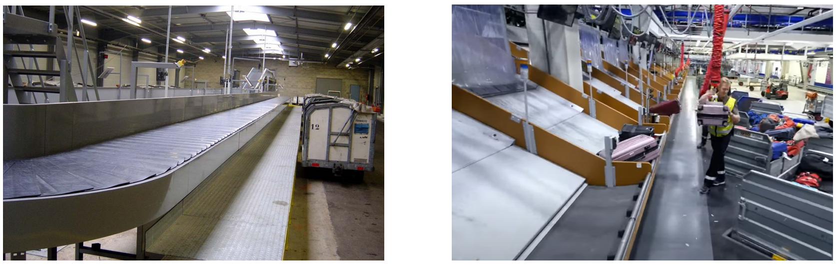
(a) Lane-based EBS (Vanderlande Industries B.V., 2024c)

(b) Crane-based EBS (Vanderlande Industries B.V., 2024b)

(c) Shuttle-based EBS (Vanderlande Industries B.V., 2024a)

Figure 2.6: Early baggage storage technologies

the carousel. All bags that leave with those flights are guided to that carousel. The cart or container is placed next to the carousel. The workers scan the bar codes of each bag and container with a hand-held device, after which they load the bag in the right container (Frey et al., 2017; Van Ganzewinkel, 2021). Another technology for loading baggage is a lateral belt conveyor. On the belt conveyor, the luggage for a flight is gathered. It works the same as in a supermarket: if a bag is taken from the lateral belt conveyor, it moves forward (Haneyah et al., 2013; Van Ganzewinkel, 2021; van Leeuwen et al., 2020). A lateral or spiral chute for collecting luggage to be loaded is presented as the third technology. A chute is a slide in which baggage can be temporarily stored. As on the lateral conveyor, the baggage moves to a single spot from where it should be retrieved. With chutes, the movement is based on gravity, compared to a motorised movement at carousels and lateral conveyors (Ridderbos, 2017). The carousel and chute technologies are illustrated in Figure 2.7.



(a) Carousel (MATREX, n.d.)

(b) Chute + lifting aid (Airportindustry News, 2024)

Figure 2.7: Make-up technologies

In all three technologies, the baggage is typically transferred to the container or cart by hand. Alternatively, baggage may be transferred with the help of lifting aids or by robots (Haneyah et al., 2013; Van Ganzewinkel, 2021; Vanderlande Industries B.V., 2024d).

The baggage can be loaded as raw baggage into carts if the luggage is to be transported in the aircraft's bulk department. The baggage is loaded into unit load devices (ULDs) if the luggage is to be transported in the aircraft's cargo department (Barth et al., 2021; Malandri et al., 2018). A ULD is a reusable container which is loaded onto an aircraft with the baggage (or other cargo) it is filled with. At the destination, the ULD is taken out of the plane. At the unloading area in the terminal, the baggage is unloaded from the ULD (Lu & Chen, 2012).

2.2.7. Identification

Identification is not a process on its own. Still, it is integrated into most processes and therefore presented as context.

All pieces of baggage should be uniquely identified to track the baggage through the BHS and to ensure the items are guided towards the right process or location (Barth et al., 2021). The conventional way of labelling is to provide the luggage with a paper tag carrying a bar code in the drop-off process. In a conveyor-based system, the bar code is read just before each junction in transportation such that the sorter can function accordingly. Additionally, the bar code is used to identify the luggage in EBS and to lead it to the right make-up position (Tarău et al., 2009). Multiple bar code scanners are placed circularly around the conveyor, such that at least one scanner catches a view of the bar code (Viswanadham et al., 2006).

For the ICS-based systems, Radio Frequency Identification (RFID) is used. It is integrated into the trays (Yang et al., 2023). When a bag is loaded on a tray, its bar code is scanned and matched to the RFID tag of the tray. Instead of reading the bag's bar code along the track, the tray's RFID tag is scanned. RFID tags are not required to be in the scanner's line of sight, which causes an increased success rate of the identification of luggage (Mishra & Mishra, 2010).

2.3. High-level overview of energy-consuming devices

In the following, the processes are reassessed to identify the devices that are responsible for energy consumption. This serves as a starting point for the model presented in chapter 3.

2.3.1. Drop-off

In the drop-off process, the devices that contribute to energy consumption include drop-off stations, the conveyor that transports baggage from the drop-off point to the collector belt conveyor, and the collector belt conveyor itself. According to Van Enter (2018), only 1% of the energy usage of the BHS at Rotterdam-The Hague Airport is caused by the drop-off desks, although the methodology for obtaining this number was not presented.

2.3.2. Transportation

In a conveyor-based system, the energy-consuming devices are the conveyors that transport the baggage. If such a system makes use of tilt-tray conveyors or an ICS, the energy consumed by the conveyor that returns the trays or totes should be considered, as well. For DCV- and AGV-based systems, the vehicles are the only devices contributing to transportation energy consumption. It is important to note that a BHS may employ a combination of these technologies. According to Vijlbrief (2019), the DCV technology consumes less energy than a belt or track technology as only the vehicle requires propulsion, not the conveyor. Similarly, Van Enter (2018) found that AGV-based transportation consumes less energy per bag than conveyor-based transportation. The percentage difference depends on load, arrival, and speed parameters. This study also revealed that transportation accounts for 55% of the BHS energy consumption at Rotterdam-The Hague Airport. Yet, this is an example. The energy usage for transportation may differ highly depending on the length of the conveyors or track and the technologies applied.

2.3.3. Hold baggage screening

The HBS process involves transportation and diverting devices to move luggage through the process and segregate cleared from uncleared baggage. Additional energy is consumed by the EDS devices in the first level of screening. In the second level of screening, OSR, a desktop computer and a monitor are used to analyse the images. However, its energy consumption is negligible. The third level of screening involves manual swabbing of the bag's surfaces. Energy is used to test the cloth in the ETD device. Still, as the number of bags entering level 3 screening is considered low, the energy consumed by the ETD device can be omitted. The fourth level of screening is performed manually and thus does not count towards the total energy used. Kierzkowski et al. (2021) highlighted that the HBS process is one of the processes that contributes most to BHS energy consumption. This is supported by Van Enter (2018), who mentioned that the HBS is held responsible for 34% of the BHS energy consumption at Rotterdam-The Hague Airport.

2.3.4. Sortation

The energy consumption in the sortation process primarily stems from the transportation of baggage throughout the sortation area. Additionally, the diverting devices require energy to change their own position as well as that of the baggage.

2.3.5. Early baggage storage

The EBS process energy consumption is attributed to the conveyors in the case of a lane technology. For crane and shuttle technologies, the cranes and shuttles themselves are the devices consuming energy. The energy required is influenced by the distance over which the device moves the luggage and the height it needs to overcome. When either of these two is employed, additional energy is consumed by a conveyor that transports the baggage to the pick-up location and from the drop-off location.

2.3.6. Make-up

When a make-up process is operated by carousels, the energy consumption only depends on the carousel devices themselves. In contrast, with the use of laterals, the energy utilisation is caused by one or multiple conveyors. The chutes, on the other hand, do not directly consume energy in the make-up process as the movement of the baggage is purely gravity-driven. However, Vijlbrief (2019) noted that this technology may require a larger sortation loop due to the constraint that chutes should not be utilised for multiple flights simultaneously. This implies that the chute technology indirectly contributes to energy consumption. Furthermore, the installed lifting aids and robots also contribute to the overall energy consumption, as these devices demand energy to operate.

2.4. Conclusion

With the use of a literature review, it is found that seven main processes can be distinguished in the BHS. In the drop-off process, the bags are inserted into the system. After a transportation process, the bags are screened in the hold baggage screening (HBS) process. This process includes four levels of screening. Still, a bag only needs to enter a higher level if it was not cleared at a lower level. Before entering the sortation process, another transportation process takes place. The sortation process is mainly aimed at guiding the bags towards their dedicated make-up location. However, the bags that need intermediate storage are diverted to the early baggage storage (EBS) process. In the make-up process, the bags are loaded into containers or carts to prepare them to be carried to the aircraft. This overview provides an answer to the first sub-question: *How can the main processes in baggage handling systems be described?*

To answer the second sub-question, *How do the main processes in baggage handling systems relate to each other?*, it is found that the bags have to undergo the seven main processes in the following order: drop-off, transportation to the HBS process, hold baggage screening, transportation to the sortation process, sortation, EBS, and return of trays. Still, some BHS may not have an EBS or employ a transportation technology that does not require the return of trays. Also, the bags generally return to the sortation process after having stayed in the EBS.

Additionally, this chapter was dedicated to finding an answer to the question *Within the set of main processes, what are the devices that contribute to the total energy consumption of baggage handling systems?* It can be concluded that the exact devices vary based on the technologies employed for each process. Independent of the design of the BHS, transportation accounts for a significant number of energy-consuming devices. Namely, it is present in many processes and in between some processes.

3
Estimating energy consumption

Based on the energy-consuming devices found in the literature review, a model is set up that represents the BHS. This leads to the answer to the fourth sub-question: *How can the energy consumption of the energy-consuming devices within a baggage handling system be quantified regarding different configurations?* The model includes the main processes of the BHS and their energy-consuming devices. Although the model is based on a midsize airport in Scandinavia, it is designed to be as generic as possible. With the MoSCoW method, the model requirements are assessed in a structured way, which helps in choosing a suitable implementation of the modelling method (Agile Business Consortium Limited, 2024; Miranda, 2022). By executing validation and verification, it is checked whether the model works as expected, and reasonable results are found, respectively (Zenina et al., 2020).

3.1. Airport X: A basis for the model

The BHS of a midsize airport in Scandinavia, hereafter referred to as Airport X, served as a basis for the energy consumption model. The information on this airport comes from NACO's database. The airport's capacity is 7.5 million passengers per year. The BHS in the terminal is equipped with 24 check-in counters and 8 self-service bag drop kiosks to facilitate efficient baggage drop-off. The BHS at Airport X employs a tray-based ICS for luggage transportation. The use of belt conveyors is limited to the transportation of luggage from the drop-off point to the tray-loading location. Even in the HBS process, the luggage remains in the tray. The airport uses X-ray devices for Level 1 screening. To ensure that luggage reaches its correct destination, the system incorporates plough diverters, pop-up belts, and tilting conveyors. However, in this project, only the plough diverters and tilting conveyors are considered for the sortation and the discharge of bags from their trays. The EBS system is crane-based and can hold up to 600 bags simultaneously. The sortation process includes a total of 42 chutes for make-up. The accumulative length of conveyors in the system is 1058 meters.

3.1.1. BHS representation

The knowledge from the literature review and the information on the BHS of Airport X are combined in a system representation, as shown in Figure 3.1. The representation takes the technologies used in the BHS of Airport X into account. The description of the BHS can be seen as a foundation for the model for estimating energy consumption. For that reason, only the devices contributing to energy consumption are included.

The model represents the BHS at a macroscopic level, corresponding to the conceptual design phase. At that stage, the system's details are not worked out yet. A good example of this level of abstraction is the self-service baggage drop-off process. The process elements include the kiosk for scanning and labelling luggage, the first set of conveyors, and the collector belt that gathers bags from the drop-off points and directs them to the remainder of the BHS.

In Figure 3.1, the coloured rectangles differentiate the main processes in the system, and the numbers distinguish the elements within a process. Each circle represents a device or set of devices of the same type. The pill shape symbolises the point where the bags exit the system. The steps in the processes are outlined with a blue, red, or black colour. These represent the steps taken by only the bags, only the trays, or both bags and trays, respectively.

The bag flow begins when the bag arrives. After processing at the drop-off device, the bags are induced to the drop-off belt (Process 1a in Figure 3.1). The collector belt transports them to the end of the drop-off process where the bags from all desks and kiosks are aggregated (Process 1b). The baggage is then transported by a belt conveyor (Process 2a), loaded in the trays of the ICS (Process 2b), and transported further to HBS (Process 2c). HBS L1 and L3 are indicated as processes 3a and 3b, respectively. Process 4 represents the transportation by

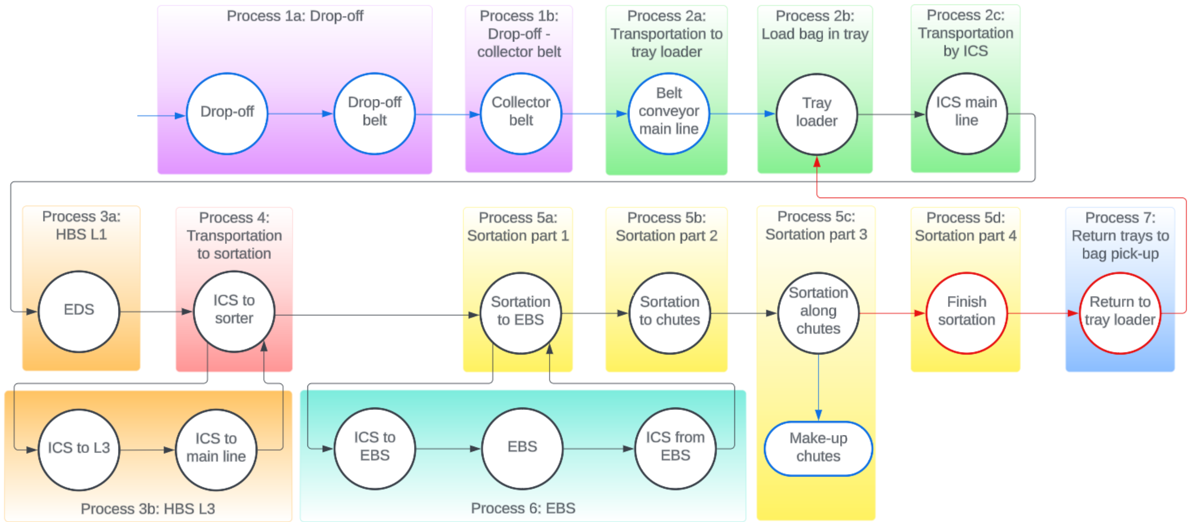


Figure 3.1: BHS representation

the ICS to the start of the sortation process. In process 5, the luggage is transported through sortation. All bags traverse the first part of the sortation: until the EBS (Process 5a). There, a portion of the bags takes the junction to the EBS (process 6) and resumes their journey later. The bags that are not entering the EBS and the bags that just exited the EBS continue the sortation process. The bags travel over the second part of the sortation process: to the first make-up chute (Process 5b). The infrastructure for transportation along the chutes consists of dynamic discharge devices, instead of a general ICS conveyor (Process 5c). When the bags have left the system, the trays have to be returned to the ICS loader device to pick up new bags. This is illustrated by processes 5d and 7.

3.2. Assumptions

This section explains the assumptions made for the model. These assumptions are of two types: operational and general. Operational assumptions are about how the BHS operates, whereas general assumptions are about the model's scope and describe parts that are simplified or left out.

3.2.1. Operational assumptions

- The investigation of bag arrivals at Airport X reveals minimal bag insertion into the system before 4.00 A.M. and after 10.40 P.M. (see subsection 3.6.1). Consequently, it is assumed that no bags are inserted during these hours.
- For the HBS, the devices comply with the same operational hours as the rest of the system. The devices function in three distinct states: scanning, standby, and shut down (not consuming energy). During operational hours, all EDSs alternate between the scanning and standby modes, as repeatedly shutting down and restarting between bag arrivals would be too time-consuming.
- When the trays have completed the sortation process, it is assumed that they are emptied (i.e., the baggage they carried is discharged at a chute). Thereafter, the trays return to the baggage pick-up location. It is assumed that there are enough trays in the system to carry the bags.
- In every mode of transportation, whether in a process or in between processes, a conveyor device starts to run when a bag is positioned on the preceding conveyor device. This ensures that the device has achieved the required velocity when the bag arrives. Once the bag is on the next device, the conveyor device gradually slows down until it stops. This rule also applies to tray loaders and EDSs. Whilst the device is accelerating, carrying a bag, and decelerating, the conveyor device is assumed to consume energy. The devices that do not take part in transportation, which are the drop-off devices and the EBS crane, are assumed to use energy only when processing a bag.

3.2.2. General assumptions

- The model does not consider capacity. So, before using the model, one should ensure that the considered BHS can manage the volume of bags that is introduced into it.
- Throughout the BHS, curved and straight elements in transportation are assumed to show similar behaviour. In other words, it is supposed that they consume the same amount of energy.
- The Level 2 and Level 3 HBS resources are assumed to consume a negligible amount of energy, as they primarily consist of computers and ETD devices. Nevertheless, the energy consumption for transportation

to and from HBS L3 is considered. All bags are assumed to be cleared after HBS L3. This assumption is unlikely to cause significant deviations from a real-world case, as only a small percentage of bags is not cleared after HBS L3 in the real world (0.048%, see Table 3.3 and considering a L3 clearance rate of 0.99 (AlKheder et al., 2020)).
- Lifting aids in the make-up process are considered out of scope. The BHS at Airport X has chutes, which do not consume electrical energy by definition. With this in mind, the make-up process is considered not to consume any electrical energy.
- In each configuration, the total length of the conveyors is the same. The main goal of the model is to assess the impact on energy consumption caused by different configurations, not to look into the effect of changing conveyor lengths.
- The bags and trays are assumed to be located exactly in the middle of their window. It is worth recalling that a window is a specific space, helping to keep a constant interdistance between bags or trays.
- For simplicity, the conveyor devices' speed is determined by the centre point of each bag's window: it is accelerating if on the previous device, running at full speed if on the current device, and decelerating if on the next device.
- All baggage is assumed to be of standard size, so no baggage is considered to be out of gauge.
- All processes are assumed to occur at the same elevation, such that there are no changes in height.

3.3. Model input and output

The model implementation is created in the Python environment. The code can be found in Appendix B.

The model allows to be customised to the unique features of the BHS being studied by calculating energy use based on variable values. These values are given to the model via an external file. One set of values includes the model parameters, as outlined in Table 3.3 in a later section. These parameters are usually unknown during the conceptual design phase, so the list is pre-filled with standard values. However, this list can be modified, allowing any value to be updated in the input file to make the results more reliable. The other set of values includes the BHS-dependent input values, presented in Table 3.4 later in this chapter. The table is filled with the values for Airport X, which are used for validation and verification. When the model is applied to another airport, the parameters for the relevant airport should be used. In addition to the parameters, the model requires an estimate of bag arrivals.

To achieve its main goal, the model presents both the total daily energy use and the energy used per bag for each considered configuration. The average energy expected to be used during the busiest and least busy periods is also given by the model. The results are shown in figures representing the expected energy use over the day in total and per bag. These are presented as the distribution over the processes and as its total. If needed, the expected energy use (total or per bag) can be given for each period. The model is designed to estimate energy use based on the number of bag arrivals per hourly period and per 10-minute period.

3.4. MoSCoW method

For selecting an appropriate modelling method, the MoSCoW prioritisation technique is used. This method classifies the requirements into four distinct categories. The requirements in the first category, known as 'must-have' requirements, are absolutely necessary and must be fulfilled in any case. Without meeting these requirements, the model could not be used to achieve the project's objectives. Fulfilling the requirements in the second category, called 'should-have' requirements, is helpful but not essential. There may be alternative solutions to compensate for their absence in the model. The requirements in the third category, 'could-have' requirements, are less critical. These are only expected to be fully met in a perfect situation. However, they are still desired. The last category, 'will-not-have' requirements, helps to define the project's boundaries. Nevertheless, they are not expected to be delivered (Agile Business Consortium Limited, 2024).

Must-have requirements:

1. **Generalisation:** The model needs to be general enough to handle different configurations. This flexibility makes sure the model is useful and relevant in guiding the research to answer the research question.
2. **Representation of quantitative relations:** The design of the model should facilitate the inclusion of formulas describing the energy usage of the devices in the BHS quantitatively and present them at the system level.
3. **Consistency:** With the same input values and parameters, the model needs to give the same estimates over and over. If the model is used repeatedly with the same input values and parameters and it generates different results every time, sub-optimal decisions may be made and inefficiencies in designing would occur.

Should-have requirements:

1. **Hourly detail:** The model should be able to estimate how much energy is used every hour. This implies that the model should be able to estimate energy consumption based on the number of bags processed within an hour.

2. **Efficient runtime:** The model should be designed to give results within a few minutes. This allows for the ability to consult the model as often as needed.
3. **Scalability:** Given the large scale of airport operations, the model should be able to take in data from many devices in the BHS. This scalability makes sure the model works well with BHSs of different sizes.

Could-have requirements:

1. **Visualisation capabilities:** The model could be improved with features that visualise the estimated energy use across different processes and various configurations. This could help to understand the data and to make informed decisions.
2. **10-minute period detail:** The model could estimate energy consumption for 10-minute periods for a more detailed view of energy use. This level of detail would be the most thorough possible with the data available for Airport X.

Will-not-have requirements:

1. **Integration with existing systems:** The model will not be designed to integrate seamlessly with existing BHS design systems such that the output of the design system could serve as input for the model.
2. **Energy optimisation:** The model will not suggest ways to optimise energy consumption. Its primary function is to estimate energy consumption, not to provide recommendations for energy conservation or efficiency.

A candidate for modelling was creating a simulation using the SimPy package in the Python programming language. The SimPy package makes use of the queuing theory (Battu et al., 2023). For simulations, it is required to define precisely where each bag is at any moment. In other words, the exact operating rules should be known. This knowledge is not realistic to have at the conceptual design stage. Moreover, the method is not generic enough to easily incorporate different BHS configurations. Since it does not meet one of the must-have requirements, the simulation method was not appropriate to use for estimating BHS energy consumption in this project.

Another candidate for a modelling method is equation-based modelling. Once a model is set up and the operational rules that control the interactions within and between the model's processes are defined, these rules can be described mathematically to represent the processes (Clermont, 2013; Wetter et al., 2016). In the following, it is tested whether the use of the equation-based method can be justified.

Justification for equation-based modelling

It is checked whether equation-based modelling indeed fulfils all requirements.

Equation-based modelling satisfies the must-have requirements as follows:

1. **Generalisation:** Equation-based models are flexible. Also, they can be easily updated to be applied to a new configuration. It is a case of simply adding or adapting formulas, input values, and parameters.
2. **Representation of quantitative relations:** Equation-based models consist of formulas by definition.
3. **Consistency:** Equation-based models are deterministic and hence provide the same estimates every time they are consulted for the same case.

The should-have requirements are also well addressed by equation-based modelling:

1. **Hourly detail:** Equation-based models can be designed to estimate energy consumption based on hourly periods. The unit size just needs to be taken into account while implementing each formula.
2. **Efficient runtime:** Equation-based models, being mathematical, can have efficient runtimes. It may be required to implement the model to automate the calculations.
3. **Scalability:** The formulas in equation-based models can be modified to include parameters from any number of devices in the BHS. This ensures its effectiveness across BHSs of varying sizes.

The could-have requirements can be incorporated into the model whenever possible:

1. **Visualisation capabilities:** While not inherent to equation-based models, visualisation features can be added using external libraries or tools.
2. **10-minute period detail:** The equations can potentially be adapted to estimate energy consumption based on 10-minute periods.

Finally, the will-not-have requirements are not considered as limitations to the use of equation-based modelling:

1. **Integration with existing systems:** While this could be a useful feature, it is not a requirement for the model to function effectively.
2. **Energy optimisation:** Energy optimisation is out of scope for this model. Its core function is to accurately estimate energy consumption, not to suggest optimisation strategies. This decision is made to maintain the model's focus and simplicity.

Equation-based modelling can be considered a suitable choice for modelling. Namely, it meets all critical requirements and offers a possibility for future improvements. It provides a robust yet flexible approach. In this project, an equation-based model is implemented with the Python programming language such that the calculations are automated. As the Python programming language is open-source, the model can be consulted by the company even after finishing the project.

3.5. Equation-based model

The model can be presented as an equation-based model, and thus broken down into a series of algebraic formulas. Those formulations represent the relationships between the system-level energy consumption of a BHS and its variables. The energy consumption to process the bags arriving in one 10-minute or hourly period is presented by a set of formulas. All formulas in the set of Equation 3.12 to Equation 3.76 that apply to the BHS design considered should be recalculated for each 10-minute or hourly period. The total system-level energy consumption is determined by summing the energy consumption across all periods within a day.

The series of mathematical formulations are derived from the fundamental physical energy equation presented in Equation 3.1 (Halliday et al., 2008).

$$E = P \cdot t \tag{3.1}$$

In this formula, E represents the electrical energy consumption in kilowatt-hours (kWh), P denotes the active or real power in kilowatts (kW), and t signifies the time in hours (h). Additionally, the basic distance equation, where s is the distance in meters (m), and v is the speed in meters per hour (m/h) (see Equation 3.2), is recurrently utilised (Halliday et al., 2008).

$$s = v \cdot t \tag{3.2}$$

The mathematical formulations for a process represent the process with either serial or parallel process elements. Formulas representing a serial process element are indicated by an s, and parallel process elements are indicated by a p. Additionally, it is given in which part of the BHS the serial or parallel process elements are located. The letters correspond with the letters presented in Figure 3.2. It is assumed that the number of tray loaders matches the number of EDS devices. Also, in the case of parallel process elements, the number of lines (n_{ln}) is assumed to be equal to the number of tray loaders and EDS devices.

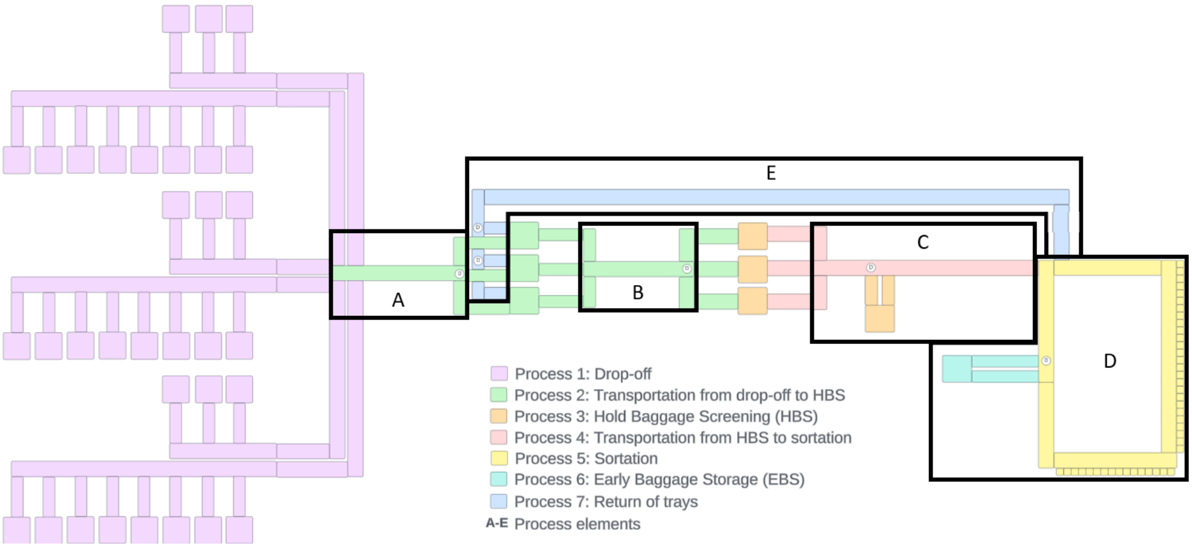


Figure 3.2: Process elements

Throughout the formulas, symbols and parameters are used. Most symbols are subject to subscripts or superscripts, explanations can be found in Table 3.1 and Table 3.2. Multiple subscripts and/or superscripts may be used simultaneously in combination with a single symbol. For example, $f_{L,b}$ refers to the time factor f for a loaded device L of a belt conveyor b as calculated in Equation 3.10. In this equation, the device length l_d and the number of windows n_w are chosen or calculated based on the knowledge of dealing with a belt conveyor b.

Before the formulas are described that contribute directly to the BHS energy consumption, some recurring formulas are presented. The subscript $_d$ (device) is replaced with the specific device when applied later.

3.5.1. Conveying

Conveyors consume energy when transporting a bag. A conveyor's total energy consumption in a 10-minute or hourly period is calculated as in Equation 3.3.

$$E_{d,L} = P_d \cdot f_L \cdot td_d \cdot n_{bags} \cdot n_d \tag{3.3}$$

The conveyor's energy consumption can be represented as Equation 3.1, where the power P is substituted by the power of the device P_d. The time t in Equation 3.1 is substituted by the time it takes to travel one device td_d, multiplied by the number of devices that need to be travelled on the considered conveyor n_d. Also, it is multiplied by

Symbol	Subscripts and superscripts	Explanation	Unit
E	d, div, Em, L, p, pe, s	Electrical energy consumption	kWh
itd		Interdistance	m
f	b, di, ^{dod}, EDS, Em, ICS, L, $load$, n^{nc}_{bags}, n_{ln}, ^{ssd}	Time factor	-
l	b, cb, d, di, do, dob, EDS, fe, fh, fl, ft, ICS, $load$, ma, ml, rb, ret, rs, $s1$, $s2$, $s4$, te, tl, toh, tot, ts, tsb	Length	m
n	$bags$, c, ch, d, ^{dod}, ^{EBS}, EDS, ^{nc}, pe, ^{ssd}, w	Number	-
P	b, d, dib, dic, dis, dit, dob, dod, ICS, li, $load$, me, re, sc, ssd, st	Power	kW
$rate$	EBS, $L1$, $L2$	Rate	-
s		Distance	m
t	dib, dis, dod, li, me, op, re, ssd	Time	h
td	b, d, di, dob, EDS, ICS, $load$	Device crossing duration	h
v	b, d, di, dob, EDS, ICS, $load$	Speed	m/s
w	d, raw, $tray$	Window	m

Table 3.1: Symbols

the time factor f_L. The time factor f_L takes into account the overlap of device usage, as explained in Equation 3.10. Then, $P_d \cdot f_L \cdot td_d \cdot n_d$ presents the energy consumption on the conveyor d per bag. When multiplying this by the number of bags that arrive in the considered period, and thus travel over these devices, n_{bags}, the conveyor's total energy consumption in a 10-minute or hourly period is found. The device crossing duration td_d is shown in Equation 3.4.

$$td_d = \frac{l_d}{v_d \cdot 3600} \tag{3.4}$$

This formula is based on Equation 3.2, with s being substituted by the length of the device l_d, v being substituted by the speed of the device v_d, and t being substituted by the time it takes to travel one device td_d. 3600 is a multiplication factor to convert the resulting time from seconds to hours.

When a bag is on a conveyor device, it is assumed that the next device starts accelerating. This ensures it is already at the right speed when the bag arrives. The same is assumed to happen in reverse: if a bag is on a device, the previous is decelerating. This happens for each bag separately. This concept is illustrated in Figure 3.3. A conveyor is assumed to consist of a series of similar devices. For example, a belt conveyor consists exclusively of belt conveyor devices. Alternatively, an ICS conveyor consists of a set of ICS devices only.

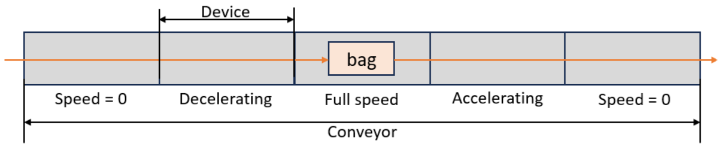


Figure 3.3: Conveyor speed

Equation 3.5 describes the energy usage for the conveyor devices that operate without transporting baggage.

$$E_{d,Em} = P_d \cdot f_{Em} \cdot 2 \cdot td_d \cdot n_{bags} \cdot n_d \tag{3.5}$$

The formula follows the same logic as Equation 3.3, with P_d representing the power and $f_{Em} \cdot td_d \cdot n_{bags} \cdot n_d$ representing the time the devices run. Since it is assumed that the time it takes for accelerating and decelerating is the same, and thus the total operating time for the conveyor without transporting baggage $f_{Em} \cdot td_d \cdot n_{bags} \cdot n_d$ is applied twice, the operating time is multiplied by 2. The formula for time factor f_{Em} is presented in Equation 3.7.

Equation 3.3 and Equation 3.5 can be combined in one formula, representing the energy consumption of a conveyor device. It can thus both be applied for devices whose only purpose is transportation of bags and for devices that include transportation, such as tray loaders. This formula is shown in Equation 3.6.

$$E_d = P_d \cdot (f_L + 2 \cdot f_{Em}) \cdot td_d \cdot n_{bags} \cdot n_d \tag{3.6}$$

Time factor

Some context is required to understand the calculations of the time factors. To start with, each bag has a window, which is a designated space around it. This window, marked in green in Figure 3.4, cannot overlap with another

Subscript	Superscript	Explanation
b		Belt conveyor device
c		Collector device (belt)
cb		Collector conveyor - branch (belt)
ch		Chutes
d		Device
di		Discharge device
dib		Diverter - belt
dic		Discharge - conveyor
dis		Diverter - switch
dit		Discharge - tipper
div		Diverter
do		Drop-off conveyor (belt)
dob		Drop-off device (belt)
dod	dod	Drop-off desk
EBS	EBS	EBS
EDS		Conveyor through EDS
Em		Empty device
fe		From EBS (ICS)
fh		Branch from HBS (ICS)
fl		HBS L3 to main line (ICS)
ft		Tray loader to main line - branch (ICS)
L		Loaded device
ICS		ICS device
$L1$		HBS L1
$L2$		HBS L2
li		EBS crane - lift
ln		Lines

(a) Subscripts and superscripts

Subscript	Superscript	Explanation
$load$		Tray loader
ma		Main line to HBS (ICS)
me		EBS crane - metering
ml		Main line to tray loader (belt)
	nc	Not cleared
op		Operation
p		Parallel
raw		Raw baggage
rb		Return trays - branch (ICS)
re		EBS crane - release
ret		Return trays (ICS)
rs		Return trays to start (ICS)
s		In series
$s1$		Start sortation to EBS (ICS)
$s2$		EBS to start chutes (ICS)
$s4$		Final part sortation (ICS)
sc		EDS - screening
ssd	ssd	Self-service drop-off
st		EDS - standby
te		To EBS (ICS)
tl		Main line to HBS L3 (ICS)
toh		Branch to HBS (ICS)
tot		Main line to tray loader - branch (belt)
$tray$		Tray
ts		Main line to sortation (ICS)
tsb		Branch to sortation (ICS)
w		Windows

(b) Subscripts and superscripts (continued)

Table 3.2: Subscripts and superscripts

bag's window. The distance between two bags, the interdistance, is indicated in the figure, as well. The devices coloured blue represent the energy-consuming devices at this very instance. For each bag, one device is operating while loaded with that bag, consuming energy following Equation 3.3. Additionally, two devices are accelerating and decelerating, together consuming energy following Equation 3.5. In summary, for two bags, two devices are operating while loaded and four devices are operating while empty, for each bag consuming energy following Equation 3.6.

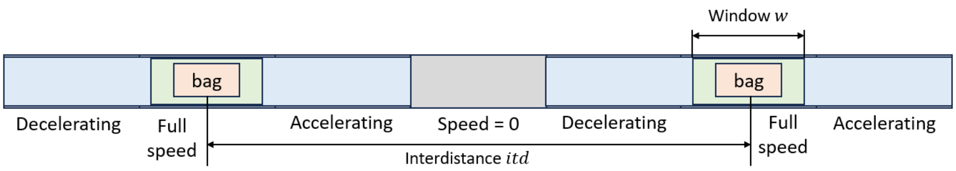


Figure 3.4: Window and interdistance of bags

Two bags may demand the same conveyor to operate. This concept is referred to as overlap of device usage and is illustrated in Figure 3.5. In this example, two loaded devices are running, and only three are operating while empty. This means that the energy required to transport these two bags is lower than in Figure 3.4.

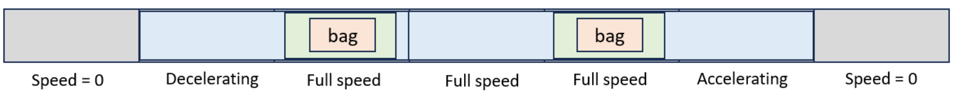


Figure 3.5: Two bags causing the same conveyor using energy

To cover this reduced energy consumption, the time factor to account for the overlap of empty device usage f_{Em} is defined in Equation 3.7. It represents the fraction of energy consumption that still occurs if an overlap of empty device usage exists. In Appendix C, it is explained how the formulas are derived.

$$f_{Em} = \begin{cases} 0.5 & \text{if } itd < l_d \\ \frac{1}{8}(5 - \frac{1}{n_w}) & \text{if } l_d \leq itd < 2l_d \\ \frac{1}{8}(7 - \frac{1}{n_w}) & \text{if } 2l_d \leq itd < 3l_d \\ 1 & \text{otherwise} \end{cases} \tag{3.7}$$

Where, l_d is the length of the conveyor devices, itd is the interdistance between bags as shown in Equation 3.8, and n_w is the number of windows on each conveyor device as presented in Equation 3.9.

$$itd = \frac{t_{op}}{n_{bags}} \cdot v_d \cdot 3600 \tag{3.8}$$

In Equation 3.8, t_{op} is the number of hours in a 10-minute or hourly period, n_{bags} is the number of bags that enters the system in the period, and $v_d \cdot 3600$ is the speed of the device.

$$n_w = \frac{l_d}{w_d} \tag{3.9}$$

In Equation 3.9, the number of windows per device is calculated by dividing the length of the conveyor device l_d by the window length for that device w_d.

Similar to f_{Em}, a time factor is present for the overlap of device usage for loaded devices f_L, see Equation 3.10. A reduction in energy consumption exists when multiple bags are on the same conveyor device at the same time. The derivation of the values can be found in Appendix C.

$$f_L = \begin{cases} 0.75 & \text{if } itd < l_d \\ 1 & \text{otherwise} \end{cases} \tag{3.10}$$

3.5.2. Diverting

Plough diverters are placed in the BHS to guide bags towards a tray loader, an EDS, HBS L3, a sortation process, EBS, and a conveyor for returning the trays. The diverter diverts an equal fraction of bags in each direction. An illustration of this action is presented in Figure 3.6.

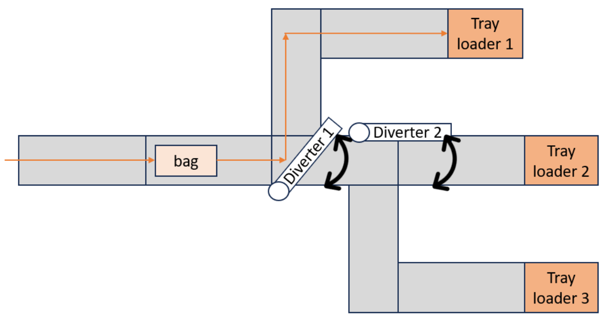


Figure 3.6: Diverting

For all destinations, it is assumed that one of the devices or processes is situated at the end of the main line. Also, if a bag's destination is the device or process at the end of the line, it can continue on its path without any changes. However, if a bag needs to go to a different device or process, it has to be diverted from the main line. In the example in Figure 3.6, Tray loader 2 is positioned at the end of the line. This means that an equal fraction of the bags is diverted to Tray loader 1 by Diverter 1, an equal fraction of the bags is diverted to Tray loader 3 by Diverter 2, and an equal fraction of the bags is not diverted and continues to Tray loader 2. The formula for diverting bags is recurrently used throughout the processes. It is presented in Equation 3.11.

$$E_{div} = n_{bags} \cdot (1 - \frac{1}{n_{ln}}) \cdot (P_{dis} \cdot \frac{t_{dis}}{3600} + P_{dib} \cdot \frac{t_{dib}}{3600}) \tag{3.11}$$

The fraction of bags that need to be rerouted thus can be described as $1 - \frac{1}{n_{ln}}$. In this formula, $P_{dis} \cdot \frac{t_{dis}}{3600}$ denotes the energy consumed for switching the plough diverter. Referring to subsection 2.2.4, a plough diverter carries a belt for guiding the bag in the right direction. Its energy consumption is represented as $P_{dib} \cdot \frac{t_{dib}}{3600}$.

3.5.3. Process 1: Drop-off

The bags can be dropped off either at a self-service kiosk or at a staffed drop-off desk. The number of bags inserted in the BHS at each type of drop-off point is calculated following Equation 3.12 and Equation 3.13.

$$n_{bags}^{ssd} = \frac{\frac{1}{t_{ssd}} \cdot n_{ssd}}{\frac{1}{t_{ssd}} \cdot n_{ssd} + \frac{1}{t_{dod}} \cdot n_{dod}} \cdot n_{bags} \tag{3.12}$$

$$n_{bags}^{dod} = \frac{\frac{1}{t_{dod}} \cdot n_{dod}}{\frac{1}{t_{ssd}} \cdot n_{ssd} + \frac{1}{t_{dod}} \cdot n_{dod}} \cdot n_{bags} \tag{3.13}$$

t_{ssd} and t_{dod} are the service times of the self-service drop-off kiosks and the staffed drop-off desks, respectively. n_{ssd} and n_{dod} are the number of self-service kiosks and drop-off desks, and n_{bags} is the total number of bags dropped off within the 10-minute or hourly period. The numerator represents the processing rate of the respective drop-off technique, and the denominator represents the total processing rate of both drop-off techniques. The ratios are multiplied by the total number of bags arriving in the considered period n_{bags} to get the number of bags processed by the devices of each drop-off technique.

Process 1a

Equation 3.14 and Equation 3.15 describe the energy consumed by the self-service kiosks and the drop-off desks, respectively.

$$E_{1a,1} = n_{bags}^{ssd} \cdot P_{ssd} \cdot \frac{t_{ssd}}{3600} \tag{3.14}$$

$$E_{1a,2} = n_{bags}^{dod} \cdot P_{dod} \cdot \frac{t_{dod}}{3600} \tag{3.15}$$

In the formulas, the general energy consumption formula, as presented in Equation 3.1, can be recognised. The power is substituted by P_{ssd} and P_{dod} and the time is substituted by $\frac{t_{ssd}}{3600}$ and $\frac{t_{dod}}{3600}$. To get the energy on the system level, the energy consumption for one bag should be multiplied by the number of bags using each of the drop-off techniques: n_{bags}^{ssd} and n_{bags}^{dod}.

Equation 3.16 represents the energy consumption of the drop-off belt conveyor dob that transports the bags from the drop-off kiosk or desk to the collector belt in process 1b.

$$E_{1a,3} = 3 \cdot P_{dob} \cdot td_{dob} \cdot n_{bags} \cdot \frac{l_{do}}{l_{dob}} \tag{3.16}$$

This formula resembles the conveyor formula, as presented in Equation 3.6. The factor $\frac{l_{do}}{l_{dob}}$ presents the number of devices the conveyor consists of n_d. It is assumed that the luggage moves faster on this conveyor belt than its process time at the drop-off kiosk or desk. So, a bag has already left the conveyor belt before the next one arrives. This means that there is no overlap in device usage, and there is at most one bag on the conveyor at any time. This implies that the time factors are always equal to 1 and thus can be left out of the formula. The energy consumption of each drop-off belt device do, is multiplied by 3. This accounts for the device running when it is loaded with a bag, and during speed changes (accelerating and decelerating).

By adding the outcomes of Equation 3.14, Equation 3.15, and Equation 3.16, the total energy consumption for process 1a can be found, see Equation 3.17.

$$E_{1a} = E_{1a,1} + E_{1a,2} + E_{1a,3} \tag{3.17}$$

Process 1b

Equation 3.18 and Equation 3.19 represent the energy consumption incurred by the transportation over the collector belts for bags dropped off at the self-service kiosks and the staffed desks, respectively.

$$E_{1b,1} = P_b \cdot ((1 - \frac{1 - f_{L,b}^{ssd}}{2}) + 2 \cdot (1 - \frac{1 - f_{Em,b}^{ssd}}{2})) \cdot td_b \cdot n_{bags}^{ssd} \cdot n_c^{ssd} \tag{3.18}$$

$$E_{1b,2} = P_b \cdot ((1 - \frac{1 - f_{L,b}^{dod}}{2}) + 2 \cdot (1 - \frac{1 - f_{Em,b}^{dod}}{2})) \cdot td_b \cdot n_{bags}^{dod} \cdot n_c^{dod} \tag{3.19}$$

The formulas are based on the conveyor formula, Equation 3.6. The power P is substituted by the power for belt conveyor devices P_b. The time to travel one device td_b is calculated for belt conveyors. The number of bags travelling over the conveyors is n_{bags}^{ssd} and n_{bags}^{dod}, respectively. The average number of collector belt devices the bags have to travel n_c is calculated as in Equation 3.20.

$$n_c = \frac{\frac{n_d}{n_{ln}} + 1}{2} \tag{3.20}$$

Where, n_d is the number of drop-off devices (n_{ssd} and n_{dod}) and n_{ln} is the number of lines. This formula is based on the assumption that the number of devices per collector belt is exactly the same as the number of drop-off points connected to that collector belt. In Figure 3.7, the number of collector belt devices each bag has to travel, given its drop-off point and $\frac{n_{ssd}}{n_{ln}} = 3$, is illustrated.

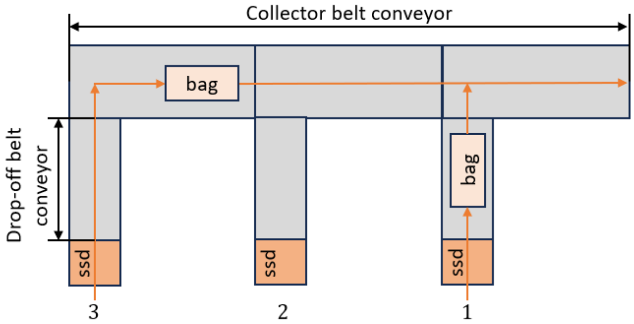


Figure 3.7: Number of collector belt devices to travel

For Equation 3.18 and Equation 3.19, the following is required to calculate the time factors: the speed and length of belt conveyor devices, v_b and l_b, the window for raw baggage w_{raw}, and the variables n^{dod}_{bags} and n^{ssd}_{bags}, which denote the number of bags. Further, as illustrated in Figure 3.8, the collector belt devices do not encounter an equal quantity of bags. The first device only receives bags from the connected drop-off point, while all bags deposited along the conveyor traverse the last device. Thus, the expected value for the energy usage savings caused by the overlap of the device usage $(1 - f)$ is half of the expected value when all bags deposited along the conveyor traverse all devices.

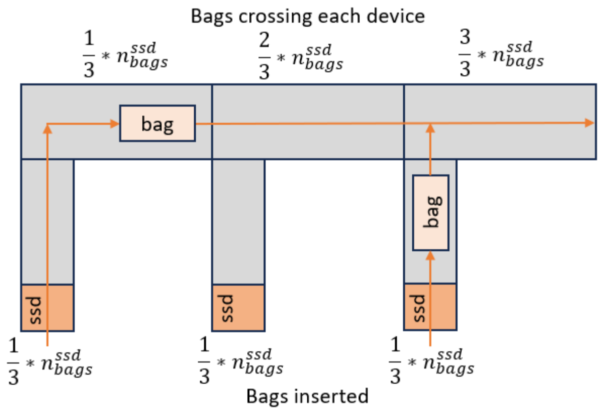


Figure 3.8: Number of bags crossing each collector belt device

Equation 3.21 and Equation 3.22 describe the energy consumption incurred when the bags travel over the conveyor that links the collector belt to the transportation line directed towards the HBS, adhering again to Equation 3.6.

$$E_{1b,3} = P_b \cdot (f^{ssd}_{L,b,n_{ln}} + 2 \cdot f^{ssd}_{Em,b,n_{ln}}) \cdot td_b \cdot n^{ssd}_{bags} \cdot \frac{l_{cb}}{l_b} \tag{3.21}$$

$$E_{1b,4} = P_b \cdot (f^{dod}_{L,b,n_{ln}} + 2 \cdot f^{dod}_{Em,b,n_{ln}}) \cdot td_b \cdot n^{dod}_{bags} \cdot \frac{l_{cb}}{l_b} \tag{3.22}$$

The conveyor formula is tailored to belt conveyors, as indicated by $_b$. Also, Equation 3.21 and Equation 3.22 include the number of devices of the conveyor (n_d in Equation 3.6), calculated by dividing the length of the conveyor l_{cb} by the length of one belt conveyor device l_b. Further, the formulas differentiate between the bags dropped off at the self-service kiosks and the staffed drop-off desks, n^{ssd}_{bags} and n^{dod}_{bags}. To calculate the time factors, $f^{ssd}_{L,b,n_{ln}}$, $f^{dod}_{L,b,n_{ln}}$, $f^{ssd}_{Em,b,n_{ln}}$, and $f^{dod}_{Em,b,n_{ln}}$ the values specific for belt conveyors are used, together with the respective number of bags. This number of bags is divided by the number of lines n_{ln}.

The energy consumption for process 1b can be found by summing over Equation 3.18, Equation 3.19, Equation 3.21, and Equation 3.22, see Equation 3.23.

$$E_{1b} = E_{1b,1} + E_{1b,2} + E_{1b,3} + E_{1b,4} \tag{3.23}$$

3.5.4. Process 2: Transportation from drop-off to screening

Process 2a

The energy consumption of process 2a is dependent on its configuration. When process element A (transportation from drop-off to tray load) is designed in parallel (see Figure 3.2), Equation 3.24 holds. Equation 3.25 holds otherwise. Both formulas are set up following Equation 3.6 for belt conveyors, once again. One of the differences between Equation 3.24 and Equation 3.25 is the length of the main line conveyor each bag has to travel. The total length designed for the conveyor l_{ml} is divided over the number of lines n_{ln} when structured in parallel. Also, the number of bags traversing each conveyor should be accounted for in calculating the time factors.

$$E_{2a,1,sA,1} = P_b \cdot (f_{L,b} + 2 \cdot f_{Em,b}) \cdot td_b \cdot n_{bags} \cdot \frac{l_{ml}}{l_b} \tag{3.24}$$

$$E_{2a,1,pA} = P_b \cdot (f_{L,b,n_{ln}} + 2 \cdot f_{Em,b,n_{ln}}) \cdot td_b \cdot n_{bags} \cdot \frac{l_{ml}}{n_{ln} \cdot l_b} \tag{3.25}$$

In the designs where process element A is structured in series, an equal share of bags should be routed to each tray loader. Its energy consumption is represented by Equation 3.11.

Regardless of the structure, bags must travel over a branch leading to a tray loader. This refers to a segment of the conveyor located immediately before the tray loader. The energy consumption for this part of process 2a can be found following Equation 3.26. It accounts for a belt conveyor, considers the number of tray loaders n_{ln}, and the length of the branches l_{tot}.

$$E_{2a,2} = P_b \cdot (f_{L,b,n_{ln}} + 2 \cdot f_{Em,b,n_{ln}}) \cdot td_b \cdot n_{bags} \cdot \frac{l_{tot}}{l_b} \tag{3.26}$$

In the case the process element A is structured in series, the energy consumption in process 2a can be described as in Equation 3.27.

$$E_{2a,sA} = E_{2a,1,sA,1} + E_{div} + E_{2a,2} \tag{3.27}$$

Alternatively, it is characterised as shown in Equation 3.28.

$$E_{2a,pA} = E_{2a,1,pA} + E_{2a,2} \tag{3.28}$$

Process 2b

Equation 3.29 represents the energy required to move the bags over the belt of the tray loader.

$$E_{2b,1} = P_{load} \cdot f_{L,load,n_{ln}} \cdot td_{load} \cdot n_{bags} \tag{3.29}$$

This resembles the part of Equation 3.6 accounting for the conveyor devices running while loaded. Where applicable, the values specified for the tray loader are applied. In the time factor $f_{L,load,n_{ln}}$, it is considered that each tray loader processes an equal share of bags.

In Equation 3.30, the energy required to run the belt of the tray loader device is determined when its speed changes. Given that the tray loader is positioned between a belt conveyor and an ICS conveyor by definition, the periods for speeding up and slowing down the tray loader belt are related accordingly. In other words, when a bag is on the belt conveyor, the tray loader increases its speed. Whereas the tray loader decreases its speed when the bag is on the subsequent ICS conveyor.

$$E_{2b,2} = P_{load} \cdot f_{Em,load,n_{ln}} \cdot (td_b + td_{ICS}) \cdot n_{bags} \tag{3.30}$$

Equation 3.31 accounts for the energy consumed as the trays traverse the ICS conveyor situated beneath the tray loader.

$$E_{2b,3} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot \frac{l_{ICS}}{v_{load} \cdot 3600} \cdot n_{bags} \cdot \frac{l_{load}}{l_{ICS}} \tag{3.31}$$

The speed of this conveyor is assumed to match that of the tray loader's belt v_{load}, facilitating the pairing of bags with trays.

When adding the energy consumption as described in Equations 3.29, 3.30, and 3.31, the energy consumption for the tray loader process is found, see Equation 3.32.

$$E_{2b} = E_{2b,1} + E_{2b,2} + E_{2b,3} \tag{3.32}$$

Process 2c
The energy consumption associated with the transportation of bags and trays along the branch after being served by the tray loader device is presented in Equation 3.33.

$$E_{2c,1} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ft}}{l_{ICS}} \tag{3.33}$$

The equations labeled as 3.34, 3.35, and 3.36 are remarkably similar to the equations labeled as 3.24, 3.25, and 3.26, respectively. This similarity is primarily because both sets of equations involve a main line and several branches leading to machines. By design, these machines are arranged in parallel. In this particular process of the BHS, the machines are the EDS for HBS L1 and the conveyors are of the ICS type. As a result, the formulas from process 2a are adjusted accordingly.

$$E_{2c,2,sB,1} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ma}}{l_{ICS}} \tag{3.34}$$

$$E_{2c,2,pB} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ma}}{n_{ln} \cdot l_{ICS}} \tag{3.35}$$

$$E_{2c,3} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{toh}}{l_{ICS}} \tag{3.36}$$

To acquire the energy consumption for process 2c with process element B (transportation from the tray loader to EDS) being in series, Equation 3.37 should be followed.

$$E_{2c,sB} = E_{2c,1} + E_{2c,2,sB,1} + E_{div} + E_{2c,3} \tag{3.37}$$

In case of a parallel process element B, the energy consumption can be calculated as in Equation 3.38.

$$E_{2c,pB} = E_{2c,1} + E_{2c,2,pB} + E_{2c,3} \tag{3.38}$$

3.5.5. Process 3: Hold Baggage Screening

Process 3a
Throughout the entire duration of operation t_{op} under consideration, equivalent to the duration of the considered 10-minute or hourly period in hours, each EDS device n_{EDS} is powered at standby power level P_{st}. This is shown in Equation 3.39.

$$E_{3a,1} = P_{st} \cdot t_{op} \cdot n_{EDS} \tag{3.39}$$

A particular example of Equation 3.6 is provided in Equation 3.40 to represent the energy consumption by the EDS devices' transportation component. The power is assumed to increase to P_{sc} only when a bag is in the machine. As a result, the EDS devices can be described as transportation devices that need an increased power supply when performing screening operations.

$$E_{3a,2} = (P_{sc} - P_{st}) \cdot (f_{L,EDS,n_{ln}} + 2 \cdot f_{Em,EDS,n_{ln}}) \cdot td_{EDS} \cdot n_{bags} \tag{3.40}$$

Irrespective of the structure of the BHS, the energy consumption of process 3a is computed as presented in Equation 3.41.

$$E_{3a} = E_{3a,1} + E_{3a,2} \tag{3.41}$$

Process 3c
Only the bags not cleared in the previous screening levels are directed to the HBS L3 screening process, which is illustrated in Equation 3.42.

$$n^{nc}_{bags} = n_{bags} \cdot (1 - rate_{L1}) \cdot (1 - rate_{L2}) \tag{3.42}$$

n^{nc}_{bags} denotes the number of bags that is not cleared before and thus directed to HBS L3. This number is defined to be the total number of bags entering the BHS in the current 10-minute or hourly period n_{bags}, multiplied by the portion of bags not cleared in HBS L1 $(1 - rate_{L1})$, and multiplied by the portion of bags that is not cleared in HBS L2 $(1 - rate_{L2})$.

The process is, by definition, separated from the main conveyor line. As such, all bags heading to HBS L3 are diverted. The energy consumption incurred can be represented as Equation 3.11 with n_{bags} being substituted by n^{nc}_{bags}.

The structure of this process determines the conveyor length that the bags need to pass over in order to move to (l_{tl}) and from (t_{fl}) the area designated for HBS L3. This also includes the corresponding overlap in the usage of these devices. The energy used for transportation in process 3c for serial and parallel structures of process element C (transportation from EDS to sortation), is demonstrated in Equation 3.43 and Equation 3.44, respectively.

$$E_{3c,2,sC} = P_{ICS} \cdot (f_{L,ICS,n_{bags}^{nc}} + 2 \cdot f_{Em,ICS,n_{bags}^{nc}}) \cdot td_{ICS} \cdot n_{bags}^{nc} \cdot \frac{l_{tl} + l_{fl}}{l_{ICS}} \tag{3.43}$$

$$E_{3c,2,pC} = P_{ICS} \cdot (f_{L,ICS,n_{ln},n_{bags}^{nc}} + 2 \cdot f_{Em,ICS,n_{ln},n_{bags}^{nc}}) \cdot td_{ICS} \cdot n_{bags}^{nc} \cdot \frac{l_{tl} + l_{fl}}{n_{ln} \cdot l_{ICS}} \tag{3.44}$$

For a BHS that has a configuration where process element C is in series, Equation 3.45 can be used to calculate the energy consumption for process 3c.

$$E_{3c,sC} = E_{div} + E_{3c,2,sC} \tag{3.45}$$

Otherwise, Equation 3.46 should be used.

$$E_{3c,pC} = E_{div} + E_{3c,2,pC} \tag{3.46}$$

3.5.6. Process 4: Transportation from screening to sortation

Regardless of the configuration, every bag needs to travel over the conveyor that is located right after the EDS fh. This conveyor leads to a main line that takes the bags towards the sortation process. This is represented in Equation 3.47.

$$E_{4,1} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{fh}}{l_{ICS}} \tag{3.47}$$

When process element C (transport from screening to sortation) is in parallel, an ICS conveyor is designed for each process element that links HBS L1 to the sortation area. The energy usage of this conveyor can be calculated using Equation 3.48.

$$E_{4,2,pC} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ts} + l_{tsb}}{n_{ln} \cdot l_{ICS}} \tag{3.48}$$

By adding the above two formulas, the energy consumption for the fourth process with a parallel process element C can be calculated, as presented in Equation 3.49.

$$E_{4,pC} = E_{4,1} + E_{4,2,pC} \tag{3.49}$$

When the configuration has a serial ICS conveyor leading from HBS L1 to the sortation area ts, the conveyor's energy consumption should be calculated as in Equation 3.50.

$$E_{4,2,sC} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ts}}{l_{ICS}} \tag{3.50}$$

When process element C is in series, the energy consumption of process 4 is dependent on the structure of process element D (sortation). The energy consumed by the conveyors located just before the sortation area tsb can be presented as in Equation 3.51 if process element D is designed in series.

$$E_{4,3,sC,sD} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{tsb}}{l_{ICS}} \tag{3.51}$$

In case process element D is in parallel, the bags must travel a branch leading to the sortation area tsb. Before reaching the branch, the bags are diverted. Its energy consumption can be described as in Equation 3.11. Additionally, the energy consumption incurred by travelling the branch is presented in Equation 3.52.

$$E_{4,3,sC,pD} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{tsb}}{n_{ln} \cdot l_{ICS}} \tag{3.52}$$

The calculation for the energy consumption for process 4 with process element C being in series can be found in Equation 3.53 and Equation 3.54. The former considers process element D in a serial structure, whereas the latter considers a parallel structure for process element D.

$$E_{4,sC,sD} = E_{4,1} + E_{4,2,sC} + E_{4,3,sC,sD} \tag{3.53}$$

$$E_{4,sC,pD} = E_{4,1} + E_{4,2,sC} + E_{div} + E_{4,3,sC,pD} \tag{3.54}$$

3.5.7. Process 5: Sortation

Process 5abd

The total energy used for the conveyors of processes 5a $s1$, 5b $s2$, and 5d $s4$ can be calculated for configurations where process element D (sortation) is in series. This can be done by using the formula in Equation 3.6 and substituting the ICS parameters. The formula thus can be represented as in Equation 3.55.

$$E_{5abd,sD} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{s1} + l_{s2} + l_{s4}}{l_{ICS}} \tag{3.55}$$

When process element D is in parallel, each bag and/or tray has to travel over $\frac{1}{n_{ln}}$ of the total length of conveyors dedicated to the sortation process ($l_{s1} + l_{s2} + l_{s4}$). The time factors for overlap of device usage take into account the number of bags and trays transiting through each sortation area $\frac{n_{bags}}{n_{ln}}$. The formula is shown in Equation 3.56.

$$E_{5abd,pD} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{s1} + l_{s2} + l_{s4}}{n_{ln} \cdot l_{ICS}} \tag{3.56}$$

Process 5c

Equation 3.57 represents the energy needed to tilt the discharge conveyor to unload a bag from its tray. This action is performed exactly once per bag.

$$E_{5c,1} = P_{dit} \cdot td_{di} \cdot n_{bags} \tag{3.57}$$

P_{dit} describes the power required to tilt the discharge conveyor. The time it takes for this movement is assumed to be the same as the time a bag spends travelling over a discharge conveyor device td_{di}. Multiplying these two values gives the energy needed to unload one bag. To find the total energy used to discharge all bags in a 10-minute or hourly period, this energy is multiplied by the total number of bags n_{bags}.

Equation 3.58 and Equation 3.59 resemble Equation 3.6 with the variables filled in for the discharge process. They represent configurations with process element D (sortation) being in series and in parallel, respectively.

$$E_{5c,2,sD} = P_{dic} \cdot (f_{L,di} + 2 \cdot f_{Em,di}) \cdot td_{di} \cdot n_{bags} \cdot n_{ch} \tag{3.58}$$

$$E_{5c,2,pD} = P_{dic} \cdot (f_{L,di,n_{ln}} + 2 \cdot f_{Em,di,n_{ln}}) \cdot td_{di} \cdot n_{bags} \cdot \frac{n_{ch}}{n_{ln}} \tag{3.59}$$

The energy consumption for process 5c with a serial sortation area can be described as Equation 3.60.

$$E_{5c,sD} = E_{5c,1} + E_{5c,2,sD} \tag{3.60}$$

Equation 3.61 presents the energy consumption for process 5c with a parallel sortation area.

$$E_{5c,pD} = E_{5c,1} + E_{5c,2,pD} \tag{3.61}$$

3.5.8. Process 6: Early Baggage Storage

All bags that need to be stored in the EBS have to be directed from the sortation area to this process. The energy consumption resulting from the usage of the plough diverter is outlined in Equation 3.11, with n_{bags} being equal to the number of bags entering the EBS n_{bags}^{EBS}, as calculated in Equation 3.62.

$$n_{bags}^{EBS} = n_{bags} \cdot rate_{EBS} \tag{3.62}$$

Where n_{bags} is the total number of bags entering the BHS in the considered 10-minute or hourly period, and $rate_{EBS}$ is the rate of bags entering the EBS.

Within the EBS, a crane is utilised to facilitate the transportation of each bag and its corresponding tray to an available storage position. The crane is equipped with three distinct drives. Each of these drives contributes to the overall operation of the crane and, consequently, to the energy consumption of the BHS. The energy consumption of these drives is determined by applying the generic energy formula (Equation 3.1). The movement of the bag, and thus the crane, involves two distinct stages. The first stage is the delivery of the bag to the storage point, and the second stage is the return of the bag from the storage point. Therefore, the energy consumption is effectively twice the amount calculated for a single stage. To determine the energy consumed during this two-stage process, one can refer to Equation 3.63.

$$E_{6,2} = n_{bags}^{EBS} \cdot 2 \cdot (P_{li} \cdot \frac{t_{li}}{3600} + P_{me} \cdot \frac{t_{me}}{3600} + P_{re} \cdot \frac{t_{re}}{3600}) \tag{3.63}$$

In this formula, the multiplication of P_{li} and t_{li} represents the energy consumed for the vertical movement of the crane. Similarly, the product of P_{me} and t_{me} corresponds to the energy consumed for the horizontal movement of the crane. The product of P_{re} and t_{re} presents the energy consumed for releasing a tray from the crane.

The transportation within the EBS process consists of two steps. The first step involves the transportation of the bag and tray to the location where it is picked up by the crane te. The second step involves retrieving the bag and tray from the point where it is released from the crane fe. The energy consumption for transportation within the EBS process for a serial process element D (sortation) can be found using Equation 3.64.

$$E_{6,3,sD} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags}^{EBS} \cdot \frac{l_{te} + l_{fe}}{l_{ICS}} \tag{3.64}$$

Similarly, the energy consumption for transportation within the EBS process for a parallel process element D can be calculated using Equation 3.65.

$$E_{6,3,pD} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags}^{EBS} \cdot \frac{l_{te} + l_{fe}}{n_{ln} \cdot l_{ICS}} \tag{3.65}$$

Equation 3.66 represents the energy consumption for the EBS process for configurations with a serial sortation area.

$$E_{6,sD} = E_{div} + E_{6,2} + E_{6,3,sD} \tag{3.66}$$

Equation 3.67 represents the energy consumption for the EBS process for configurations with parallel sortation areas.

$$E_{6,pD} = E_{div} + E_{6,2} + E_{6,3,pD} \tag{3.67}$$

3.5.9. Process 7: Return of trays

The process of returning trays from the end of the sortation process back to the tray loaders consists of three distinct parts. The first part involves the transportation of trays over a series of conveyor devices immediately after they leave the sortation process rb. This series of conveyor devices can be referred to as a branch that links the sortation process to the main conveyor for tray return. The formula used in this process depends on the structure of both process elements D (sortation) and E (return of trays). If both process elements are in series, Equation 3.68 should be used to calculate the energy consumption for transportation over the first set of conveyor devices.

$$E_{7,1,1,sD,sE} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{rb}}{l_{ICS}} \tag{3.68}$$

Otherwise, Equation 3.69 should be used.

$$E_{7,1,1} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{rb}}{n_{ln} \cdot l_{ICS}} \tag{3.69}$$

In the case that process element D is in series and process element E is in parallel, multiple branches start at the end of a single sortation process. This means that the bags are diverted towards one of the branches. Then, for the energy consumption of diverting the bags, Equation 3.11 holds.

The second part of the process of returning trays is the transportation on the main part of the return conveyor ret. The length of this main segment l_{ret}, as well as the time factors, are defined based on the structure of process element E (return of trays). When this process element is in parallel, the energy consumption for the second part of the process can be calculated with Equation 3.70.

$$E_{7,2,pE} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ret}}{n_{ln} \cdot l_{ICS}} \tag{3.70}$$

If process element E is in series, the energy consumption for the second part of the process can be calculated following Equation 3.71.

$$E_{7,2,sE} = P_{ICS} \cdot (f_{L,ICS} + 2 \cdot f_{Em,ICS}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{ret}}{l_{ICS}} \tag{3.71}$$

Thirdly, all bags traverse the branch leading to the tray loaders rs. The energy consumption incurred in this part is shown in Equation 3.72.

$$E_{7,3} = P_{ICS} \cdot (f_{L,ICS,n_{ln}} + 2 \cdot f_{Em,ICS,n_{ln}}) \cdot td_{ICS} \cdot n_{bags} \cdot \frac{l_{rs}}{l_{ICS}} \tag{3.72}$$

When process element E is in series, diverters are positioned just before the start of the branches that lead to the tray loaders. These diverters ensure that an equal share of trays reaches each tray loader. The formula representing the additional energy consumption in the third part is similar to Equation 3.11.

The total energy consumption associated with the process of returning trays to the tray loader varies based on the structure of process elements D (sortation) and E (return of trays). The formula for the energy consumption if both are in series is Equation 3.73.

$$E_{7,sD,sE} = E_{7,1,1,sD,sE} + E_{7,2,sE} + E_{7,3} + E_{div} \tag{3.73}$$

Equation 3.74 applies to configurations with a serial process element D and a parallel process element E.

$$E_{7,sD,pE} = E_{7,1,1} + E_{div} + E_{7,2,pE} + E_{7,3} \tag{3.74}$$

In complete opposite configurations, where process element D is in parallel and process element E is in series, Equation 3.75 holds.

$$E_{7,pD,sE} = E_{7,1,1} + E_{7,2,sE} + E_{7,3} + E_{div} \tag{3.75}$$

When both process elements D and E are in parallel, Equation 3.76 applies.

$$E_{7,pD,pE} = E_{7,1,1} + E_{7,2,pE} + E_{7,3} \tag{3.76}$$

3.6. Parameter calibration

The formulas in the model include several parameters. Some examples are the length of belt conveyors and the power used in HBS L1 screening. In Table 3.3, a detailed overview of all parameters with their values, units, and sources can be found. These values are chosen by combining relevant literature, data on the BHS at Airport X, internal company documents, and expert consultations. The model is designed to be general, so one still has the flexibility to change the values. In the table, it is also presented which process(es) the parameters belong to, following the BHS representation as in Figure 3.1.

Most of the model parameters are straightforward in their meaning. However, some need an explanation. To start with, all time indications (e.g., t_{ssd}, t_{dod}, and t_{dis}) and rates (i.e., $rate_{L1}$, $rate_{L2}$, and $rate_{EBS}$) are average values. The model is set up deterministically, so a single value is required to represent the time durations and rates. Further, one should take in mind that a conveyor device's power requirement depends on the device's length, speed, and the drive's efficiency. Thus, the power required to move a bag is higher if the conveyor device either is longer or has a higher speed.

The parameters identified in Table 3.4 are required as input for the model. It is not reasonable to make assumptions about the values of these parameters since their values differ from BHS to BHS. Still, for validation and verification (V&V), values are needed for applying the model. When evaluating BHS configurations, it is important to use the input parameters that match the considered BHS. In this case, the parameters associated with the BHS of Airport X should ideally be used to validate the model. However, not all parameters are available. The missing parameters can be assumed to align with those of a comparable BHS. It is indicated by a NACO expert that a midsize airport in India, referred to as Airport Y, has many similarities to the BHS of Airport X. The unknown parameters for the BHS of Airport X are assumed to be similar to those of the BHS of Airport Y.

The cumulative length of conveyors is available from the data on Airport X. This appeared to be 1058 meters. With the values from Table 3.4, the total length of the conveyors in the BHS is 1015 meters. As this difference is only 43 meters over the whole system, it is assumed justified.

To slightly simplify the model, it is assumed that the drop-off islands in each design are similar. As a consequence, each island includes three self-service drop-off points. With three islands being present, this means that there are 9 self-service drop-off points instead of 8, as is the case at Airport X.

3.6.1. Bag arrivals

To find values for the input of arrivals, data collected from the BHS of Airport X is examined. To be precise, the analysed data is recorded in 10-minute periods from midnight on June 4, 2023, to midnight on July 11, 2023. This dataset thus covers 37 full days, resulting in a sample of 5328 values. The average number of bags entering the BHS during each 10-minute period is depicted in Figure 3.9.

The figure reveals four main peaks of bag arrivals throughout the day. The highest peak, characterised by the insertion of approximately 110 bags into the BHS in 10 minutes time, occurred around 4.00 P.M. Following this, the evening time is characterised by two, albeit less high, peaks. This pattern of bag arrivals provides important insights into how the system operates. Specifically, it can be noted that minimal bag arrivals take place before 4.00 A.M. and after 10.40 P.M. The positive input values during these hours are considered outliers, and the system is assumed to be operational only between these hours.

3.7. Model verification

A verified model means that it is internally consistent. In other words, the implication of the model, being the automated calculations in Python, should give the same results as when one would do the calculations by hand.

Parameter	Explanation	Process(es)	Value	Unit	Source
w_{raw}	Raw baggage window	1, 2a	1	m	NACO (experts)
P_{ssd}	Power self-service bag drop	1a	0.65	kW	NACO (documents)
t_{ssd}	Processing time self-service bag drop	1a	60	s	NACO (experts)
P_{dod}	Power drop-off desk	1a	0.18	kW	NACO (documents)
t_{dod}	Processing time drop-off desk	1a	120	s	NACO (experts), Araujo and Repolho (2015)
P_{dob}	Power drop-off belt	1a	0.37	kW	NACO (documents)
v_{dob}	Speed drop-off belt	1a	0.45	m/s	NACO (documents)
l_{dob}	Length drop-off belt	1a	1.2	m	NACO (documents)
l_b	Belt conveyor device length	1b, 2a	2.2	m	NACO (data Airport X)
P_b	Power belt conveyor	1b, 2a	1.1	kW	NACO (documents)
v_b	Belt speed	1b, 2a	0.5	m/s	NACO (documents)
P_{dis}	Power plough diverter - switch	2ac, 3b, 4, 6, 7	2.2	kW	NACO (documents)
P_{dib}	Power plough diverter - belt	2ac, 3b, 4, 6, 7	0.75	kW	NACO (documents)
t_{dis}	Time for diverting - switch	2ac, 3b, 4, 6, 7	1	s	NACO (documents)
t_{dib}	Time for diverting - belt	2ac, 3b, 4, 6, 7	2	s	NACO (documents)
w_{tray}	Tray window	2bc, 3, 4, 5, 6, 7	1.5	m	NACO (experts)
l_{ICS}	ICS conveyor device length	2bc, 3b, 4, 5abd, 6, 7	2.2	m	NACO (data Airport X)
P_{ICS}	Power ICS conveyor	2bc, 3b, 4, 5abd, 6, 7	0.75	kW	NACO (documents)
v_{ICS}	ICS speed	2bc, 3b, 4, 5abd, 6, 7	2	m/s	NACO (documents)
P_{load}	Power tray loader	2b	1.1	kW	NACO (documents)
v_{load}	Speed tray loader	2b	0.5	m/s	NACO (documents)
l_{load}	Length tray loader	2b	3.258	m	NACO (data Airport X)
P_{sc}	Power EDS - screening	3a	2.2	kW	NACO (documents)
P_{st}	Power EDS - standby	3a	0.7	kW	NACO (documents)
l_{EDS}	Length of belt conveyor - through EDS	3a	5	m	NACO (data Airport X)
v_{EDS}	Speed of belt conveyor - through EDS	3a	0.5	m/s	NACO (documents)
$rate_{L1}$	Clearance rate HBS L1	3a	0.7	-	NACO (documents), AlKheder et al. (2020), Van Noort (2018)
$rate_{L2}$	Clearance rate HBS L2	3b	0.84	-	NACO (documents), AlKheder et al. (2020)
P_{dic}	Power discharge device - conveyor	5c	0.75	kW	NACO (documents)
P_{dit}	Power discharge device - tipper	5c	1.75	kW	NACO (documents)
l_{di}	Length discharge device	5c	2.35	m	NACO (data Airport X)
v_{di}	Conveying speed discharge device	5c	1.2	m/s	NACO (documents)
$rate_{EBS}$	Rate of bags entering EBS	6	0.2	-	NACO (experts)
P_{li}	Power crane - lift	6	4.4	kW	NACO (documents)
t_{li}	Time for lifting - crane	6	2	s	NACO (documents)
P_{me}	Power crane - metering	6	0.55	kW	NACO (documents)
t_{me}	Time for metering - crane	6	2	s	NACO (documents)
P_{re}	Power crane - release	6	0.37	kW	NACO (documents)
t_{re}	Time for releasing - crane	6	2	s	NACO (documents)

Table 3.3: Model parameters

Therefore, the energy consumption is calculated manually for a single hourly period for a specific configuration. In these manual calculations, the equations as presented in section 3.5 are filled in for one case. In this way, a small sample is tested for correctness. The selected instance was the seventh hour (7 A.M. - 7.59 A.M.), as the number of bags arriving in this period (341.1622) is closest to the average hourly bag input (324.0754). This made it a representative period. The first scenario is chosen since it is the scenario that involves most formulas, allowing for the verification of the maximum number of terms simultaneously. The verification is performed at the process level. This allows for a more precise indication of output correctness than when only computed at the system level.

The manually calculated energy consumption per process, as well as the results from the model implementation, are presented in Table 3.5. Minor differences between the two are observed, which can likely be ascribed to the rounding of values during the manual computation. The differences are at most 0.1482%, which is not considered so high that the assumption of correctness of the implementation should be rejected. Consequently, it is concluded that the model is internally consistent.

3.8. Model validation

In accordance with the principles outlined by Sargent (2013), validation is an essential step in the modelling process. A validated model means that it provides an accurate representation of the real-world case it is intended to mirror. Since the model is based on the BHS of Airport X, the parameters as presented in Table 3.3 and Table 3.4 are

Parameter	Explanation	Process	Value for V&V	Unit	Source airport
n_{ssd}	Number of self-service drop-off kiosks	1a	9	-	X
n_{dod}	Number of drop-off desks	1a	24	-	X
l_{do}	Length of drop-off belt	1a	2.4	m	Y
l_{cb}	Length of collector belt - branch	1b	10	m	Y
l_{ml}	Length of belt conveyor - main line to tray loader	2a	100	m	Y
l_{tot}	Length of belt conveyor - branch main line to tray loader	2a	20	m	Y
n_{load}	Number of tray loaders	2b	3	-	X
l_{ft}	Length of ICS track - branch from tray loader to main line	2c	20	m	Y
l_{ma}	Length of ICS track - main line to HBS	2c	20	m	Y
l_{toh}	Length of ICS track - branch to HBS	2c	5	m	Y
n_{EDS}	Number of EDS devices	3a	3	-	X
l_{tl}	Length of ICS track - main line to HBS L3	3b	50	m	Y
l_{fl}	Length of ICS track - HBS L3 to main line	3b	50	m	Y
l_{fh}	Length of ICS track - branch from HBS	4	5	m	Y
l_{ts}	Length of ICS track - main line to sortation	4	90	m	Y
l_{tsb}	Length of ICS track - branch to sortation	4	30	m	Y
l_{s1}	Length of ICS track - start sortation to EBS	5a	40	m	Y
l_{s2}	Length of ICS track - EBS to start chutes	5b	40	m	Y
n_{ch}	Number of chutes	5c	42	-	X
l_{s4}	Length of ICS track - final part sortation	5d	10	m	Y
l_{te}	Length of ICS track - to EBS	6	20	m	Y
l_{fe}	Length of ICS track - from EBS	6	20	m	Y
l_{rb}	Length of ICS track - branch return trays	7	15	m	Y
l_{ret}	Length of ICS track - return trays	7	20	m	Y
l_{rs}	Length of ICS track - branch return trays to start	7	5	m	Y

Table 3.4: Input parameters

used as model inputs, such that model results can be compared with actual data. In this way, the existing BHS of Airport X is represented by the model.

3.8.1. Face validity

Sargent (2013) has highlighted face validity as a robust technique for model validation. This method involves asking for feedback from experts in the field on the logical accuracy of the model, as well as the reasonableness of the assumptions, parameters, and the relationships set up between the inputs and outputs. Together with domain experts from NACO, the main design decisions are identified. In this research, the focus is on the structure of process elements, which was crucial in building the model. The assumptions and parameters that were found for the model are shown to the experts from NACO for their review. The experts declared these assumptions and parameters reasonable and reflective of the real-world situation the model was designed to portray. As can be seen in Table 3.3, the experts have filled in the gaps in the model's parameters, improving its accuracy and reliability. Also, the experts have confirmed the logic of using predetermined parameters as inputs to the model and having the system-level energy use as the output. The model could thus be validated in terms of face validity.

3.8.2. Historical data validation

Another type of validation Sargent (2013) proposed is historical data validation. When the historical data aligns with the outcomes found with the model, the model could be considered to represent reality. The energy consumption estimated by the model can be compared to the actual energy consumption measured in the existing BHS of the same airport. The estimations from the model can be considered reliable, as the model is verified in the previous section.

The energy consumption data from Airport X indicates an average energy consumption of 0.40 kWh per bag over the same set of days. However, due to the lack of information about the configuration at Airport X, it remains unclear which scenario's results should be used for comparison. Therefore, the model could only be partially validated. The model developed in this study yields an average energy consumption per bag ranging from 0.2066 to 0.4017 kWh, calculated as the total energy consumption over the day divided by the number of bags in the day. This outcome seemed plausible, given that it has the same order of magnitude as the real energy consumption per bag. This research does not account for all devices present in the BHS, such as fire shutters, tray stackers, and bag identification cameras. This could explain why the model's estimated value could be somewhat lower than the actual value.

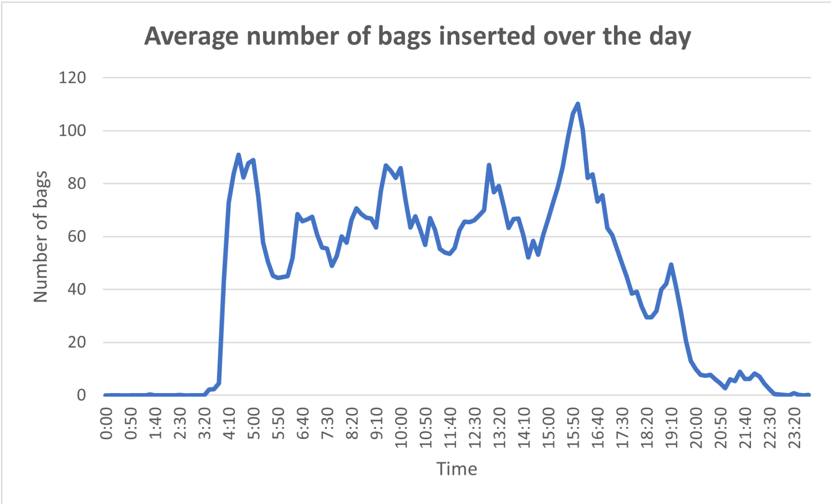


Figure 3.9: Average number of bags inserted over the day

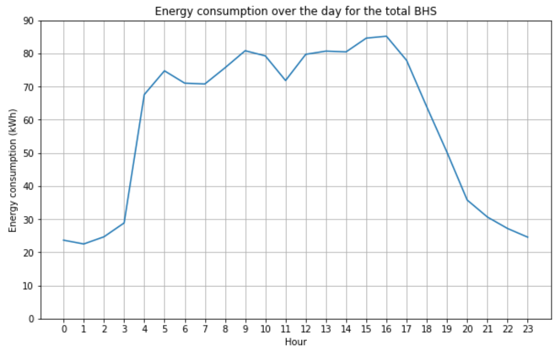
Process	Manual computation [kWh]	Model implementation [kWh]	Difference
1a	3.3147	3.3147	-0.0355%
1b	10.9724	10.9724	0.0002%
2a	67.7025	67.7081	0.0082%
2b	2.6420	2.6420	-0.0008%
2c	5.0250	5.0314	0.1264%
3a	3.8342	3.8342	0.0011%
3c	0.5282	0.5286	0.0708%
4	13.3267	13.3266	-0.0004%
5abd	9.5952	9.5952	-0.0001%
5c	17.8627	17.8626	-0.0003%
6	1.3244	1.3264	0.1482%
7	4.4919	4.4983	0.1422%

Table 3.5: Manual verification

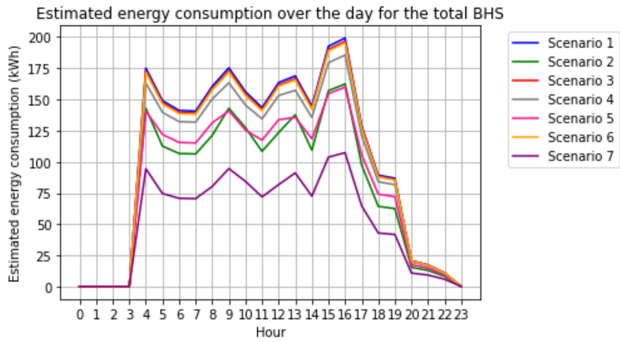
Furthermore, the graph of the actual energy consumption of the BHS of Airport X over the day can be compared to the graph of the estimated energy consumption of the same airport. Those can be found in Figure 3.10. Figure 3.10a and Figure 3.10c illustrate the actual energy consumption over the day, whereas Figure 3.10b and Figure 3.10d represent the estimated energy consumption for several possible BHS configurations for Airport X, referred to as scenarios. The values in Figure 3.10a and Figure 3.10b are based on the same bag insertion values, which are the averages per hour. Both sub-figures show a similar trend in energy consumption. Namely, they both have peaks in energy consumption around hours 4, 9, and 16, and a higher-than-average energy consumption around hours 12 and 13. Also, they both have relatively low energy consumption at the beginning and end of the day. However, the estimated energy consumption presents more pronounced peaks compared to the actual energy consumption. This difference can be partly explained by the type of the estimated values. The historical data values were recorded whenever the threshold of 10 kWh was reached. For the figure, these values were spread evenly over the interval between reaching the current threshold and reaching the previous threshold. The recorded energy consumption values thus show a close representation of the energy used by the BHS of Airport X at a specific moment, whereas the model values show the energy used for each bag that enters the system in a certain 10-minute or hourly period. To give an example, all energy estimated to be consumed to process a bag that arrived at 10 A.M. is added to the value of the estimated energy consumption at 10 A.M. in Figure 3.10b. In Figure 3.10a, the energy consumed by a bag entering at 10 A.M. is spread over the time span that the bag is in the BHS.

Similar observations are found for the calculations based on 10-minute periods, which are presented in Figure 3.10c and Figure 3.10d.

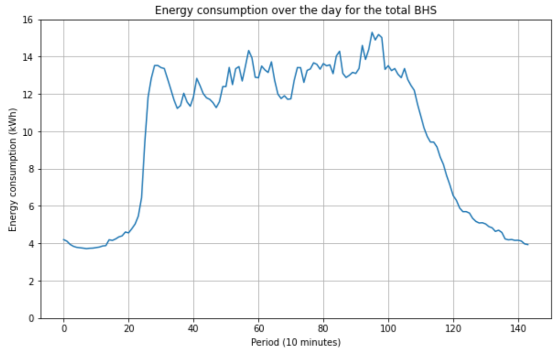
As it is not known what the configuration of the BHS in Aiport X looks like, there is not one line in Figure 3.10b and Figure 3.10d to which the lines of Figure 3.10a and Figure 3.10c can be compared. Still, the results from the model can be considered plausible, as the real values are within the range of the estimated values. The peaks in



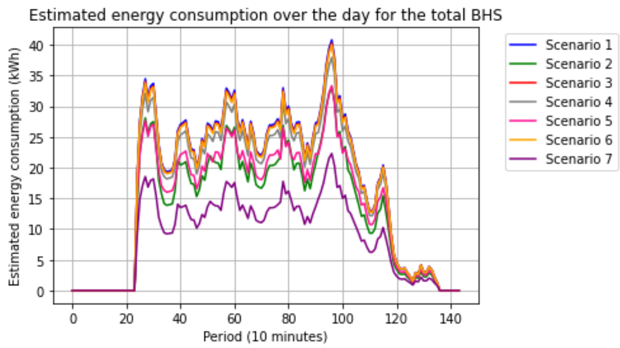
(a) Energy consumption over the day (hourly period)



(b) Estimated energy consumption over the day (hourly period)



(c) Energy consumption over the day (10-minute period)



(d) Estimated energy consumption over the day (10-minute period)

Figure 3.10: Estimated energy consumption per process over the day

energy consumption in Figure 3.10a are between 70 and 85 kWh, whereas the peaks in Figure 3.10b are between 75 and 200 kWh. When recalling that the bags arriving before 4.00 A.M. and after 10.40 P.M. are assumed to be spread over the day in the estimation, it is even more persuasive that the model can represent the energy consumption of the very case of the BHS of Airport X. Namely, the energy consumption that is actually incurred outside the operational hours assumed in the model, are evenly spread over the day in the results of the model. This could explain the higher values of the estimated energy consumption peaks compared to the actual energy consumption peaks. The same holds when comparing Figure 3.10c and Figure 3.10d.

To conclude, as far as the available data allows, the model can be validated in terms of historical data validation, as well.

3.9. Conclusion

As this chapter presented a model for estimating energy consumption in BHS, the fourth sub-question, *How can the energy consumption of the energy-consuming devices within a baggage handling system be quantified regarding different configurations?*, can be answered. In this project, the BHS of a midsize airport in Scandinavia (Airport X) is used as a basis for the model, such that the technologies in the model are similar to those in Airport X. The MoSCoW analysis showed that an equation-based model could be created to fulfil the modelling requirements. For each process, a set of formulas is set up to describe its energy consumption. The formulas depend on the structure of the process elements, such that the formulas can be customised for different BHS configurations. The model is proved to be internally consistent and to represent reality.

4 Results

Several configurations are analysed to gain insight into the relationship between BHS configurations and their estimated energy consumption. The result leads to answering the fifth sub-question: ***How does the energy consumption vary across different configurations of baggage handling systems?*** Firstly, several configuration scenarios are set up and a hypothesis is given on the expected outcomes. Thereafter, the results are shown, which are acquired using the model presented in chapter 3. The results are interpreted using a sensitivity analysis.

4.1. Configuration scenarios

When designing a BHS, two critical factors should be considered according to NACO experts: capacity and structure. Capacity refers to the system's ability to process all bags within a certain time frame to prevent bottlenecks and maintain efficiency. Since it is assumed in this research that all configurations meet the capacity requirements, the BHS structure is varied throughout several scenarios.

BHS experts do not have control over the design of the drop-off process. They receive a pre-determined configuration for this process, which they use as a starting point to design the rest of the system.

To ensure a fair comparison between the scenarios, the number of devices of each type stays the same. To give an example, consider a case with 50 devices available for transportation from drop-off to tray load. When this transportation is designed in series, all 50 devices are placed in 1 line. Alternatively, when there are 5 parallel lines designed, each of those 5 lines consists of 10 devices in series. When process elements are structured in parallel, the number of lines matches the number of tray loaders and EDS devices. This complies with the BHS of Airport X, where these devices are present in triplicate. As a result, the drop-off configuration consists of three 'islands', each with two collector belts and an equal number of staffed drop-off desks and self-service kiosks.

Seven scenarios are analysed, which are presented in Table 4.1. For each scenario, a unique set of formulas is used to calculate the energy consumption of the configuration it represents, as presented in section 3.5. The scenarios are detailed further in the following sections. Figure 4.1 provides a visual representation of the differences between serial and parallel process elements.

Scenario	Process element				
	Drop-off to tray load (A)	Tray load to EDS (B)	EDS to sortation (C)	Sortation (D)	Return of trays (E)
1	In series	In series	In series	In series	In series
2	In parallel	In series	In series	In series	In series
3	In series	In parallel	In series	In series	In series
4	In series	In series	In parallel	In series	In series
5	In series	In series	In series	In parallel	In series
6	In series	In series	In series	In series	In parallel
7	In parallel	In parallel	In parallel	In parallel	In parallel

Table 4.1: Scenarios

4.1.1. Scenario 1: All process elements in series

The first scenario is the BHS with most process elements in series, where bags follow a single line as much as possible. The only elements structured in parallel are the tray loaders and HBS L1 (processes 2b and 3a in Figure 3.1). This scenario serves as a benchmark for the comparison of the scenarios. A representation of scenario 1 is given in Figure 3.2.

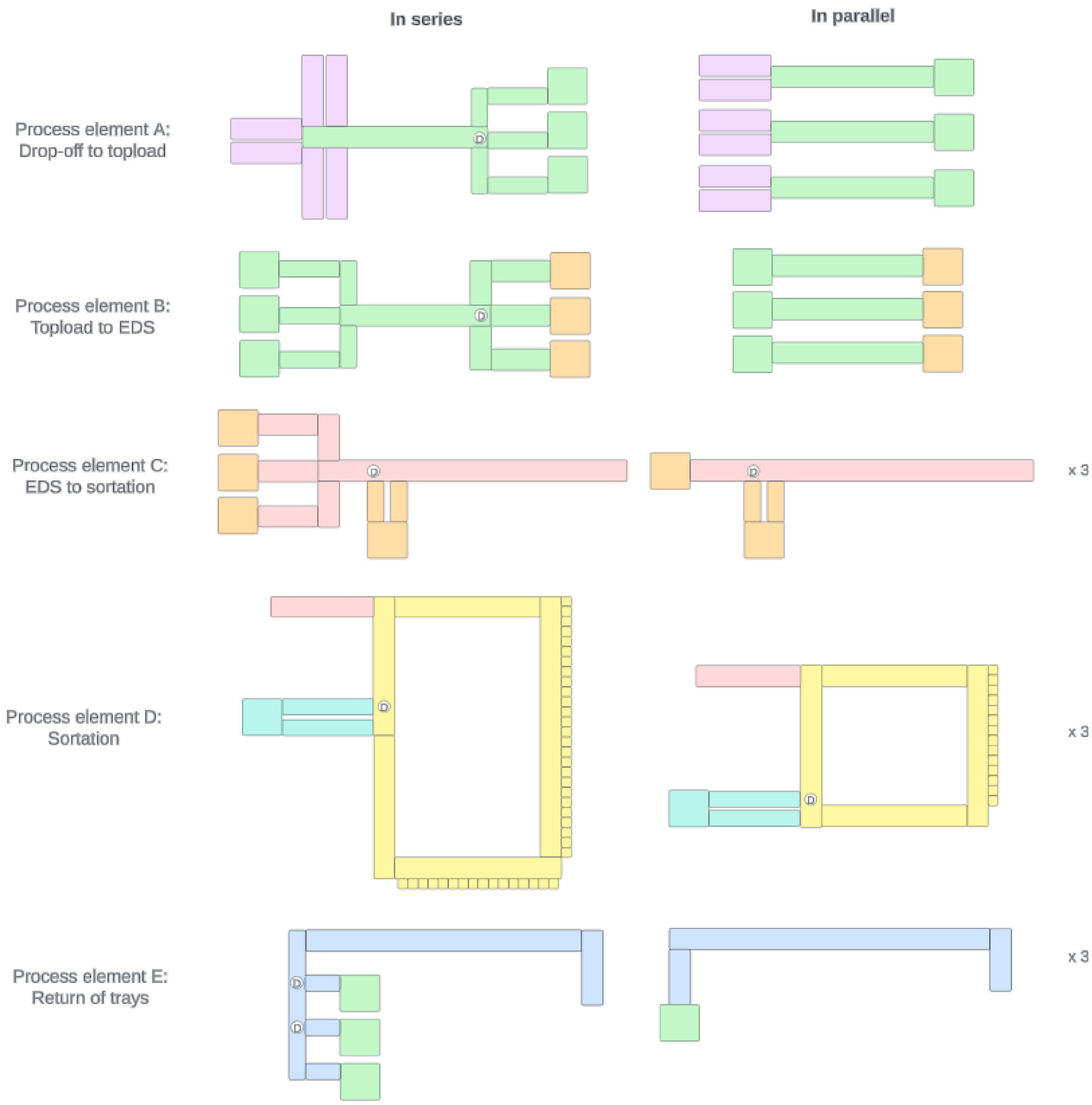


Figure 4.1: Process elements in series or in parallel

4.1.2. Scenarios 2 - 6: One process element in parallel

In scenarios 2 through 6, each process element is structured in parallel in one of the scenarios, but only one at a time. Since the processes are mostly independent, the effects of a serial or parallel structure can be assessed. The process elements for which the structure is varied include the conveyor between the drop-off conveyor and the tray loader, the conveyor between the tray loader and HBS L1, the conveyor between HBS L1 and the sortation process (including HBS L3), the sortation process, and the conveyor for returning trays.

4.1.3. Scenario 7: All process elements in parallel

The five process elements can be either in series or in parallel, leading to a total of 32 possible scenarios. By analysing scenarios 1 through 6, the difference in energy consumption between having a process element in series versus in parallel can be assessed. With this information, the BHS energy consumption for any other possible scenario can be calculated. Therefore, not all 32 possible scenarios are included in the analysis. However, to identify the range of energy consumption estimations for a BHS, scenario 7 is included in the analysis. In scenario 7, all considered process elements are in parallel. So, it is the other extreme configuration compared to scenario 1. This scenario is illustrated in Figure 4.2.

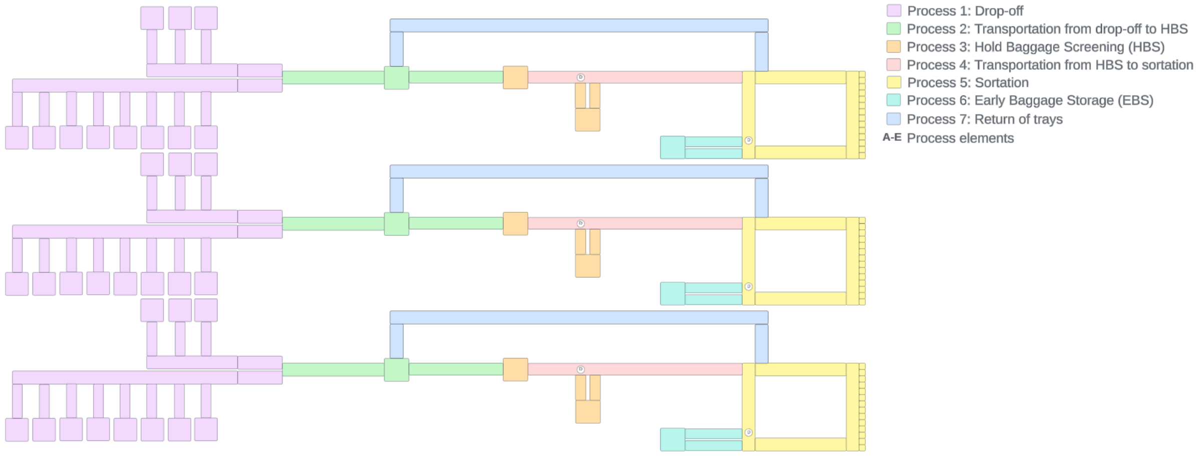


Figure 4.2: Scenario 7: All process elements in parallel

4.1.4. Hypothesis

The differences in energy consumption across the configurations are expected to be partly explained by the length of conveyors each bag needs to travel. Even though the total conveyor length is the same in all configurations, the actual distance a bag and its tray travel depends on the structure of the BHS. More process elements in parallel means shorter travel distances for bags, which in turn reduces the energy used by the conveyors. The input values used in the experiments, as presented in Table 3.4, allow for the computation of the average conveyor length per bag, as shown in Table 4.2. From this, it is expected that scenario 7 results in the least energy consumption because it requires the lowest length to process a bag. Similarly, scenarios 1, 3, and 6 are likely to cause the highest energy consumption because they require the longest travel distances per bag and thus most devices to operate.

Scenario	Conveyor length [m]
1	558.84
2	492.18
3	545.51
4	475.64
5	397.71
6	535.51
7	241.18

Table 4.2: Average conveyor length crossed per bag per scenario

The amount of overlap in conveyor usage changes based on the interdistance between the bags. This can happen in two ways: multiple bags using the same device at the same time, or sharing a device's time for acceleration and deceleration. So, if differences in energy consumption would only originate from the overlap of device usage, it is expected that the configuration of scenario 1, which has the most process elements in series, causes the least energy consumption. Meanwhile, scenario 7, which has the most process elements in parallel, likely uses the most energy.

Two main factors can help to estimate energy usage across different scenarios: the number of devices moving bags and trays, and the amount of overlap of conveyor usage. However, these factors contradict each other, making it hard to determine their exact impact on the total energy consumption.

4.2. Sensitivity analysis

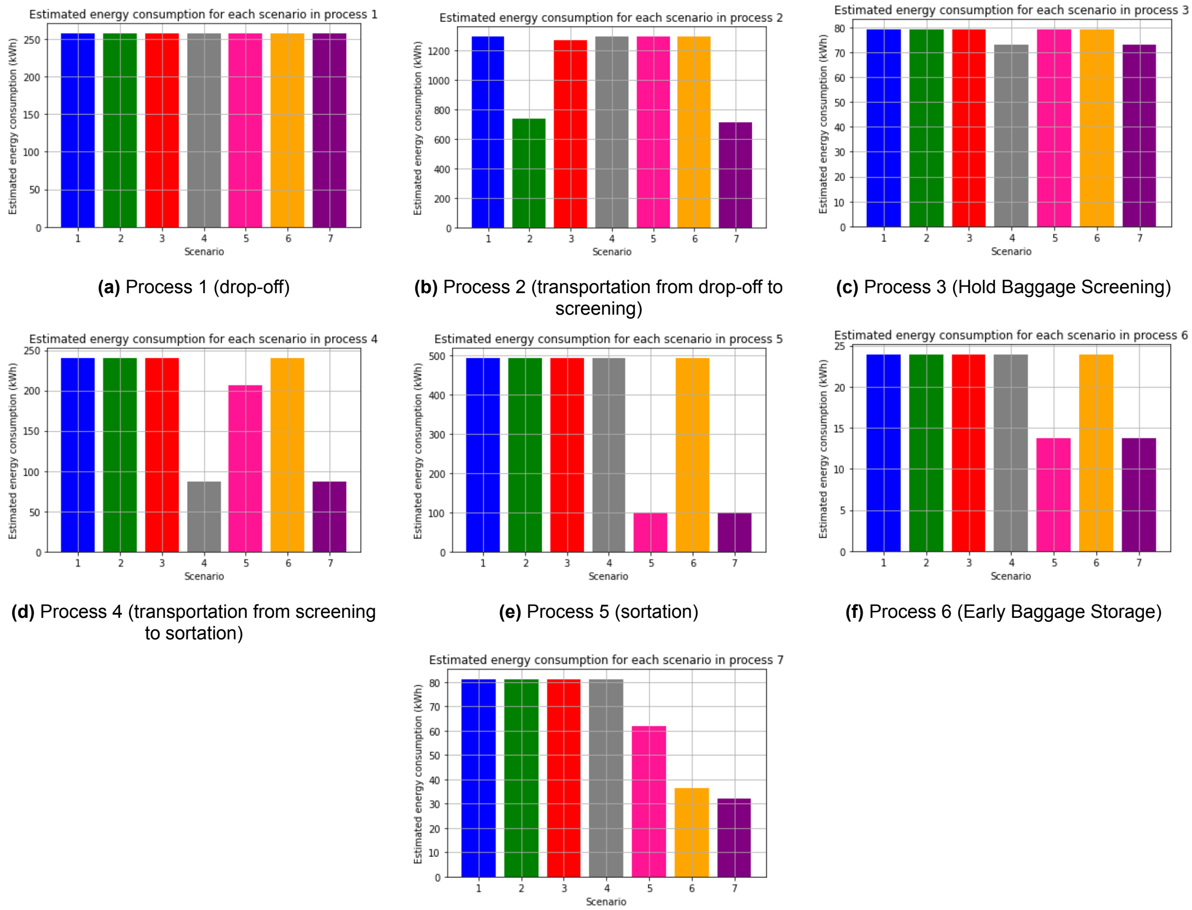
Sensitivity analysis can be defined as a thorough investigation of the differences in energy consumption for various design configurations. The emphasis is on examining the results that arise from the structure of process elements. Sensitivity analysis allows to trace variations in output back to changes in input factors (Pianosi et al., 2016; Razavi et al., 2021). A common practice in such analyses is to set a reference point for comparison with all alternative cases. For this research, multiple scenarios for BHS configurations are developed. The first scenario serves as the reference point. The other scenarios are subject to a modification to a single process element at a time. This method enables the identification of the impact of each individual element on the output, given that it is the only process element that differs from the reference case. The parameters are consciously kept the same when comparing different configurations.

The sensitivity analysis carried out in this research is both quantitative and qualitative, as it entails a visual examination of the estimates provided by the model. Pianosi et al. (2016) identified three potential goals of sensitivity analysis. The goal that aligns best with this research is factor prioritisation (or ranking), which involves ordering the scenarios according to their relative impact on output variability. However, it is crucial to note that the goal of this study is not essentially to rank the outcomes. Instead, the relations between BHS configurations and their estimated energy consumption are identified.

In the remainder of this chapter, process numbers, process elements, and scenario numbers are frequently referred to. The process numbers are outlined in Figure 3.1, the process elements are illustrated in Figure 4.1, and the scenario numbers are depicted in Table 4.1.

4.2.1. Estimated energy consumption per process

To gain an understanding of the overall impact of the different configurations, the processes of the BHS are considered. The energy consumption of each process is influenced by at most two process elements, which allows for a systematic identification of the effects of different configurations. Figure 4.3 presents a bar chart for each process, illustrating the total daily energy consumption for each scenario. One should be aware that the scale of the y-axis varies across the figures.



(a) Process 1 (drop-off)

(b) Process 2 (transportation from drop-off to screening)

(c) Process 3 (Hold Baggage Screening)

(d) Process 4 (transportation from screening to sortation)

(e) Process 5 (sortation)

(f) Process 6 (Early Baggage Storage)

(g) Process 7 (return of trays)

Figure 4.3: Estimated energy consumption per process over the day (based on 10-minute periods)

The drop-off process, as shown in Figure 4.3a, resulted in identical energy consumption for all scenarios. This outcome was expected, given that the configuration of this process is predetermined before the design of the remaining system processes.

Figure 4.3b displays the energy consumption for each scenario in the second process (transportation from drop-off to screening). In scenarios 2 and 7, process element A (transportation from drop-off to tray load) is in parallel, leading to almost halving the energy consumption for these scenarios. For a great deal, this could be explained by the reduced distance each bag needs to travel. Namely, the distance the bags have to travel with scenario 2 in process 2 decreased by 38.87% compared to scenario 1. Furthermore, in the configurations of scenarios 3 and 7, process element B (transportation from tray load to screening) is in parallel. This appears to result in only a relatively minor reduction in energy consumption, although a 7.78% reduction was expected from the decrease in conveyor length. Hence, transportation length does not seem the only predictor for energy consumption throughout the scenarios.

In the third process (Hold Baggage Screening), scenarios 4 and 7 involve parallel conveyors between the HBS L1 and the sortation area(s), represented by process element C. The implications for this process are solely that parallel conveyors are present to transport bags and their trays to and from HBS L3. As seen in Figure 4.3c, this process element being structured in parallel results in both a relative and absolute low reduction in energy consumption. Still, the total conveyor length the bags have to travel is 32.65% lower for scenarios 4 and 7 compared to the other scenarios. The EDS devices result in the same energy consumption for each bag independent of the scenario, which could explain that the estimated energy consumption is not as low as the conveyor length in this process suggested.

In the fourth process (transportation from screening to sortation), as can be seen in Figure 4.3d, scenarios 4, 5, and 7 result in a lower energy consumption than the rest of the scenarios. Scenario 4 is subject to a parallel process element C (transportation from screening to sortation), whereas scenario 5 is subject to the parallel structure of process element D (sortation). Scenario 7 has both process elements structured in parallel. From the figure, it can be interpreted that the structure of process element C, has the most significant impact on the energy consumption in process 4, as it causes a decrease of more than 60%. This is almost similar to the decrease of transport length per bag. Also, the combination of the structure of process elements C and D matters. The energy consumption for scenario 7 is approximately similar to that of scenario 4, indicating that the parallel structure of process element D does not cause much additional reduction in energy usage. Process 4 is the only process that solely consists of transportation, besides from the plough diverter included in the configuration of scenario 5. This means that there is no static energy consumption and thus all energy consumption originates from bag transportation. As the decrease in conveyor length is almost similar to the decrease in energy consumption, it could be proven that the conveyor length each bag has to travel has a significant impact on the energy consumption for Airport X. The remaining differences are likely to be ascribed to the overlap of device usage.

As illustrated in Figures 4.3e and 4.3f, the parallel sortation areas and Early Baggage Storage in processes 5 and 6 both result in reduced energy consumption for scenarios 5 and 7. However, the percentage of reduction is higher in process 5 (sortation) than in process 6 (EBS).

Lastly, process 7 (return of trays) is subject to a parallel structure of process elements D (sortation) and E (return of trays). In Figure 4.3g, it is shown that this combination results in lower energy consumption than only having either of the process elements in parallel, as is the case for scenarios 5 and 6 respectively. The structure of process element E has the most significant impact on the energy consumption for process 7.

4.2.2. Clusters

The energy consumption estimates for each scenario can be compared using Figure 4.4 and Table 4.3. Both represent the total estimated energy consumption per scenario per day. The blue bars and left columns represent the daily system-level energy consumption estimated based on calculations for each 10-minute period, whereas the orange bars and right columns represent the daily system-level energy consumption based on calculations for each hourly period. The differences between the two are discussed in subsection 4.2.3.

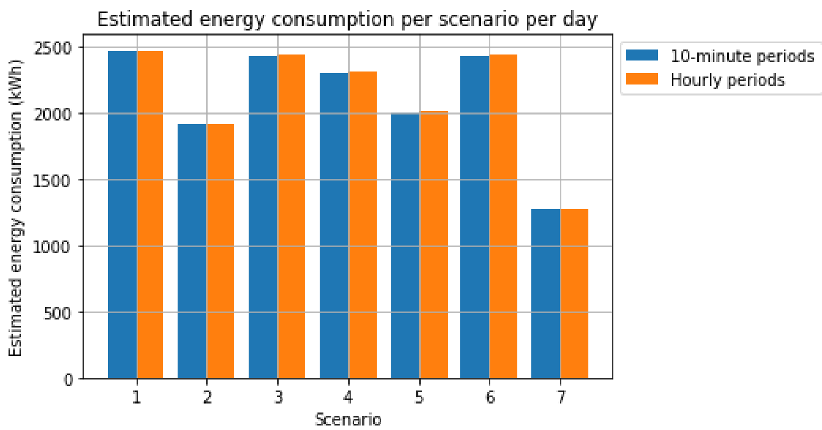


Figure 4.4: Estimated energy consumption per scenario per day

Three clusters of energy consumption can be identified. The first, which includes scenarios 1, 3, 4, and 6, has the highest energy consumption. The second cluster, with intermediate energy consumption, includes scenarios

Scenario	10-minute interval			Hourly interval		
	Total energy per day [kWh]	Average energy per bag [kWh]	Average energy per meter [kWh]	Total energy per day [kWh]	Average energy per bag [kWh]	Average energy per meter [kWh]
1	2473.4404	0.4017	4.4260	2464.3519	0.4002	4.4097
2	1917.0511	0.3113	3.8950	1919.0816	0.3117	3.8992
3	2443.5654	0.3968	4.4794	2434.4769	0.3954	4.4627
4	2313.3471	0.3757	4.8636	2304.2587	0.3742	4.8445
5	2014.3788	0.3271	5.0649	2003.7703	0.3254	5.0383
6	2428.5424	0.3944	4.4350	2419.454	0.3929	4.5180
7	1272.4114	0.2066	5.2758	1272.9218	0.2067	5.2779

Table 4.3: Estimated energy consumption per scenario

2 and 5. Scenario 7 forms the third cluster with the lowest estimated energy consumption. These clusters largely align with the hypothesis that the total length of the conveyors the bags travel over is the main factor affecting energy consumption. For example, scenarios 1, 3, and 6 were expected to use the most energy according to their conveyor lengths (see Table 4.2). However, the configuration of scenario 4 appeared to result in the fourth-highest energy consumption. Based on the total conveyor length, scenario 2 was expected to take this place. The clusters of scenarios 5 and 7 met the expectations based on conveyor length. To explain scenario 2 resulting in less energy consumption than scenario 5, although having a longer conveyor length per bag, one should have a look at Figure 4.5. The figure shows a visualisation of the estimated energy consumption per meter conveyor the bags have to travel in each scenario. The energy consumption per meter conveyor is not stable over the conveyor length per bag. In general, the longer the conveyor length per bag, the lower the energy consumption. This can be partly explained by the larger relative energy consumption of the fixed components (e.g., drop-off kiosks and desks, EDS). Also, the overlap of device usage is responsible. Namely, a low conveyor length is the result of one or more process elements designed in parallel. In those process elements, less overlap of device usage occurs, thus a lower decrease of energy consumption.

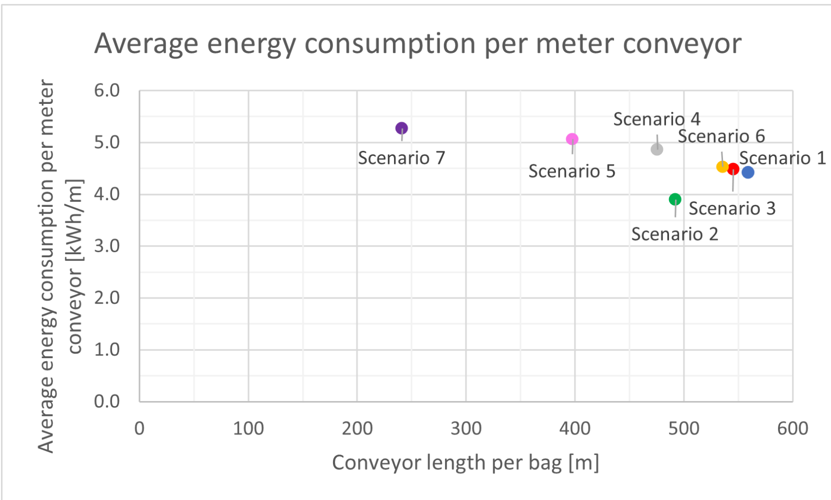


Figure 4.5: Average energy consumption per meter conveyor (based on 10-minute periods)

The average energy consumption per meter conveyor in scenario 2 is not in line with the almost linear trend for the other scenarios. This is expected to be the result of having a configuration with the belt conveyors placed in parallel. In scenarios 3-6, the configuration differences are in the design of ICS conveyors, thus the length of belt conveyors being similar. With the parameter values used for Airport X (Table 3.3), 2.2 kWh is needed for to transport 1 bag over 1 meter of belt conveyor, whereas 0.375 kWh is required for moving 1 bag over 1 meter of ICS conveyor. This indicates that more energy can be saved by decreasing the belt conveyor length than by decreasing the ICS conveyor length. More generally, it is important to take into account the energy consumption for the conveyor types considered when designing transportation through the BHS.

4.2.3. Estimation based on 10-minute or hourly periods

There are slight differences between the energy estimates based on 10-minute or hourly periods. These differences are likely due to the calculation of the time factor to account for overlap of device usage. Specifically, the time factors are determined based on the average distance between bags. Since this is a piecewise (rational) function, averaging values could lead to discrepancies. The distance between bags is calculated based on the number of bags arriving in a 10-minute or hourly period. An example is provided in Table 4.4, which shows bag arrivals during the first operational hour (4:00 A.M. - 4:59 A.M.). Using the number of arriving bags and a belt speed parameter value of 0.5 m/s (v_b, see Table 3.3), the distance between bags is calculated. This distance then determines the time factor category.

	10-minute periods						Hourly periods
Number of arriving bags	43.1351	72.8649	83.7838	90.9730	82.3514	87.8108	460.9189
Interdistance [m]	6.95	4.12	3.58	3.30	3.64	3.42	3.91
Time factor category: < 2.2 m							
Time factor category: 2.2 - 4.4 m		x	x	x	x	x	x
Time factor category: 4.4 m <	x						
f_L	1	1	1	1	1	1	1
f_{Em}	0.8182	0.5682	0.5682	0.5682	0.5682	0.5682	0.5682

Table 4.4: Time factor categories

For the hourly period, the second category applied. Within the same hour, five of the 10-minute periods also resulted in the second category. However, one period resulted in the third time factor category. This means the time factor for overlapping device usage of a loaded device (f_L) is always 1. Still, the average time factor for overlapping device usage of an empty device (f_{Em}) is 0.5682 for hourly periods and 0.6098 for 10-minute periods.

Figure 4.4 shows that the estimations based on 10-minute or hourly periods are almost identical for the case of Airport X. This is confirmed by the energy consumption results in Table 4.3. The biggest difference between the 10-minute and hourly estimates is just 0.53%. However, in extreme cases, the estimations based on 10-minute or hourly periods would result in bigger differences in energy consumption estimations. An example is when all bags arrive in the first 10 minutes of an hour. The time factor is low for the first 10-minute period and highest in the 5 remaining 10-minute periods. Still, the weighted average time factor is low. The bag arrivals are assumed to be distributed evenly over the period. So, for the hourly period, the time factor is expected to be higher than for the 10-minute period, which would result in a higher estimated energy consumption for the BHS.

4.3. Conclusion

Having analysed the energy consumption incurred by seven different scenarios for BHS configurations, the sub-question *How does the energy consumption vary across different configurations of baggage handling systems?* can be answered. A factor influencing the estimated energy consumption of the BHS is found to be the total distance each bag is required to travel. Despite the presence of identical devices across all configurations, the configurations that feature the most conveyor devices in series are observed to have the highest energy consumption. This is primarily due to the increased energy required to move bags over longer distances. Nevertheless, the transportation technology employed may impact the system-level energy consumption more than the conveyor length. The remaining differences in estimated energy consumption across the various scenarios can likely be attributed to the overlap of device usage. When a greater number of bags enter a conveyor within the same period, the distance between individual bags decreases. This reduction in interdistance leads to a lower time factor, which in turn results in lower energy consumption. However, for the BHS of Airport X, the impact of this effect is less obvious than the effects of conveyor length and conveyor parameters on energy consumption. Still, it could be concluded that the analysis is in line with the hypothesis, although the effect of the overlap of device usage on the BHS energy consumption is not proven.

5

Conclusion and discussion

5.1. Conclusion

This research focused on answering the research question: ***What influence does the configuration of an airport's baggage handling system have on its estimated system-level energy consumption?*** It started by describing the main processes in BHSs and their interrelations. Seven main processes are distinguished: drop-off, transportation from drop-off to screening, hold baggage screening (HBS), transportation from screening to sortation, sortation, early baggage storage (EBS), and make-up. In finding the devices that contribute to the total energy consumption of a BHS, it was found that the exact devices vary based on the technologies operated for each process. However, transportation appears to be responsible for energy consumption for a big part, as it is present within many processes and in between some processes. To estimate the energy consumption of a BHS with regard to different configurations, an equation-based model is developed. The model, which is based on the BHS of a midsize airport in Scandinavia (Airport X), uses a series of formulas for each BHS process to represent its energy consumption. The formulas depend on the structure of process elements. This allows for customisation for different BHS configurations. Further, the energy consumption incurred by seven different scenarios for BHS configurations is analysed. A factor proven to determine the estimated energy consumption of the BHS is the total distance each bag travels in the BHS. Configurations with the most conveyor devices in series resulted in the highest energy consumption due to the increased energy required to move bags over longer distances. Also, the features of the transportation devices are found to have a considerable effect on energy consumption. Other differences in the estimated energy consumption throughout the scenarios are suggested to be attributed to the overlap in device usage.

The proven influence of an airport's BHS configuration on its estimated system-level energy consumption thus is twofold. Firstly, more process elements structured in series result in bags travelling a longer distance on the conveyor within the BHS, thereby increasing energy usage. Secondly, the parameter values for transportation impact energy consumption notably. The research suggested that more process elements structured in series decrease the overlap of device usage, which in turn reduces energy consumption. To state it differently, an optimal configuration should cause the bags to travel a short distance, employ a transportation technique that involves a low energy consumption per meter, and cause maximum overlap.

5.2. Discussion

The model needs the number of bags arriving in each period as an input. Throughout the calculations, it is assumed that the bags' arrival times are equally spread over the period. However, in reality, bags are dropped off less evenly within the period, resulting in smaller or bigger interdistances. In turn, this has an impact on the overlap of device usage, and thus on energy consumption. Still, the model is created to be used in the conceptual design phase. In this phase, it is unlikely that the estimated bag arrivals are known for periods smaller than one hour or 10 minutes. Therefore, the 10-minute and hourly intervals provide a reasonable level of detail for this stage of the design process.

It may not be straightforward that the BHS representation showed both HBS L3 and EBS as being present multiple times within the BHS in parallel designs. Namely, this depiction does not align with the assumption that all configurations have an equal number of each device type. Having multiple HBS L3 in the system, as mentioned in subsection 2.2.3, is not realistic. Still, it is possible to have several EBSs within a single BHS, as outlined in subsection 2.2.5. This scenario is plausible when there are multiple terminals, for instance. However, considering the moderate size of Airport X, a parallel EBS would not be reasonable. Yet, the number of HBS L3 stations and EBSs does not impact the energy consumption estimation results. For HBS L3, the energy consumption is assumed negligible, and the model only accounts for transportation to and from this screening level. Similarly, for the EBS, the location count does not affect the results, and transportation is also accounted for. Moreover, the crane's usage does not overlap, meaning a deterministic value is added for each bag using the crane. In summary, including multiple HBS L3 and EBSs in parallel process elements simplified the BHS representation.

5.2.1. Implications

This study shows that the design of the BHS affects its energy consumption. This idea was also suggested by Balaras et al. (2003), although the researcher considered HVAC systems at airports, thus not BHS. Other researchers, Kierzkowski and Kisiel (2022), studied how resources are used in the HBS process. They found that this can also affect the BHS energy consumption. This study did not take into account all processes of the BHS and the system's configuration. Still, the idea that how the BHS works can affect its energy use is found in the current research, as well.

This research adds new information to the current knowledge on the topic of BHS energy consumption. The main new finding is that the transportation of bags highly contributes to the energy consumption of the BHS, as it is present both within and in between processes. Also, the concept of overlap of device usage is introduced. This represents the impact of the interdistance of bags on energy consumption, both when devices are loaded and when they are speeding up or slowing down to facilitate smooth transportation of luggage.

Practical implications

For NACO, the developed model can be used to gain insight into the estimated energy consumption of BHSs. This model can serve as a valuable aid during the conceptual design process, which enables testing various configurations on the impacts on energy consumption.

The model's input parameters should be carefully customised to align with the BHS under consideration. This includes the parameters directly related to the system's configuration, as well as the list of general parameters. Keeping these parameters up-to-date is essential to maintain the model's accuracy and relevance. When technology develops and new types of devices become the standard in industry, these changes should be reflected in the model. By updating the list of general parameters with the latest device values, the model can provide representative estimations for the BHS's energy consumption. When NACO is involved in a BHS renovation, the model could be useful, as well. It can be used to compare the energy consumption of the old and new BHS designs, which gives a clear picture of the improvements achieved through the renovation.

The model's output, which is the estimated energy consumption, could be applied in various ways. It can help to find the power requirements for the BHS and its operational costs. Additionally, it can guide decision-making towards more sustainable designs by identifying the configurations that result in lower energy consumption. This corresponds to a larger goal of promoting sustainability in the aviation industry. Referring back to the current way of estimating energy consumption, the model supplies BHS designers with a more detailed estimation. Namely, the general factors that were previously used are replaced in the model by calculations customised for the airport under consideration.

The insights acquired by applying the model to the case of Airport X are valuable for both NACO and Greenbaggage Alliance. In their quest to make all baggage handling more sustainable, the results of this research may expand their knowledge and can be used as a basis for further research on this topic.

5.2.2. Limitations

In the model, it is assumed that the number of lines is equal to the number of tray loaders and EDS devices when a process element is structured in parallel. However, this is a simplification and may not reflect the complexities of real-world scenarios. In practice, there could be cases where the numbers of these devices do not match. This discrepancy could occur due to various factors, of which a non-matching capacity would be a common example.

Another limitation of this study is that the formulas for the calculation of the time factors are piecewise rational. These factors connect the distance between bags to the energy consumption of a device. They depict that the closer the bags are to each other, the less time a device needs to work, and so it uses less energy. The formula gives the average values of these factors for each section. However, the results would be more precise if a linear formula was used. A linear formula would create a better understanding on the effects of the overlap of device usage on the energy consumption for each configuration. Additionally, the formulas for the time factors are based on the assumption that the speed of the conveyor devices depends on the centre of the bag's window. This implies that a device only starts accelerating when the centre of the window is on the preceding device. As a consequence, the device has only reached its required speed if the centre of the window is on that device. In reality, a conveyor device should reach its required speed already when the beginning of the bag's window is on the device. Namely, a bag can be anywhere within the window, and this is the first moment that a bag may enter the conveyor device. Therefore, the values of the factors are lower than they should be. However, this effect is partly offset by basing the formulas on the relative positions of only two bags. Ideally, the formulas should have been derived based on all bags arriving in a period. To give an example, when the average interdistance between bags is less than a conveyor device's length in a period, no conveyor devices are operating while empty, as all devices are loaded. From this perspective, the factors for empty device usage are given higher values than they should.

In practice, it is unlikely that a process element structured in series has the same number of devices as a process element structured in parallel. Generally, the total distance a bag needs to travel is fixed, and not the number of devices in the system. As such, the explicit results from the research may not be directly applicable to real-world situations, which can be recognised as a limitation of the study. Nevertheless, the general conclusions are relevant.

Lastly, the conclusions can be considered trivial. Still, the model is capable of producing results that are in line with expectations. A deeper investigation into the quantitative effects of BHS configurations on its energy consumption would strengthen the conclusions.

5.2.3. Recommendations for further research

The model resulting from the current research can be further developed by adding the inbound and transfer baggage flows. Achieving this requires a thorough understanding of these baggage movements within the BHS. It is essential to identify how these movements can be divided into processes and what the processes make to consume energy. A similar approach could be taken as in the current research. The main difference would be an enlargement of scope from only the outbound baggage flow to including inbound and transfer baggage flow, as well.

Also, the devices that were not taken into account in the model could be added for an even more precise result. For example, tray stackers and bag identification cameras are known to use energy but are not yet included. Namely, too little information was available on these devices in terms of how many of these devices are present in a BHS and how they operate. Research should be done on what these devices exactly entail, where they are located in the BHS, and how they interact with the other devices and processes. Further, values should be found to represent their power and runtime.

Moreover, further research can overcome the limitations of the current study. It should be investigated what common configurations are when the number of tray loaders and EDS devices do not match. The calculation of the time factors should be revised such that it correctly represents the effect of the interdistance of bags on the overlap of device usage. Both changes can be added to the model, such that it is even more generally applicable and gives more detailed results. Further, it should be studied what influence the configuration of a BHS has on its system-level energy consumption given that the distance a bag has to travel is fixed, instead of the number of devices in the BHS being fixed. This would make the conclusions more applicable to real-world situations. Lastly, to strengthen the conclusions drawn, some tests should be done. As the conclusion is threefold, three tests should be performed. In each of the tests, one factor is varied and two are constant, as shown in Table 5.1. When only one factor is varied in each test while the others are fixed, all differences in estimated energy consumption throughout the scenarios should originate from the varied factor. In other words, these tests would allow to find the impact of each factor on the BHS system-level energy consumption and thus quantify the conclusions.

Test	Factor		
	Length	Overlap	Transportation features
1	Vary	Fix to 0, such that $f_L = f_{Em} = 1$	Fix (choose one technique)
2	Fix	Vary	Fix (choose one technique)
3	Fix	Fix to 0, such that $f_L = f_{Em} = 1$	Vary power, speed, and length of device

Table 5.1: Tests for quantifying conclusions

In this study, the BHS operating strategy is kept the same throughout the analysis. This means that the bags are evenly spread over conveyors and that the drop-off points are used equally. It would be worthwhile to change the operating strategy in the model to see how it affects energy use. This could be done with a fixed BHS configuration or while changing the structure of the process elements. One case that could be looked at is using redundancy. This is when some conveyors or devices are placed in parallel. Usually, not all of these conveyors or devices are used simultaneously. A redundant line only opens when it is needed. Redundancy is like a safety net that keeps the system running even if a part breaks down. Another insightful case is changing the operating strategy of the configuration used in scenario 7. This configuration can be called a modular system, where each separate system is a module. In BHS design, this kind of system usually only operates an extra module when the others are filled to capacity. So, only the smallest number of modules needed to handle the bags is operated, and the others are turned off. The concept of modular systems can be applied to save energy or to handle more bags in the future.

5.2.4. Recommendations for NACO

The model could be further developed by incorporating it directly into the digital design tool. This integration would fairly facilitate the model's usage. The reason is that the input values required by the model could be directly acquired from the design tool itself. This means that the user does not need to manually check or input the parameter values, such that the probability of errors is reduced and time is saved. Also, this would allow for real-time updates and adjustments. In the design process, the model could automatically update its calculations based on the latest design parameters. Moreover, this integration could facilitate iterative design phases. The designers could instantly see the impact of their design choices on energy consumption. This would enable them to make more informed decisions.

Another recommendation for developing the model further is that the model could offer suggestions for optimising energy consumption. The main function of the current model is to calculate energy usage. Still, it could be useful if the model had a feature to present the most energy-efficient configurations. The model would evaluate all possible alternatives and then present either the optimal choice or a selection of the best options.

References

Abdelghany, A., Abdelghany, K., & Narasimhan, R. (2006). Scheduling baggage-handling facilities in congested airports. *Journal of Air Transport Management*, *12*(2), 76–81. https://doi.org/10.1016/j.jairtraman.2005.10.001

ACI EUROPE Airport Business. (2009, December). ALSTEF signs 20-year ADM contract. http://www.airport-business.com/2009/12/alstef-signs-20-year-adm-contract/

Agile Business Consortium Limited. (2024). Chapter 10: MoSCoW Prioritisation. https://www.agilebusiness.org/dsdm-project-framework/moscow-prioririsation.html

Airport Suppliers. (2017, October). BEUMER Group to Install First ICS Baggage Handling System in the U.S. at San Francisco International Airport. https://www.airport-suppliers.com/supplier-press-release/beumer-group-install-first-ics-baggage-handling-system-u-s-san-francisco-international-airport/

Airport Technology. (2017, October). Vanderlande to deliver baggage handling system at Lelystad Airport, Netherlands. https://www.airport-technology.com/news/newsvanderlande-wins-contract-to-deliver-baggage-handling-system-at-lelystad-airport-5939575/

Airport Technology. (2024). Conveying Units for Baggage Handling Systems. https://www.airport-technology.com/contractors/baggage/transnorm/

Airportindustry News. (2024). Baggage Handling System and Bag Storage at Bergen Airport. https://airportindustry-news.com/videos/beumer-baggage-handling-system-bag-storage-bergen-airport/

Alba, S. O., & Manana, M. (2016). Energy research in airports: A review. *Energies*, *9*(5). https://doi.org/10.3390/en9050349

AlKheder, S., Alomair, A., & Aladwani, B. (2020). Hold baggage security screening system in Kuwait International Airport using Arena software. *Ain Shams Engineering Journal*, *11*(3), 687–696. https://doi.org/10.1016/j.asej.2019.10.016

Alstef Group. (2024a). Sortation Conveyors. https://alstefgroup.com/baggage-handling/baggage-handling-products/sortation-conveyors/

Alstef Group. (2024b). Storage shuttles. https://alstefgroup.com/intralogistics-solutions/our-products/storage-shuttles/

Araujo, G. E., & Repolho, H. M. (2015). Optimizing the Airport Check-In Counter Allocation Problem. *Journal of Transport Literature*, *9*(4), 15–19. https://doi.org/10.1590/2238-1031.jtl.v9n4a3

AVIATIONPROS. (2022, October). Multisorting Baggage Handling System (MBHS). https://www.aviationpros.com/gse/baggage-cargo/airport-baggage-handling-systems/product/21285373/leonardo-multisorting-baggage-handling-system-mbhs

Balaras, C. A., Dascalaki, E., Gaglia, A., & Droutsa, K. (2003). Energy conservation potential, HVAC installations and operational issues in Hellenic airports. *Energy and Buildings*, *35*(11), 1105–1120. https://doi.org/10.1016/j.enbuild.2003.09.006

Barth, T. C., Holm, J. T., Larsen, J. L., & Pisinger, D. (2021). Optimization of Transfer Baggage Handling in a Major Transit Airport. *Operations Research Forum*, *2*(2). https://doi.org/10.1007/s43069-021-00058-z

Battu, A., Venkataramanaiah, S., & Sridharan, R. (2023). Patient Flow Optimization in an Emergency Department Using SimPy-Based Simulation Modeling and Analysis: A Case Study. *Lecture Notes in Mechanical Engineering*, 271–280. https://doi.org/10.1007/978-981-19-6032-1{_}22

Boysen, N., Briskorn, D., Fedtke, S., & Schmickerath, M. (2019, August). Automated sortation conveyors: A survey from an operational research perspective. https://doi.org/10.1016/j.ejor.2018.08.014

Bradley, A. L. (2010). Airport baggage handling design. *The Independent Airport Planning Manual*, 59–80. https://doi.org/10.1533/9780857090355.59

Brice, D., Marinov, M., & Rüger, B. (2015). A Newly Designed Baggage Transfer System Implemented Using Event-Based Simulations. *Urban Rail Transit*, *1*(4), 194–214. https://doi.org/10.1007/s40864-015-0027-4

Briskorn, D., Emde, S., & Boysen, N. (2017). Scheduling shipments in closed-loop sortation conveyors. *Journal of Scheduling*, *20*(1), 25–42. https://doi.org/10.1007/s10951-016-0498-5

Chien, J.-Y., Wu, C.-Y., Lin, K.-H., & Hsiung, P.-A. (n.d.). *RFID-based Automatic Airport Baggage Handling System* (tech. rep.).

Clermont, G. (2013). Translational Equation-Based Modeling. In *Complex systems and computational biology approaches to acute inflammation* (pp. 11–28). Springer New York. https://doi.org/10.1007/978-1-4614-8008-2{_}2

Danjuma Mambo, A., Eftekhari, M., Steffen, T., Abdulhameed, D., Mambo, M., & Eftekhari, T. S. (2015). Evaluation of Indoor Environment System Performance for Airport Buildings. *International Journal of Sustainable and Green Energy*, *4*(3), 73–84. https://doi.org/10.11648/j.ijrse.20150403.12

DCS aero. (2022). CCM Hybrid Self Bag Drop. https://dcs.aero/product/self-bag-drop-sbd-ccm-technologies-hybrid/

DeDonato, M. P., Dimitrov, V. D., & Padir, T. (2014). Towards an automated checked baggage inspection system augmented with robots. *Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense XIII*, *9074*, 90740N. https://doi.org/10.1117/12.2053866

Dimark. (n.d.). vertisorter. https://dimark.eu/airport/airport-vertisorter/

European Union. (2010). REGULATION (EC) No 300/2008 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 March 2008 on common rules in the field of civil aviation security and repealing Regulation (EC) No 2320/2002. https://op.europa.eu/en/publication-detail/-/publication/9383cde7-0ae8-4a01-9162-6a7b890fe8a0

Farah, A. (2018, June). “Australia’s airports are investing in runways, terminals and technology”. https://autobagdrop.com.au/newsroom/categories/industry-news/page/2/

Fay, B., Ramasubramanian, A. K., Murphy, R. D., Adderley, T., & Papakostas, N. (2022). Using a process simulation platform for reviewing automated airport baggage handling system configurations. *Procedia CIRP*, *112*, 180–185. https://doi.org/10.1016/j.procir.2022.09.069

Frey, M., Kolisch, R., Artigues, C., Markus, F., & Rainer, K. (2017). Column Generation for Outbound Baggage Handling at Airports. Transportation Science. https://doi.org/10.1287/trsc.2017.0739

Gaurav Airport Consulting. (n.d.). GAC. https://www.ga-consult.com/

Greenbaggage Alliance. (n.d.). Sustainable Air Travel. https://www.greenbaggage.org/

Halliday, D., Resnick, R., & Walker, J. (2008). *Fundamentals of physics*.

Haneyah, S. W., Schutten, J. M., Schuur, P. C., & Zijm, W. H. (2013). A generic control architecture for material handling systems applied to a baggage handling system. *ICINCO 2013 - Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics*, *1*, 121–130. https://doi.org/10.5220/0004427201210130

Hattenschwiler, N., Merks, S., & Schwaninger, A. (2018). Airport Security X-Ray Screening of Hold Baggage: 2D Versus 3D Imaging and Evaluation of an on-Screen Alarm Resolution Protocol. *Proceedings - International Carnahan Conference on Security Technology*, *2018-October*. https://doi.org/10.1109/CCST.2018.8585713

Hättenschwiler, N., Mendes, M., & Schwaninger, A. (2019). Detecting Bombs in X-Ray Images of Hold Baggage: 2D Versus 3D Imaging. *Human Factors*, *61*(2), 305–321. https://doi.org/10.1177/0018720818799215

IATA. (2016). *Baggage Reference Manual* (tech. rep.).

Kalbarczyk, I., Kwasiborska, A., & GŁADYŚ, S. (2023). THE DECISION SUPPORT FACILITATING THE CHECK-IN SERVICE AT THE CHOPIN AIRPORT WITH THE USE OF COMPUTATIONAL EXPERIMENTS IN SIMIO. *Transport*, *38*(2), 67–76. https://doi.org/10.3846/transport.2023.18334

Kay, M. G. (2012). *Material Handling Equipment* (tech. rep.).

Khan Academy. (2024). Arithmetic series worksheet. https://www.khanacademy.org/math/precalculus/x9e81a4f98389efdf:series/x9e81a4f98389efdf:arith-series/a/evaluating-arithmetic-series-worksheet

Kierzkowski, A., & Kisiel, T. (2022). Simulation Model for the Estimation of Energy Consumption of the Baggage Handling System in the Landside Area of the Airport. *Energies*, *15*(1). https://doi.org/10.3390/en15010256

Kierzkowski, A., Kisiel, T., & Uchroński, P. (2021). Simulation model of airport security lanes with power consumption estimation. *Energies*, *14*(20). https://doi.org/10.3390/en14206725

Lu, H. A., & Chen, C. Y. (2012). Safety stock estimation of unit load devices for international airline operations. *Journal of Marine Science and Technology (Taiwan)*, *20*(4), 431–440. https://doi.org/10.6119/JMST-011-0322-1

Malandri, C., Briccoli, M., Mantecchini, L., & Paganelli, F. (2018). A Discrete Event Simulation Model for Inbound Baggage Handling. *Transportation Research Procedia*, *35*, 295–304. https://doi.org/10.1016/j.trpro.2018.12.008

Materna IPS GmbH. (2021, January). Denver International Airport (DEN) opens the United States' largest Self-Bag Drop (SBD) installation. https://www.materna-ips.com/denver-international-airport-opens-the-us-largest-sbd/

MATREX. (n.d.). Baggage carousel. https://www.matrex-airport.com/en/products-and-solutions/baggage-carousel/

Merks, S., Hattenschwiler, N., Zeballos, M., & Schwaninger, A. (2018). X-ray Screening of Hold Baggage: Are the Same Visual-Cognitive Abilities Needed for 2D and 3D Imaging? *Proceedings - International Carnahan Conference on Security Technology*, *2018-October*. https://doi.org/10.1109/CCST.2018.8585715

Miranda, E. (2022). Moscow Rules: A Quantitative Exposé. *Lecture Notes in Business Information Processing*, *445 LNBIP*, 19–34. https://doi.org/10.1007/978-3-031-08169-9{_}2

Mishra, A., & Mishra, D. (2010). Application of rfid in aviation industry: An exploratory review. *Promet - Traffic - Traffico*, *22*(5), 363–372. https://doi.org/10.7307/ptt.v22i5.201

NACO International Aviation Consultancy. (2024a). Aruba International Airport Reina Beatrix. https://p-naco.royalhaskoningdhv.nl/en/projects/aruba-international-airport-reina-beatrix

NACO International Aviation Consultancy. (2024b). Traversing complexity to strengthen climate resilience at Changi Airport. https://p-naco.royalhaskoningdhv.nl/en/projects/navigating-changi-airports-climate-resilience-journey

Oftring, C. (2024). IMPROVE BAGGAGE HANDLING EFFICIENCY WITH MULTI-PURPOSE BAGGAGE STORAGE. https://www.beumergroup.com/knowledge/airport/early-baggage-storage/

Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., & Wagener, T. (2016, May). Sensitivity analysis of environmental models: A systematic review with practical workflow. https://doi.org/10.1016/j.envsoft.2016.02.008

Pisinger, D., & Rude, S. Í. (2020). Advanced algorithms for improved baggage handling. *Journal of Airport Management*, *14*(3), 280–290. https://www.henrystewartpublications.com/jam/v14

Price, J., & Forrest, J. (2013). Passenger and Baggage Screening. In *Practical aviation security* (2nd ed., pp. 257–286).

Razavi, S., Jakeman, A., Saltelli, A., Prieur, C., Iooss, B., Borgonovo, E., Plischke, E., Lo Piano, S., Iwanaga, T., Becker, W., Tarantola, S., Guillaume, J. H., Jakeman, J., Gupta, H., Melillo, N., Rabitti, G., Chabridon, V., Duan, Q., Sun, X., … Maier, H. R. (2021). The Future of Sensitivity Analysis: An essential discipline for systems modeling and policy support. *Environmental Modelling and Software*, *137*. https://doi.org/10.1016/j.envsoft.2020.104954

Ridderbos, N. (2017). *Analysing capacity utilization through simulation in a baggage handling environment* (tech. rep.). https://research.tue.nl/en/studentTheses/analysing-capacity-utilization-through-simulation-in-a-baggage-ha

Robson Handling Technology Ltd. (2024, January). Airport Check-in Conveyors. https://www.robson.co.uk/airport-handling/what-we-do/products/check-in-lanes/

Romanenko, V. A., Skorokhod, M. A., & Guzha, E. D. (2020). Fuzzy control in the simulation model of airport baggage handling systems. *IOP Conference Series: Materials Science and Engineering*, *919*(4). https://doi.org/10.1088/1757-899X/919/4/042017

Ross, A. (2017). A Brief Look at Arithmetic and Geometric Sequences. In *Pedagogy and content in middle and high school mathematics* (pp. 77–80). SensePublishers. https://doi.org/10.1007/978-94-6351-137-7{_}19

Saibabu, P. C., Sai, H., Yadav, S., & Srinivasan, C. R. (2019). Synthesis of model predictive controller for an identified model of MIMO process. *Indonesian Journal of Electrical Engineering and Computer Science*, *17*(2), 941–949. https://doi.org/10.11591/ijeecs

Sargent, R. G. (2013). Verification and validation of simulation models. *Journal of Simulation*, *7*(1), 12–24. https://doi.org/10.1057/jos.2012.20

Shen, K., Li, C., Xu, D., Wu, W., & Wan, H. (2020). Sensor-network-based navigation of delivery robot for baggage handling in international airport. *International Journal of Advanced Robotic Systems*, *17*(4). https://doi.org/10.1177/1729881420944734

Siemens Logistics GmbH. (2024). A first of its kind: Siemens launches VarioBelt TilterPlus. https://www.siemens-logistics.com/en/news/press-releases/a-first-of-its-kind-siemens-launches-variobelt-tilterplus

Sørensen, R. A., Nielsen, M., & Karstoft, H. (2020). Routing in congested baggage handling systems using deep reinforcement learning. *Integrated Computer-Aided Engineering*, *27*(2), 139–152. https://doi.org/10.3233/ICA-190613

Srivastava, H., Kaushal, A., Kumar, H., Tripathi, A., & Sharma, A. K. (2022). A Design and Development of Baggage Sorting Robotic System at the Airport. *Evergreen*, *9*(1), 86–92. https://doi.org/10.5109/4774219

Tarău, A. N., De Schutter, B., & Hellendoorn, J. (2009). Decentralized route choice control of automated baggage handling systems. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, *42*(15), 70–75. https://doi.org/10.3182/20090902-3-US-2007.0036

Van Enter, E. (2018). Energy consumption of baggage handling systems. https://repository.tudelft.nl/islandora/object/uuid%3A51d2838b-88b3-4fc1-864a-fde1ff12a0e7?collection=research

Van Ganzewinkel, S. H. J. (2021). *Optimizing the baggage handling process for flight handling at Schiphol Airport* (tech. rep.). https://research.tue.nl/en/studentTheses/optimizing-the-baggage-handling-process-for-flight-handling-at-sc

Van Noort, L. (2018). Automating Baggage Handling System Concept Design using Generative Design Techniques. https://repository.tudelft.nl/islandora/object/uuid%3A7a63857f-6a65-42b5-84ec-5a02c5aca400?collection=research

Vanderlande Industries B.V. (2024a). ADAPTO BAGSTORE. https://www.vanderlande.com/systems/bag-storage/adapto-bagstore/

Vanderlande Industries B.V. (2024b). BAGSTORE. https://www.vanderlande.com/systems/bag-storage/bagstore/

Vanderlande Industries B.V. (2024c). Lane storage. https://www.vanderlande.com/systems/bag-storage/lane-storage/

Vanderlande Industries B.V. (2024d). Make-up. https://www.vanderlande.com/airports/systems/make-up/

Vanderlande Industries B.V. (2024e). VERTISORTER. https://www.vanderlande.com/systems/sorting-regulars/vertisorter/

van Leeuwen, H., Zhang, Y., Zervanou, K., Mullick, S., Kaymak, U., & de Ruijter, T. (2020). Lost and found: Predicting airline baggage at-risk of being mishandled. *ICAART 2020 - Proceedings of the 12th International Conference on Agents and Artificial Intelligence*, *2*, 172–181. https://doi.org/10.5220/0008977801720181

Vijlbrief, M. F. (2019). Automation of the conceptual design stage for material handling systems. https://repository.tudelft.nl/islandora/object/uuid%3A1fd7727b-f2bd-4c24-a9c2-f2225b6325b2?collection=research

Viswanadham, N., Prakasam, A., & Gaonkar, R. (2006). DECISION SUPPORT SYSTEM FOR EXCEPTION MANAGEMENT IN RFID ENABLED AIRLINE BAGGAGE HANDLING PROCESS. *2006 IEEE International Conference on Automation Science and Engineering*, 351–356. https://doi.org/10.1109/COASE.2006.326907

Wetter, M., Bonvini, M., & Nouidui, T. S. (2016). Equation-based languages - A new paradigm for building energy modeling, simulation and optimization. *Energy and Buildings*, *117*, 290–300. https://doi.org/10.1016/j.enbuild.2015.10.017

Yang, X., Feng, R., Xu, P., Wang, X., & Qi, M. (2023). Internet-of-Things-augmented dynamic route planning approach to the airport baggage handling system. *Computers and Industrial Engineering*, *175*. https://doi.org/10.1016/j.cie.2022.108802

Yunnan KSEC International Trading Co. Ltd. (2020). Parallel Sortation Unit. http://www.cstckm.cn/html/Products/Baggagehandlingsystem/Sorters/2932.html

Zenina, N., Merkuryev, Y., & Romanovs, A. (2020). The general principles of the transportation simulation model development and validation. *WSEAS Transactions on Systems and Control*, *15*, 81–92. https://doi.org/10.37394/23203.2020.15.10

A

Scientific research paper

Estimating system-level energy consumption of airport baggage handling system configurations at an early stage of designing

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Abstract—**The relationship between energy consumption and baggage handling systems (BHSs) has not been widely studied. In this study, this relationship is explored by considering BHS configurations - the designed arrangement of devices. The BHS consists of seven main processes: drop-off, transportation from drop-off to screening, hold baggage screening (HBS), transportation from screening to sortation, sortation, early baggage storage (EBS), and make-up. Transportation appears to cause a high share of the system's energy consumption, as it is a part of and connects several processes. An equation-based model is developed to estimate the energy consumption of BHSs with varying configurations. The model only contains parameters available at the BHS's conceptual design phase and is based on the BHS of a midsize airport in Scandinavia. It includes a series of formulas for each process, which depend on the structure of the process elements. The study proved a twofold effect of an airport's BHS configuration on the overall energy consumption. Firstly, more process elements structured in series result in bags travelling a longer distance on the conveyor within the BHS, thereby increasing energy usage. Secondly, the parameter values for transportation impact energy consumption notably. The research suggested that more process elements structured in series decrease the overlap of device usage, which in turn reduces energy consumption.**

Keywords—**Baggage Handling System (BHS), energy consumption, configurations, conceptual design**

I. Introduction

In the context of environmental sustainability, the aviation sector is exploring ways to decrease the energy usage of airport baggage handling systems (BHS). A deep understanding of BHS energy consumption is crucial for mitigating an airport's environmental footprint. This knowledge aids in the selection of energy-saving designs, enables the incorporation of renewable energy and cooling systems customised to demand profiles and avoids system oversizing. This approach not only encourages the development of environmental sustainability but also supports operational efficiency and cost-effectiveness.

Among the various aspects of airport design, a significant impact can be made on the design of BHSs. Departing baggage has to be introduced to the system, screened, and prepared for boarding [1], [2]. Additionally, the bags need to be transported, sorted, and possibly stored intermediately [3]. For each process, a technology is employed. To give an example for the case of transportation, the technologies refer to its infrastructure. This may vary from belts to Automated Guided Vehicles (AGV) [3]–[7]. Bradley [8], IATA [9], Vijlbrief [10], and Pisinger and Rude [11] described the sequence of processes in the BHS for departing baggage being the following: drop-off, transportation from drop-off to screening, Hold Baggage Screening (HBS), transportation from screening to sortation, sortation, and make-up. From sortation, the bags may enter the Early Baggage Storage (EBS), when having arrived early. When time has passed and the bags can be processed further, the bags return to sortation. Transportation does not only exist as a process in the BHS but is incorporated in the remainder of processes, as well [9], [12]–[15]. The design and size of the space for the BHS and the required capacity have an influence on the design of the BHS [8]. Airports are found to consume serious amounts of energy [16]. The highest contributor is the heating, ventilation, and air conditioning (HVAC), which has been widely researched [17], [18]. The BHS is another big contributor to airport energy consumption. In BHS, most energy is consumed by IT, HBS, and baggage transportation. However, Kierzkowski and Kisiel [19] mentioned that little research is done on the topic of BHS energy consumption.

Much research has been done on the processes in the BHS. Guiding into the direction of energy consumption of airports, the scope of most studies entails HVAC. However, little research includes the link between energy consumption and BHS. More specifically, there is a lack of understanding about how the energy consumption of a BHS is affected by its design. These BHS designs are defined to be designed arrangements of devices and will be referred to as configurations. As a consequence of this knowledge gap, the energy consumption of such systems cannot be accurately predicted or improved.

This research is focused on developing a model that estimates the operational energy usage of a BHS. This model is specifically designed to estimate system-level energy consumption during the conceptual design phase when many design details are yet to be determined. The model allows for the comparison of energy consumption associated with processing hold baggage across various system configurations. The energy consumption related to carry-on baggage handling and transfer and inbound baggage is not included in this analysis. Also, overhead energy such as lighting and HVAC, and ground handling energy consumption are not taken into account. The BHS at a midsize airport in Scandinavia serves as the basis for this model, as energy consumption data for this system is readily available, thereby facilitating model validation. Throughout the analysis of the considered system configurations, the technologies for the processes and their parameters remain constant. The only variable factor is the structure of process elements, which is a subset of the devices in the BHS, often consisting of an entire process or a part of a process.The structure of a process element describes whether the process element is designed to be in series or in parallel. Still, the total amount of devices of a type is constant throughout the scenarios.

The structure of this paper is outlined as follows. Section II presents a literature review on the main processes in BHSs and how these processes relate to one another. The technologies for each process are highlighted. Additionally, the devices in the main processes of the BHS that are responsible for energy consumption are identified. Section III introduces a model for the estimation of energy consumption in the BHS. A sensitivity analysis is applied in section IV. Finally, the conclusion and discussion are presented in sections V and VI.

II. MAIN PROCESSES

With the goal in mind of estimating the energy consumption of the BHS at airports, the first step is to examine the system's processes systematically. In this section, the processes are described and their various technologies are presented.

The BHS is characterised as a series of processes. The first process is the drop-off of baggage. The final process within the scope of the project is make-up. Intermediate processes are transportation from drop-off to screening, HBS, transportation from screening to sortation, sortation, and EBS [20]. There are multiple technologies available to perform these processes. These technologies are implemented as devices, which are the actual installed machines. The used terminology is based on its prevalence in literature and is used by authors such as Yang, Feng, Xu, *et al.* [3], Bradley [8], Pisinger and Rude [11], Kierzkowski and Kisiel [19], and Romanenko, Skorokhod, and Guzha [21], among others.

A. Drop-off

The passenger takes his carry-on baggage with him but leaves the hold baggage at the baggage drop-off. At conventional drop-off desks, staff is present to facilitate the process. At some airports, passengers can drop off their baggage themselves [2]. In a hybrid option, the desk can easily be switched between a staffed counter and a self-service kiosk [22].

The hold baggage screening (HBS) process typically occurs immediately after the baggage drop-off. At that stage, no distinction is made yet between the luggage of different flights. In other words, the baggage is transported to the HBS area without any sortation [8].

B. Transportation

Belt, track, and cart technologies can be used to transport luggage through the BHS [3]. Although bags enter the conveying device one by one, there could be multiple bags on the same belt device. Alternatively, each piece of baggage could be assigned a carrier such as a tote or tray, that moves around over a track. This technology is referred to as an Individual/Independent Carrier System (ICS) [23], [24]. The baggage is generally loaded into a tote by a tray loader, which consists of a belt conveyor transporting the raw baggage above an ICS conveyor with empty totes/trays. The lanes operate at the same speed, enabling a piece of raw baggage to drop into the tote/tray at the end of the belt conveyor [23]. Both belt and track technologies give each bag a specific space, often called a window, to keep the bags in order. This window helps to keep a steady interdistance between bags or trays. Baggage may also be transported using destination-coded vehicles (DCVs), which consists of carts that choose their route over a fixed line network, such as rails [3], [23], [25]. Automated Guided Vehicles (AGVs) are similar to DCVs, except that they do not require any sort of track. Instead, they can move around freely [5]–[7].

Transportation can be considered a standalone process when it only consists of a conveyor that connects two processes. Nevertheless, transportation is a part of a process if its goal is to facilitate the movement of luggage through the process [9], [12]–[15].

C. Hold baggage screening

Regulations require that bags are screened for prohibited items before departure [26]. Hold Baggage (Security) Screening (HBS or HBSS) consists of four steps, called levels. At each level, the bag may be cleared, meaning there is no suspicion of possible dangerous contents. When cleared, the bag does not need to be screened any further. Otherwise, the bag is screened again at a higher level of the HBS process. The screening levels are as follows [9], [27]–[29]:

1) The Explosive Detection System (EDS) checks luggage automatically on the presence of forbidden items with the use of an X-ray or a computer tomography (CT) scan [30]–[32].
2) The screening images are evaluated by a staff member. This On Screen Resolution (OSR) takes place in the screener room. However, the baggage does not need to travel along this room since the evaluation is executed remotely.
3) The bag's exterior and interior surfaces are swabbed manually with a special cloth. The cloth is tested by an Explosive Trace Detection (ETD) device on the presence of elements from explosive compounds.
4) The piece of baggage is opened and checked manually by a staff member in the presence of the passenger.

In case the luggage could still not be cleared after the manual inspection, it finds its destination in the bomb container.

D. Sortation

Upon leaving the HBS process, the baggage is transported to the sortation process. Sortation consists of conveyors and sorting devices that change the bags' direction. Before each junction, the system needs to identify each bag. This way, it knows whether and how to change the bag's direction. As per the study of Vijlbrief [10], these destinations could either be a make-up station or the EBS. This is conditional on the availability of the make-up station and the presence of an EBS.

Bradley [8], Kay [33], Boysen, Briskorn, Fedtke, *et al.* [34], and Briskorn, Emde, and Boysen [35] distinguished several sortation technologies. These can be applied in combination with the belt conveyor-based BHS. Firstly, horizontal diverters are arms that guide or push the object in a different direction. The pushing arm of the push diverter applies a physical force to the luggage for the object to reach a perpendicular conveyor or container [36]. Alternatively, the plough diverter is an arm that blocks the direction that the bag should not go, resulting in the bag moving to the right path. Secondly, devices that are by default hidden below the surface of the conveyor and pop up when a bag should change direction are used as a sortation technology. The devices popping up are rollers, wheels, or chains. Thirdly, cross-belt sortation requires a conveyor that is split up into equally sized pieces. Each piece is equipped with a small, perpendicularly directed belt conveyor able to move individually. Fourthly, a tilting technology could be used for changing the baggage's direction with the use of elevation changes. A tilt tray sorter requires a special type of conveyor that consists of a sequence of trays that can tilt individually. The tilt results in discharging the bag. It should be noted that the term 'tray' is used for both a wooden surface in the tilt tray sorter technology and as a synonym for tote in ICS transportation.

Most of the described sortation technologies can be applied in combination with an ICS, as well. However, tilt-tray sorters and cross-belt devices are not considered suitable for totes in the ICS. The sortation with a DCV-based system works differently than for a belt conveyor-based system. The vehicles run over a track which has switches installed at the junctions. Just before a junction, the vehicle is identified. Based on this information, it is decided whether or not the switch has to change the vehicle's direction [25]. AGVs move around independently, such that the sorting step is integrated into the routing of the vehicles.

E. Early baggage storage

When a bag is ready to go to the make-up process and the make-up stations are not yet open, it is temporarily stored in the EBS. After storage, the bag re-enters the sortation process.

The simplest EBS technology is lane-based, in which conveyors are used as buffer space. Typically, the baggage stored in a lane is filtered on departure time, flight, or class before entering the lane [5]. Alternatively, baggage could be stored temporarily on vertical shelves with a racking and crane technology. In this technology, cranes move in a 2D direction. Thereby, they insert luggage, together with their tote, into an empty storage position in a rack [24], [37], [38]. In the shuttle-based technology, the bags and trays are transported in a 1D direction by carts [39], [40].

F. Make-up

Baggage is transported to the aircraft in a container or cart. Filling the container or cart takes place in the make-up process.

Generally, baggage is loaded onto a carousel in the make-up area. One or several flights are assigned to the carousel. The cart or container is placed next to the carousel. The workers scan the bar codes of each bag and container with a hand-held device, after which they load the bag in the right container [12], [41]. Another technology is the lateral belt conveyor. On the belt conveyor, the luggage for a flight is gathered. If a bag is taken from the lateral belt conveyor, it moves forward [41]–[43]. A lateral or spiral chute for collecting luggage to be loaded is presented as the third technology. A chute is a slide in which baggage can be temporarily stored [44].

In all three technologies, the baggage is typically transferred to the container or cart by hand. Alternatively, baggage may be transferred with the help of lifting aids or by robots [41], [43], [45].

G. High-level overview of energy-consuming devices

In the following, the processes are reassessed to identify the devices that are responsible for energy consumption. This serves as a starting point for the model.

1) Drop-off: In the drop-off process, the devices that contribute to energy consumption include drop-off stations, the conveyor that transports baggage from the drop-off point to the collector belt conveyor, and the collector belt conveyor itself.

2) Transportation: In a conveyor-based system, the energy-consuming devices are the conveyors that transport the baggage. If a BHS makes use of tilt-tray conveyors or an ICS, the energy consumed by the conveyor that returns the trays should be considered, as well. For DCV- and AGV-based systems, the vehicles are the only energy-consuming devices. It is important to note that a BHS may employ a combination of these technologies. According to Vijlbrief [10], the DCV technology consumes less energy than a belt- or track-based technology as only the vehicle requires propulsion, not the conveyor. Similarly, Van Enter [13] found that an AGV-based transportation process consumes less energy per baggage item than a conveyor-based process, with the percentage of difference depending on load, arrival, and speed parameters.

3) Hold baggage screening: The HBS process involves transportation and diverting devices to move luggage through the process and to segregate cleared from uncleared baggage. Additional energy is consumed by the EDS devices in the first level of screening. In the second level of screening, OSR, a desktop computer and a monitor are used to analyse the images. However, its energy consumption is negligible. The third level of screening involves manual swabbing of the bag's surfaces. Energy is used to test the cloth in the ETD device. Still, as the number of bags entering level 3 screening is considered low, the energy consumed by the ETD device can be omitted. The fourth level of screening is performed manually and thus does not count towards the total energy used. Kierzkowski, Kisiel, and Uchroński [46] and Van Enter [13] highlighted that the HBS process is one of the processes that contributes the most to BHS energy consumption.

4) Sortation: The energy consumption in the sortation process primarily stems from the transportation of baggage. Additionally, the diverting devices require energy to change their own position as well as that of the baggage.

5) Early baggage storage: The EBS process energy consumption is attributed to the conveyors in the case of a lane technology. For crane and shuttle technologies, the cranes and shuttles themselves are the devices consuming energy. The energy required is influenced by the distance over which the device moves the luggage and the height it needs to overcome. When either of these two is employed, additional energy is consumed by a conveyor that transports the baggage to the pick-up location and from the drop-off location.

6) Make-up: When a make-up process is operated by carousels, the energy consumption only depends on the carousel devices themselves. In contrast, with the use of laterals, the energy utilisation is caused by the conveyors. The chutes, on the other hand, do not directly consume energy as the movement of the baggage is purely gravity-driven. However, Vijlbrief [10] noted that this technology may require a larger sortation loop due to the constraint that chutes should not be utilised for multiple flights simultaneously. This implies that the chute technology indirectly contributes to energy consumption. Furthermore, the installed lifting aids and robots also contribute to the overall energy consumption, as these devices demand energy to operate.

III. Modelling

The BHS of a midsize airport in Scandinavia, referred to as Airport X, served as a basis for the energy consumption model. The BHS at Airport X employs a tray-based ICS for luggage transportation. The use of belt conveyors is limited to the transportation of luggage from the drop-off point to the tray-loading location. To ensure that luggage reaches its correct destination, the system incorporates plough diverters, pop-up belts, and tilting conveyors. However, in this research, only the plough diverters and tilting conveyors are considered for the sortation and the discharge of bags from their trays. The EBS system is crane-based.

A BHS representation with the technologies used in the BHS of Airport X is shown in Figure 1. Only the process elements contributing to energy consumption are included.

The selected methodology for the model's implementation is equation-based modelling. Equation-based modelling entails that once a model is set up and the operational rules that control the interactions within and between the model's processes are defined, these rules can be put into a mathematical form to represent the processes [47], [48].

A. Assumptions

These assumptions for the model are of two types: operational and general. Operational assumptions are about how the BHS operates, whereas general assumptions are about the scope of the model and describe parts that are simplified or left out.

1) Operational assumptions:

- The investigation of bag arrivals at Airport X reveals minimal bag insertion into the system before 4.00 A.M. and after 10.40 P.M. Consequently, it is assumed that no bags are inserted during these hours.
- For the HBS, the devices comply with the same operational hours as the rest of the system. The devices function in three distinct states: scanning, standby, and shut down. During operational hours, all EDSs alternate between the scanning and standby modes, as repeatedly shutting down and restarting between bag arrivals would be too time-consuming.
- When the trays have completed the sortation process, it is assumed that they are emptied. Thereafter, the trays return to the baggage pick-up location. It is assumed that there are enough trays in the system to carry the bags.
- In every mode of transportation, whether in a process or in between processes, a conveyor device starts to run when a bag is positioned on the preceding conveyor device. This ensures that the device has achieved the required velocity when the bag arrives. Once the bag is on the next device, the conveyor device gradually slows down until it stops. This rule also applies to tray loaders and EDSs. Whilst the device is accelerating, carrying a bag, and decelerating, the conveyor device is assumed to consume energy. The devices that do not take part in transportation, which are the drop-off devices and the EBS crane, are assumed to use energy only when they are processing a bag.

2) General assumptions:

- The model does not consider capacity. So, before using the model, one should ensure that the considered BHS can manage the volume of bags that is introduced into it.
- Throughout the BHS, curved and straight elements in transportation are assumed to consume the same amount of energy.
- The Level 2 and Level 3 HBS resources are assumed to consume a negligible amount of energy, as they primarily consist of computers and ETD devices. All bags are assumed to be cleared after HBS L3.
- Lifting aids in the make-up process are considered out of scope. The BHS at Airport X has chutes, which do not consume electrical energy by definition. So, the make-up process is considered not to consume any electrical energy.
- In each configuration, the total length of the conveyors is the same. The main goal of the model is to assess the impact on energy consumption caused by different configurations, not to look into the effect of changing conveyor lengths.
- The bags are assumed to be located exactly in the middle of their window.
- The conveyor device's speed is determined by the bag's window centre point: it is accelerating if on the previous device, running at full speed if on the current device, and

decelerating if on the next device.

- All baggage is assumed to be of standard size, so no baggage is considered to be out of gauge.
- All processes are assumed to occur at the same elevation, such that there are no changes in height.

B. Equation-based model

The model can be presented as an equation-based model, and thus broken down into a series of algebraic formulas. Those formulations represent the relationships between system-level energy consumption of a BHS and its variables. The total system-level energy consumption is determined by summing the energy consumption across all periods in a day.

The series of mathematical formulations are derived from the fundamental physical energy equation presented in Equation 1 [49].

$$E = P \cdot t \tag{1}$$

In this formula, E represents the electrical energy consumption in kilowatt-hours (kWh), P denotes the active or real power in kilowatts (kW), and t signifies the time in hours (h).

Also, the formulas include the concept of overlap of device usage. The bag's window, marked in green in Figure 2, cannot overlap with another bag's window. The distance between two bags, the interdistance, is indicated in the figure, as well. The devices coloured blue represent the energy-consuming devices at this very instance. For each bag, one device is operating while loaded with that bag and two devices are accelerating and decelerating.

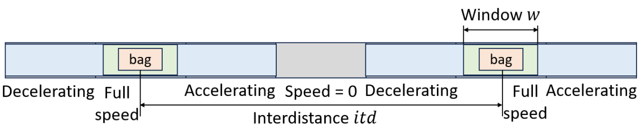

Fig. 2. Window and interdistance of bags

Two bags may demand the same conveyor to operate. This concept is referred to as overlap of device usage and is illustrated in Figure 3. In this example, two loaded devices are running, and only three are operating while empty. This means that the energy required to transport these two bags is lower than in Figure 2.

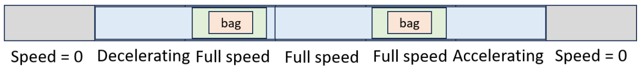

Fig. 3. Overlap of device usage

To cover this reduced energy consumption, the power factor pf_{Em} is defined to represent the fraction of energy consumption that still occurs if an overlap of device usage exists while the device is empty. The power factor pf_L comes into play when multiple bags are on the same conveyor device at the same time.

C. Verification and validation

To ensure that the model gives the correct output, such that the implementation represents the model's description, a manual verification method is employed. This involved manually calculating the energy consumption for a single period for a specific configuration. In this way, a small sample is tested for correctness. Minor differences between the two are observed, which can likely be ascribed to the rounding of values during the manual computation. The differences are at most 0.1482%, which is not considered so high that the assumption of correctness of the implementation should be rejected.

The model is validated, such that it is ensured that it provides an accurate representation of the real-world case it is intended to simulate [50]. With face validity, the model is confirmed through expert feedback on its logic, assumptions, and parameters. With historical data validation, the model's

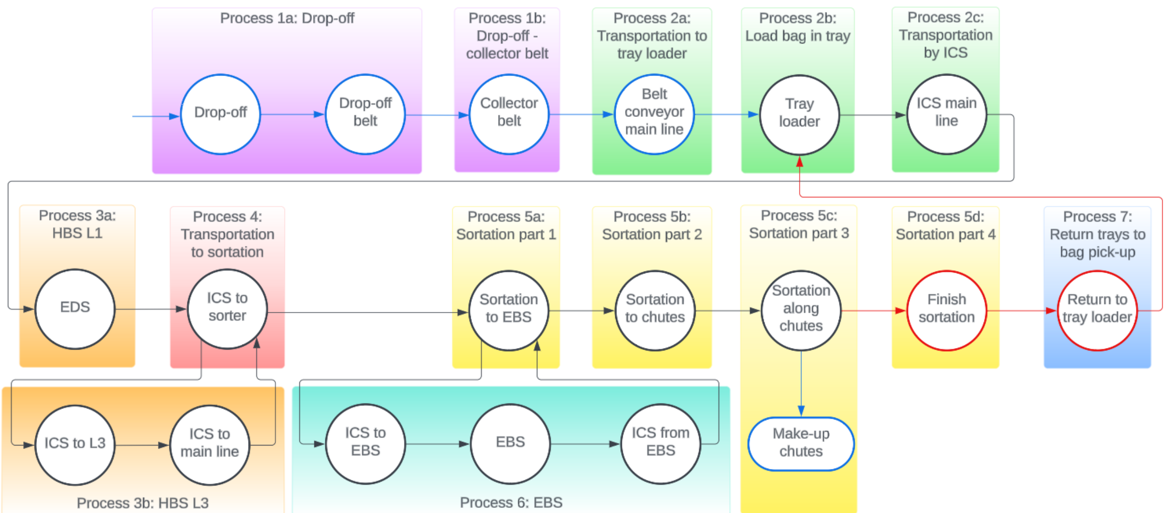

Fig. 1. BHS representation

output is compared to actual data. The model's energy consumption estimates were within the same order of magnitude as the actual values.

IV. Sensitivity analysis

Sensitivity analysis can be defined as a thorough investigation of the differences in energy consumption for various design configurations. In this study, the emphasis is on examining the results that arise from varying the structure of process elements. Sensitivity analysis allows to trace variations in output back to changes in configurations [51], [52].

A. Configuration scenarios

When designing a BHS, two critical factors should be considered: capacity and structure. Since it is assumed in this research that all configurations meet the capacity requirements, the BHS structure is varied throughout several scenarios. The process elements for which the structure is varied include the belt conveyor between the drop-off conveyor belt and the tray loader, the ICS conveyor between the tray loader and HBS L1, the conveyor between HBS L1 and the sortation process (including HBS L3), the sortation process, and the conveyor for returning trays. This is depicted in Figure 4.

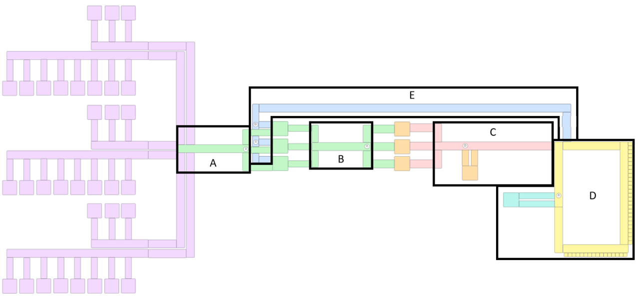

Fig. 4. Process elements

To ensure a fair comparison between the scenarios, the number of devices of each type stays the same. When process elements are structured in parallel, the number of parallel elements matches the number of tray loaders and EDS devices.

Seven scenarios are analysed. For each scenario, a unique set of formulas is used to calculate the energy consumption of the configuration it represents.

1) Scenario 1: All process elements in series: The first scenario is the BHS with most process elements in series, where bags follow a single line as much as possible. The only elements structured in parallel are the tray loaders and HBS L1. The illustration of Figure 4 represents the first scenario.

2) Scenarios 2 - 6: One process element in parallel: Each process element is structured in parallel in one of the scenarios, but only one at a time. Since the processes are mostly independent, the effects of a serial or parallel structure can be assessed.

3) Scenario 7: All process elements in parallel: By analysing scenarios 1 through 6, the difference in energy consumption between having a process element in series versus in parallel can be assessed. With this information, the BHS energy consumption for any other possible scenario can be calculated. Therefore, not all 32 possible scenarios are included in the analysis. However, to identify the range of energy consumption estimations for a BHS, scenario 7 is included in the analysis. In scenario 7, all considered process elements are in parallel. So, it is the other extreme configuration compared to scenario 1.

B. Results

Even though the total conveyor length is the same in all configurations, the actual distance a bag and its tray travel depends on the structure of the BHS. More process elements in parallel means shorter travel distances for bags, which in turn reduces the energy used by the conveyors. The average conveyor length per bag is shown in Table I.

TABLE I
Average conveyor length travelled per bag

Scenario	Conveyor length [m]
1	558.84
2	492.18
3	545.51
4	475.64
5	397.71
6	535.51
7	241.18

Three clusters of system-level estimated energy consumption can be identified in Figure 5. The figure represents the total estimated energy consumption per scenario per day. The first cluster, which includes scenarios 1, 3, 4, and 6, has the highest energy consumption. The second cluster, with intermediate energy consumption, includes scenarios 2 and 5. Scenario 7 forms the third cluster with the lowest estimated energy consumption.

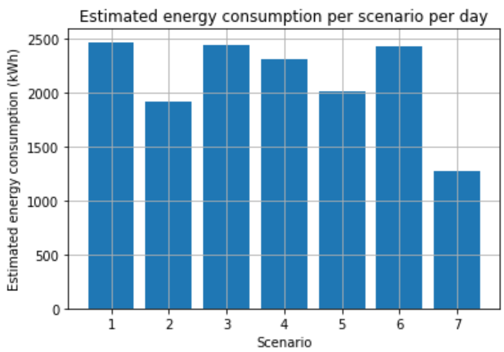

Fig. 5. Estimated energy consumption per scenario per day

These clusters largely align with the expectations that the total length of the conveyors the bags travel over is the main factor affecting energy consumption. However, the configuration of scenario 4 appeared to result in the fourth-highest energy consumption. Based on the total conveyor length, scenario 2 was expected to take this place. This is expected to be the result of having a configuration with the belt conveyors placed in parallel. In scenarios 3-6, the configuration differences are in the design of ICS conveyors, thus the length of belt conveyors being similar. The clusters of scenarios 5 and 7 met the expectations based on conveyor length.

Process 4 (transportation from screening to sortation) is the only process that solely consists of transportation, besides from the plough diverter included in the configuration of scenario 5. This means that there is no static energy consumption and thus all energy consumption originates from bag transportation. From comparing Table I to Figure 6 for scenarios 1 and 4, it can be learned that the decrease in conveyor length is almost similar to the decrease in energy consumption. It thus is proven that the conveyor length each bag has to travel has a significant impact on the energy consumption for Airport X. The remaining differences are likely to be ascribed to the overlap of device usage. Namely, the amount of overlap in conveyor usage changes based on how many bags or trays are simultaneously on the same conveyor device. The higher the number of bags traversing a conveyor, the lower the interdistance, leading to more overlap in device usage, and thus lower energy consumption.

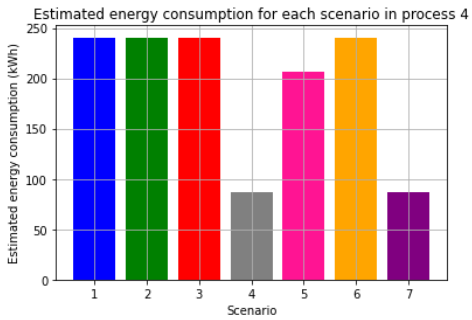

Fig. 6. Estimated energy consumption in process 4 per scenario

V. Conclusion

This research started by describing the main processes in BHSs and their interrelations. Seven main processes are distinguished: drop-off, transportation from drop-off to screening, hold baggage screening (HBS), transportation from screening to sortation, sortation, early baggage storage (EBS), and make-up. In finding the devices that contribute to the total energy consumption of a BHS, it was found that the exact devices vary based on the technologies operated for each process. However, transportation appears to be responsible for energy consumption for a big part, as it is present within many processes and in between some processes. To estimate the energy consumption of a BHS with regard to different configurations, an equation-based model is developed. The model, which is based on the BHS of a midsize airport in Scandinavia (Airport X), uses a series of formulas for each BHS process to represent its energy consumption. The formulas depend on the structure of process elements. This allows for customisation for different BHS configurations. Further, the energy consumption incurred by seven different scenarios for BHS configurations is analysed. A factor proven to determine the estimated energy consumption of the BHS is the total distance each bag travels in the BHS. Configurations with the most conveyor devices in series resulted in the highest energy consumption due to the increased energy required to move bags over longer distances. Also, the features of the transportation devices are found to have a considerable effect on energy consumption. Other differences in the estimated energy consumption throughout the scenarios are suggested to be attributed to the overlap in device usage.

The proven influence of an airport's BHS configuration on its estimated system-level energy consumption thus is twofold. Firstly, more process elements structured in series result in bags travelling a longer distance on the conveyor within the BHS, thereby increasing energy usage. Secondly, the parameter values for transportation impact energy consumption notably. The research suggested that more process elements structured in series decrease the overlap of device usage, which in turn reduces energy consumption. To state it differently, an optimal configuration should cause the bags to travel a short distance, employ a transportation technique that involves a low energy consumption per meter, and cause maximum overlap.

VI. Discussion

This section presents the research's practical implications, limitations and recommendations for future research.

A. Implications

This study shows that the design of the BHS can affect its energy consumption. This idea was also suggested by Balaras, Dascalaki, Gaglia, *et al.* [18], although the researcher considered HVAC systems at airports, thus not BHS. Other researchers, Kierzkowski and Kisiel [19], studied how resources are used in the HBS process. They found that this can also affect the BHS energy consumption. This study did not take into account all processes of the BHS and the system's configuration. Still, the idea that how the BHS works can affect its energy use is found in the current research, as well.

This research adds new information to what is currently known on the topic of BHS energy consumption. The main new finding is that the transportation of bags highly contributes to the energy consumption of the BHS, as it is present both within and in between processes. Also, the concept of overlap of device usage is introduced. This represents the impact of the interdistance of bags on energy consumption, both when devices are loaded and when they are accelerating or decelerating.

B. Limitations

In the model, it is assumed that the number of lines is equal to the number of tray loaders and EDS devices when a process element is structured in parallel. However, this is a simplification and may not reflect the complexities of real-world scenarios.

Another limitation is that the formulas for the calculation of the time factors are piecewise rational. They depict that the more overlap of device usage, the less time a device needs to work, and so it uses less energy. The results would be more precise if a linear formula was used. Additionally, the formulas for the time factors are based on the assumption that the speed of the conveyor devices depends on the centre of the bag's window. As a consequence, the device has only reached its required speed if the centre of the window is on that device. In reality, a conveyor device should reach its required speed already when the beginning of the bag's window is on the device. Therefore, the values of the factors are lower than they should be. However, this effect is partly offset by basing the formulas on the relative positions of only two bags. Ideally, the formulas should have been derived based on all bags arriving in a period.

In practice, it is unlikely that a process element structured in series has the same number of devices as a process element structured in parallel. Generally, the total distance a bag needs to travel is fixed, and not the number of devices in the system. As such, the explicit results from the research may not be directly applicable to real-world situations, which can be recognised as a limitation of the study. Nevertheless, the general conclusions are relevant.

Lastly, the conclusions can be considered trivial. Still, the model is capable of producing results that are in line with expectations. A deeper investigation into the quantitative effects of BHS configurations on its energy consumption would strengthen the conclusions.

C. Recommendations for further research

The model resulting from the current research can be further developed by adding the inbound and transfer baggage flows. A similar approach could be taken as in the current study.

Moreover, further research can overcome the limitations of the current study. It should be investigated what common configurations are when the number of tray loaders and EDS devices do not match. The calculation of the power factors should be revised such that it correctly represents the effect of the interdistance of bags on the overlap of device usage. Both changes can be added to the model, such that it is even more generally applicable and gives more detailed results.

Moreover, further research can overcome the limitations of the current study. It should be investigated what common configurations are when the number of tray loaders and EDS devices do not match. The calculation of the time factors should be revised such that it correctly represents the effect of the interdistance of bags on the overlap of device usage. Further, it should be studied what influence the configuration of a BHS has on its system-level energy consumption given that the distance a bag has to travel is fixed, instead of the number of devices in the BHS being fixed. Lastly, to strengthen the conclusions drawn, some tests should be done. As the conclusion is threefold, three tests should be performed. In each of the tests, one factor is varied and two are constant. Then, all differences in estimated energy consumption throughout the scenarios should originate from the varied factor.

In this study, the BHS operating strategy is kept the same throughout the analysis. This means that the bags are evenly spread over conveyors and that the drop-off points are used equally. It would be worthwhile to change the operating strategy in the model to see how it affects energy use. One case that could be looked at is using redundancy. Usually, not all of the conveyors or devices placed in parallel are used simultaneously. A redundant line only opens when it is needed. Alternatively, the operating strategy of the configuration used in scenario 7 can be changed. This configuration can be called a modular system, where each separate system is a module. In BHS design, this kind of system usually only uses a module when the others are filled to capacity. So, only the smallest number of modules needed to handle the bags is operated, and the others are turned off.

References

[1] C. Malandri, M. Briccoli, L. Mantecchini, and F. Paganelli, "A Discrete Event Simulation Model for Inbound Baggage Handling," *Transportation Research Procedia*, vol. 35, pp. 295–304, 2018. DOI: 10.1016/j.trpro.2018.12.008.

[2] I. Kalbarczyk, A. Kwasiborska, and S. GŁADYŚ, "THE DECISION SUPPORT FACILITATING THE CHECK-IN SERVICE AT THE CHOPIN AIRPORT WITH THE USE OF COMPUTATIONAL EXPERIMENTS IN SIMIO," *Transport*, vol. 38, no. 2, pp. 67–76, Sep. 2023. DOI: 10.3846/transport.2023.18334.

[3] X. Yang, R. Feng, P. Xu, X. Wang, and M. Qi, "Internet-of-Things-augmented dynamic route planning approach to the airport baggage handling system," *Computers and Industrial Engineering*, vol. 175, Jan. 2023. DOI: 10.1016/j.cie.2022.108802.

[4] T. C. Barth, J. T. Holm, J. L. Larsen, and D. Pisinger, "Optimization of Transfer Baggage Handling in a Major Transit Airport," *Operations Research Forum*, vol. 2, no. 2, Jun. 2021. DOI: 10.1007/s43069-021-00058-z.

[5] B. Fay, A. K. Ramasubramanian, R. D. Murphy, T. Adderley, and N. Papakostas, "Using a process simulation platform for reviewing automated airport baggage handling system configurations," in *Procedia CIRP*, vol. 112, Elsevier B.V., 2022, pp. 180–185. DOI: 10.1016/j.procir.2022.09.069.

[6] K. Shen, C. Li, D. Xu, W. Wu, and H. Wan, "Sensor-network-based navigation of delivery robot for baggage handling in international airport," *International Journal of Advanced Robotic Systems*, vol. 17, no. 4, Jul. 2020. DOI: 10.1177/1729881420944734.

[7] H. Srivastava, A. Kaushal, H. Kumar, A. Tripathi, and A. K. Sharma, "A Design and Development of Baggage Sorting Robotic System at the Airport," *Evergreen*, vol. 9, no. 1, pp. 86–92, 2022. DOI: 10.5109/4774219.

[8] A. L. Bradley, "Airport baggage handling design," *The Independent Airport Planning Manual*, pp. 59–80, Jan. 2010. DOI: 10.1533/9780857090355.59.

[9] IATA, "Baggage Reference Manual," Tech. Rep., 2016.

[10] M. F. Vijlbrief, "Automation of the conceptual design stage for material handling systems," 2019. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A1fd7727b-f2bd-4c24-a9c2-f2225b6325b2?collection=research.

[11] D. Pisinger and S. Í. Rude, "Advanced algorithms for improved baggage handling," *Journal of Airport Management*, vol. 14, no. 3, pp. 280–290, 2020. [Online]. Available: https://www.henrystewartpublications.com/jam/v14.

[12] M. Frey, R. Kolisch, C. Artigues, F. Markus, and K. Rainer, "Column Generation for Outbound Baggage Handling at Airports. Transportation Science," 2017. DOI: 10.1287/trsc.2017.0739.

[13] E. Van Enter, "Energy consumption of baggage handling systems," 2018. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A51d2838b-88b3-4fc1-864a-fde1ff12a0e7?collection=research.

[14] L. Van Noort, "Automating Baggage Handling System Concept Design using Generative Design Techniques," 2018. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A7a63857f-6a65-42b5-84ec-5a02c5aca400?collection=research.

[15] N. Viswanadham, A. Prakasam, and R. Gaonkar, "DECISION SUPPORT SYSTEM FOR EXCEPTION MANAGEMENT IN RFID ENABLED AIRLINE BAGGAGE HANDLING PROCESS," *2006 IEEE International Conference on Automation Science and Engineering*, pp. 351–356, 2006. DOI: 10.1109/COASE.2006.326907.

[16] A. Danjuma Mambo, M. Eftekhari, T. Steffen, D. Abdulhameed, M. Mambo, and T. S. Eftekhari, "Evaluation of Indoor Environment System Performance for Airport Buildings," *International Journal of Sustainable and Green Energy*, vol. 4, no. 3, pp. 73–84, 2015. DOI: 10.11648/j.ijrse.20150403.12.

[17] S. O. Alba and M. Manana, "Energy research in airports: A review," *Energies*, vol. 9, no. 5, 2016. DOI: 10.3390/en9050349.

[18] C. A. Balaras, E. Dascalaki, A. Gaglia, and K. Droutsa, "Energy conservation potential, HVAC installations and operational issues in Hellenic airports," *Energy and Buildings*, vol. 35, no. 11, pp. 1105–1120, 2003. DOI: 10.1016/j.enbuild.2003.09.006.

[19] A. Kierzkowski and T. Kisiel, "Simulation Model for the Estimation of Energy Consumption of the Baggage Handling System in the Landside Area of the Airport," *Energies*, vol. 15, no. 1, 2022. DOI: 10.3390/en15010256.

[20] A. Abdelghany, K. Abdelghany, and R. Narasimhan, "Scheduling baggage-handling facilities in congested airports," *Journal of Air Transport Management*, vol. 12, no. 2, pp. 76–81, 2006. DOI: 10.1016/j.jairtraman.2005.10.001.

[21] V. A. Romanenko, M. A. Skorokhod, and E. D. Guzha, "Fuzzy control in the simulation model of airport baggage handling systems," *IOP Conference Series: Materials Science and Engineering*, vol. 919, no. 4, 2020. DOI: 10.1088/1757-899X/919/4/042017.

[22] Materna IPS GmbH, *Denver International Airport (DEN) opens the United States' largest Self-Bag Drop (SBD) installation*, Jan. 2021. [Online]. Available: https://www.materna-ips.com/denver-international-airport-opens-the-us-largest-sbd/.

[23] R. A. Sørensen, M. Nielsen, and H. Karstoft, "Routing in congested baggage handling systems using deep reinforcement learning," *Integrated Computer-Aided Engineering*, vol. 27, no. 2, pp. 139–152, 2020. DOI: 10.3233/ICA-190613.

[24] D. Brice, M. Marinov, and B. Rüger, "A Newly Designed Baggage Transfer System Implemented Using Event-Based Simulations," *Urban Rail Transit*, vol. 1, no. 4, pp. 194–214, Dec. 2015. DOI: 10.1007/s40864-015-0027-4.

[25] A. N. Tarău, B. De Schutter, and J. Hellendoorn, "Decentralized route choice control of automated baggage handling systems," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 42, IFAC Secretariat, 2009, pp. 70–75. DOI: 10.3182/20090902-3-US-2007.0036.

[26] European Union, "REGULATION (EC) No 300/2008 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 March 2008 on common rules in the field of civil aviation security and repealing Regulation (EC) No 2320/2002," Jan. 2010. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/9383cde7-0ae8-4a01-9162-6a7b890fe8a0.

[27] M. P. DeDonato, V. D. Dimitrov, and T. Padir, "Towards an automated checked baggage inspection system augmented with robots," in *Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense XIII*, vol. 9074, SPIE, May 2014, 90740N. DOI: 10.1117/12.2053866.

[28] S. AlKheder, A. Alomair, and B. Aladwani, "Hold baggage security screening system in Kuwait International Airport using Arena software," *Ain Shams Engineering Journal*, vol. 11, no. 3, pp. 687–696, Sep. 2020. DOI: 10.1016/j.asej.2019.10.016.

[29] J. Price and J. Forrest, "Passenger and Baggage Screening," in *Practical Aviation Security*, 2nd ed., 2013, ch. 7, pp. 257–286.

[30] N. Hattenschwiler, S. Merks, and A. Schwaninger, "Airport Security X-Ray Screening of Hold Baggage:

2D Versus 3D Imaging and Evaluation of an on-Screen Alarm Resolution Protocol," in *Proceedings - International Carnahan Conference on Security Technology*, vol. 2018-October, Institute of Electrical and Electronics Engineers Inc., Dec. 2018. DOI: 10.1109/CCST.2018.8585713.

[31] N. Hättenschwiler, M. Mendes, and A. Schwaninger, "Detecting Bombs in X-Ray Images of Hold Baggage: 2D Versus 3D Imaging," *Human Factors*, vol. 61, no. 2, pp. 305–321, Mar. 2019. DOI: 10.1177/0018720818799215.

[32] S. Merks, N. Hattenschwiler, M. Zeballos, and A. Schwaninger, "X-ray Screening of Hold Baggage: Are the Same Visual-Cognitive Abilities Needed for 2D and 3D Imaging?" In *Proceedings - International Carnahan Conference on Security Technology*, vol. 2018-October, Institute of Electrical and Electronics Engineers Inc., Dec. 2018. DOI: 10.1109/CCST.2018.8585715.

[33] M. G. Kay, "Material Handling Equipment," Tech. Rep., 2012.

[34] N. Boysen, D. Briskorn, S. Fedtke, and M. Schmickerath, *Automated sortation conveyors: A survey from an operational research perspective*, Aug. 2019. DOI: 10.1016/j.ejor.2018.08.014.

[35] D. Briskorn, S. Emde, and N. Boysen, "Scheduling shipments in closed-loop sortation conveyors," *Journal of Scheduling*, vol. 20, no. 1, pp. 25–42, Feb. 2017. DOI: 10.1007/s10951-016-0498-5.

[36] J.-Y. Chien, C.-Y. Wu, K.-H. Lin, and P.-A. Hsiung, "RFID-based Automatic Airport Baggage Handling System," Tech. Rep.

[37] C. Oftring, *IMPROVE BAGGAGE HANDLING EFFICIENCY WITH MULTI-PURPOSE BAGGAGE STORAGE*, 2024. [Online]. Available: https://www.beumergroup.com/knowledge/airport/early-baggage-storage/.

[38] Vanderlande Industries B.V., *BAGSTORE*, 2024. [Online]. Available: https://www.vanderlande.com/systems/bag-storage/bagstore/.

[39] Alstef Group, *Storage shuttles*, 2024. [Online]. Available: https://alstefgroup.com/intralogistics-solutions/our-products/storage-shuttles/.

[40] Vanderlande Industries B.V., *ADAPTO BAGSTORE*, 2024. [Online]. Available: https://www.vanderlande.com/systems/bag-storage/adapto-bagstore/.

[41] S. H. J. Van Ganzewinkel, "Optimizing the baggage handling process for flight handling at Schiphol Airport," Tech. Rep., 2021. [Online]. Available: https://research.tue.nl/en/studentTheses/optimizing-the-baggage-handling-process-for-flight-handling-at-sc.

[42] H. van Leeuwen, Y. Zhang, K. Zervanou, S. Mullick, U. Kaymak, and T. de Ruijter, "Lost and found: Predicting airline baggage at-risk of being mishandled," in *ICAART 2020 - Proceedings of the 12th International Conference on Agents and Artificial Intelligence*, vol. 2, SciTePress, 2020, pp. 172–181. DOI: 10.5220/0008977801720181.

[43] S. W. Haneyah, J. M. Schutten, P. C. Schuur, and W. H. Zijm, "A generic control architecture for material handling systems applied to a baggage handling system," in *ICINCO 2013 - Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics*, vol. 1, 2013, pp. 121–130. DOI: 10.5220/0004427201210130.

[44] N. Ridderbos, "Analysing capacity utilization through simulation in a baggage handling environment," Tech. Rep., 2017. [Online]. Available: https://research.tue.nl/en/studentTheses/analysing-capacity-utilization-through-simulation-in-a-baggage-ha.

[45] Vanderlande Industries B.V., *Make-up*, 2024. [Online]. Available: https://www.vanderlande.com/airports/systems/make-up/.

[46] A. Kierzkowski, T. Kisiel, and P. Uchroński, "Simulation model of airport security lanes with power consumption estimation," *Energies*, vol. 14, no. 20, Oct. 2021. DOI: 10.3390/en14206725.

[47] G. Clermont, "Translational Equation-Based Modeling," in *Complex Systems and Computational Biology Approaches to Acute Inflammation*, New York, NY: Springer New York, 2013, ch. 2, pp. 11–28. DOI: 10.1007/978-1-4614-8008-2{_}2.

[48] M. Wetter, M. Bonvini, and T. S. Nouidui, "Equation-based languages - A new paradigm for building energy modeling, simulation and optimization," *Energy and Buildings*, vol. 117, pp. 290–300, Apr. 2016, ISSN: 03787788. DOI: 10.1016/j.enbuild.2015.10.017.

[49] D. Halliday, R. Resnick, and J. Walker, *Fundamentals of physics*. 2008.

[50] R. G. Sargent, "Verification and validation of simulation models," *Journal of Simulation*, vol. 7, no. 1, pp. 12–24, 2013. DOI: 10.1057/jos.2012.20.

[51] F. Pianosi, K. Beven, J. Freer, *et al.*, *Sensitivity analysis of environmental models: A systematic review with practical workflow*, May 2016. DOI: 10.1016/j.envsoft.2016.02.008.

[52] S. Razavi, A. Jakeman, A. Saltelli, *et al.*, "The Future of Sensitivity Analysis: An essential discipline for systems modeling and policy support," *Environmental Modelling and Software*, vol. 137, Mar. 2021. DOI: 10.1016/j.envsoft.2020.104954.

B

Code model implementation in Python

```
import pandas as pd
import matplotlib.pyplot as plt

#%%
# Model parameters
parameters = pd.read_csv('Model parameters.csv')
input_values = pd.read_csv('Input values model.csv')

def get_value(parameter_name, input_file):
    return input_file.loc[input_file['Parameter'] == parameter_name, 'Value'].iloc[0]

# Get parameters
w_raw = get_value('w_raw', parameters)
P_dob = get_value('P_dob', parameters)
v_dob = get_value('v_dob', parameters)
l_dob = get_value('l_dob', parameters)
l_b = get_value('l_b', parameters)
P_b = get_value('P_b', parameters)
v_b = get_value('v_b', parameters)
P_dis = get_value('P_dis', parameters)
P_dib = get_value('P_dib', parameters)
t_dis = get_value('t_dis', parameters)
t_dib = get_value('t_dib', parameters)
w_tray = get_value('w_tray', parameters)
l_ICS = get_value('l_ICS', parameters)
P_ICS = get_value('P_ICS', parameters)
v_ICS = get_value('v_ICS', parameters)
P_load = get_value('P_load', parameters)
v_load = get_value('v_load', parameters)
l_load = get_value('l_load', parameters)
P_sc  = get_value('P_sc', parameters)
P_st = get_value('P_st', parameters)
l_EDS = get_value('l_EDS', parameters)
v_EDS = get_value('v_EDS', parameters)
rate_L1 = get_value('rate_L1', parameters)
rate_L2 = get_value('rate_L2', parameters)
P_dic = get_value('P_dic', parameters)
P_dit = get_value('P_dit', parameters)
l_di = get_value('l_di', parameters)
v_di = get_value('v_di', parameters)
rate_EBS = get_value('rate_EBS', parameters)
P_li = get_value('P_li', parameters)
t_li = get_value('t_li', parameters)
P_me = get_value('P_me', parameters)
t_me = get_value('t_me', parameters)
P_re = get_value('P_re', parameters)
t_re = get_value('t_re', parameters)
```

```python

# Get input values
n_ssd = get_value('n_ssd', input_values)
n_dod = get_value('n_dod', input_values)
l_do = get_value('l_do', input_values)
l_cb = get_value('l_cb', input_values)
l_ml = get_value('l_ml', input_values)
l_tot = get_value('l_tot', input_values)
n_load = get_value('n_load', input_values)
l_ft = get_value('l_ft', input_values)
l_ma = get_value('l_ma', input_values)
l_toh = get_value('l_toh', input_values)
n_EDS = get_value('n_EDS', input_values)
l_tl = get_value('l_tl', input_values)
l_fl = get_value('l_fl', input_values)
l_fh = get_value('l_fh', input_values)
l_ts = get_value('l_ts', input_values)
l_tsb = get_value('l_tsb', input_values)
l_s1 = get_value('l_s1', input_values)
l_s2 = get_value('l_s2', input_values)
l_s4 = get_value('l_s4', input_values)
n_ch = get_value('n_ch', input_values)
l_te = get_value('l_te', input_values)
l_fe = get_value('l_fe', input_values)
l_rb = get_value('l_rb', input_values)
l_ret = get_value('l_ret', input_values)
l_rs = get_value('l_rs', input_values)

#%%

def energy_conveyor(kind, n_bags, n_devices, empty_overlap, loaded_overlap):
    if kind == 'belt':
        return P_b * (1 - loaded_overlap) * l_b/(v_b*(60*60)) * n_bags * n_devices\
            + 2 * P_b * (1 - empty_overlap) * l_b/(v_b*(60*60)) * n_bags * n_devices
    elif kind == 'ICS':
        return P_ICS * (1 - loaded_overlap) * l_ICS/(v_ICS*(60*60)) * n_bags * n_devices\
            + 2 * P_ICS * (1 - empty_overlap) * l_ICS/(v_ICS*(60*60)) * n_bags * n_devices

def divert(number_bags):
    return number_bags * (P_dis * t_dis/3600 +\
                          P_dib * t_dib/3600)

def num_modules():
    n_modules_tot = n_load or n_EDS

    return n_modules_tot

#%%
def drop_off(t_op, n_bags_tot):

    rate_kiosks = 1/get_value('t_ssd', parameters)
    rate_desks = 1/get_value('t_dod', parameters)
    total_rate = rate_kiosks*n_ssd + rate_desks*n_dod

    percentage_kiosks = (rate_kiosks*n_ssd) / total_rate
    percentage_desks = (rate_desks*n_dod) / total_rate

    n_bags_desk = percentage_desks * n_bags_tot
    n_bags_kiosk = percentage_kiosks * n_bags_tot

    E_kiosks = n_bags_kiosk * get_value('P_ssd', parameters) * get_value('t_ssd', parameters)
        /3600
    E_dod = n_bags_desk * get_value('P_dod', parameters) * get_value('t_dod', parameters)
        /3600

    E_dropbelt = 3 * P_dob * l_dob/(v_dob*3600) * n_bags_tot * l_do/l_dob

    E_collectorbelt_1bag = 0
    E_collectorbelt_empty = 0

    n_modules_tot = num_modules()
```

```python

    # Number of devices to travel when dropped off at desk or kiosk
    n_devices_desk = ((n_dod/n_modules_tot)/2)+0.5
    n_devices_kiosk = ((n_ssd/n_modules_tot)/2)+0.5

    bags = n_bags_tot

    empty_overlap_belt_desks, loaded_overlap_belt_desks = overlap(t_op, bags/n_modules_tot*percentage_desks, v_b, l_b, w_raw)
    empty_overlap_belt_kiosks, loaded_overlap_belt_kiosks = overlap(t_op, bags/n_modules_tot*percentage_kiosks, v_b, l_b, w_raw)

    E_collectorbelt_1bag += P_b*(1-loaded_overlap_belt_desks/2) * l_b/(v_b*(60*60)) * (n_bags_desk * n_devices_desk)
    E_collectorbelt_1bag += P_b*(1-loaded_overlap_belt_kiosks/2) * l_b/(v_b*(60*60)) * (n_bags_kiosk * n_devices_kiosk)
    E_collectorbelt_empty += 2* P_b*(1-empty_overlap_belt_desks/2) * l_b/(v_b*(60*60)) * (n_bags_desk * n_devices_desk)
    E_collectorbelt_empty += 2* P_b*(1-empty_overlap_belt_kiosks/2) * l_b/(v_b*(60*60)) * (n_bags_kiosk * n_devices_kiosk)

    E_collectorbelt_1bag += P_b*(1-loaded_overlap_belt_desks) * l_b/(v_b*(60*60)) * (n_bags_desk * l_cb/l_b) +\
        2 * P_b*(1-empty_overlap_belt_desks) * l_b/(v_b*(60*60)) * (n_bags_desk * l_cb/l_b)

    E_collectorbelt_1bag += P_b*(1-loaded_overlap_belt_kiosks) * l_b/(v_b*(60*60)) * (n_bags_kiosk * l_cb/l_b) +\
        2 * P_b*(1-empty_overlap_belt_kiosks) * l_b/(v_b*(60*60)) * (n_bags_kiosk * l_cb/l_b)

    E_drop = [E_kiosks, E_dod, E_dropbelt, E_collectorbelt_1bag, E_collectorbelt_empty]
    return E_drop

#%%
def transport_trayload(t_op, n_bags_tot, drop_off_trayload, trayload_EDS):

    n_modules_tot = num_modules()

    E_2a, E_2b, E_2c = 0, 0, 0

    bags = n_bags_tot

    empty_overlap_belt, loaded_overlap_belt = overlap(t_op, bags, v_b, l_b, w_raw)
    empty_overlap_belt_lines, loaded_overlap_belt_lines = overlap(t_op, bags/n_modules_tot, v_b, l_b, w_raw)
    empty_overlap_ICS, loaded_overlap_ICS = overlap(t_op, bags, v_ICS, l_ICS, w_tray)
    empty_overlap_ICS_lines, loaded_overlap_ICS_lines = overlap(t_op, bags/n_modules_tot, v_ICS, l_ICS, w_tray)
    empty_overlap_trayload_lines, loaded_overlap_trayload_lines = overlap(t_op, bags/n_modules_tot, v_load, l_load, w_tray)

    E_2a += energy_conveyor('belt', bags, l_tot/l_b, empty_overlap_belt_lines, loaded_overlap_belt_lines)

    E_2b += bags * P_load*l_load/(v_load*3600)*(1-loaded_overlap_trayload_lines) +\
        bags * P_load *(1-empty_overlap_trayload_lines) * ((l_b/(v_b*3600)) + (l_ICS/(v_ICS*3600))) +\
            P_ICS * (1 - loaded_overlap_trayload_lines) * l_ICS/(v_load*(60*60)) * bags * l_load/l_ICS +\
                2 * P_ICS * (1 - empty_overlap_trayload_lines) * l_ICS/(v_load*(60*60)) * bags * l_load/l_ICS

    E_2c += energy_conveyor('ICS', bags, l_ft/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines) +\
        energy_conveyor('ICS', bags, l_toh/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

    if drop_off_trayload == 'Series':
        E_2a += energy_conveyor('belt', bags, l_ml/l_b, empty_overlap_belt, loaded_overlap_belt) +\
                divert(n_bags_tot*(1-(1/n_modules_tot))) # Only the bags that do not go straight are diverted.
```

```

    elif drop_off_trayload == 'Parallel':
        E_2a += energy_conveyor('belt', bags, (l_ml/n_modules_tot)/l_b, empty_overlap_belt_lines, loaded_overlap_belt_lines)

    if trayload_EDS == 'Parallel':
        E_2c += energy_conveyor('ICS', bags, (l_ma/n_modules_tot)/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

    elif trayload_EDS == 'Series':
        E_2c += energy_conveyor('ICS', bags, l_ma/l_ICS, empty_overlap_ICS, loaded_overlap_ICS) +\
            divert(bags*(1-(1/n_modules_tot))) # Only the bags that do not go straight are diverted.

    E_transport = [E_2a, E_2b, E_2c]
    return E_transport

#%%
def HBS(t_op, n_bags_tot, EDS_sorter):

    n_modules_tot = num_modules()

    E_L1, E_L3 = 0, 0

    bags = n_bags_tot
    empty_overlap_HBS_lines, loaded_overlap_HBS_lines = overlap(t_op, bags/n_modules_tot, v_EDS, l_EDS, w_tray)

    E_L1 += bags * (P_sc-P_st)*(1-loaded_overlap_HBS_lines) * l_EDS/(v_EDS * 3600)\
            + 2 * bags * (P_sc-P_st)*(1-empty_overlap_HBS_lines) * (l_ICS/(v_ICS*3600))\
            + P_st*t_op*n_modules_tot

    E_L3 += divert(bags*(1-rate_L1)*(1-rate_L2))

    if EDS_sorter == 'Parallel':
        empty_overlap_ICS_L3_lines, loaded_overlap_ICS_L3_lines = overlap(t_op, (bags*(1-rate_L1)*(1-rate_L2))/n_modules_tot, v_ICS, l_ICS, w_tray)

        E_L3 += energy_conveyor('ICS', (bags*(1-rate_L1)*(1-rate_L2)), (l_tl/n_modules_tot)/l_ICS, empty_overlap_ICS_L3_lines, loaded_overlap_ICS_L3_lines) +\
            energy_conveyor('ICS', (bags*(1-rate_L1)*(1-rate_L2)), (l_fl/n_modules_tot)/l_ICS, empty_overlap_ICS_L3_lines, loaded_overlap_ICS_L3_lines)

    elif EDS_sorter == 'Series':
        empty_overlap_ICS_L3, loaded_overlap_ICS_L3 = overlap(t_op, bags*(1-rate_L1)*(1-rate_L2), v_ICS, l_ICS, w_tray)

        E_L3 += energy_conveyor('ICS', (bags*(1-rate_L1)*(1-rate_L2)), l_tl/l_ICS, empty_overlap_ICS_L3, loaded_overlap_ICS_L3) +\
            energy_conveyor('ICS', (bags*(1-rate_L1)*(1-rate_L2)), l_fl/l_ICS, empty_overlap_ICS_L3, loaded_overlap_ICS_L3)

    E_HBS = [E_L1, E_L3]
    return E_HBS

#%%
def transport_sorter(t_op, n_bags_tot, EDS_sorter, sortation_loop):

    n_modules_tot = num_modules()

    E_transport_sorter = 0

    bags = n_bags_tot

    empty_overlap_ICS_lines, loaded_overlap_ICS_lines = overlap(t_op, bags/n_modules_tot, v_ICS, l_ICS, w_tray)
    empty_overlap_ICS, loaded_overlap_ICS = overlap(t_op, bags, v_ICS, l_ICS, w_tray)

    E_transport_sorter += energy_conveyor('ICS', bags, l_fh/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines)
```

```

    if EDS_sorter == 'Series':
        E_transport_sorter += energy_conveyor('ICS', bags, l_ts/l_ICS, empty_overlap_ICS,
            loaded_overlap_ICS)

        if sortation_loop == 'Series':
            E_transport_sorter += energy_conveyor('ICS', bags, l_tsb/l_ICS, empty_overlap_ICS
                , loaded_overlap_ICS)

        elif sortation_loop == 'Parallel':
             E_transport_sorter += energy_conveyor('ICS', bags, (l_tsb/n_modules_tot)/l_ICS,
                 empty_overlap_ICS_lines, loaded_overlap_ICS_lines) +\
                 divert(bags*(1-(1/n_modules_tot)))

    elif EDS_sorter == 'Parallel':
        E_transport_sorter += energy_conveyor('ICS', bags, (l_ts/n_modules_tot)/l_ICS,
            empty_overlap_ICS_lines, loaded_overlap_ICS_lines)  +\
            energy_conveyor('ICS', bags, (l_tsb/n_modules_tot)/l_ICS, empty_overlap_ICS_lines
                , loaded_overlap_ICS_lines)

    return E_transport_sorter

#%%
def sorter(t_op, n_bags_tot, sortation_loop):

    n_modules_tot = num_modules()

    E_5a, E_5b, E_5c, E_5d = 0, 0, 0, 0

    bags = n_bags_tot

    empty_overlap_ICS_lines, loaded_overlap_ICS_lines = overlap(t_op, bags/n_modules_tot,
        v_ICS, l_ICS, w_tray)
    empty_overlap_discharge_lines, loaded_overlap_discharge_lines = overlap(t_op, bags/
        n_modules_tot, v_di, l_di, w_tray)
    empty_overlap_ICS, loaded_overlap_ICS = overlap(t_op, bags, v_ICS, l_ICS, w_tray)
    empty_overlap_discharge, loaded_overlap_discharge = overlap(t_op, bags, v_di, l_di,
        w_tray)

    if sortation_loop == 'Parallel':
        E_5a += energy_conveyor('ICS', bags, (l_s1/n_modules_tot)/l_ICS,
            empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

        E_5b += energy_conveyor('ICS', bags, (l_s2/n_modules_tot)/l_ICS,
            empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

        E_5c += bags * l_di/(v_di*3600) * P_dit +\
            bags/n_modules_tot * l_di/(v_di*3600) * (P_dic*(1-loaded_overlap_discharge_lines)
                * (n_ch/n_modules_tot)) + \
                bags/n_modules_tot * l_di/(v_di*3600) * (2 * P_dic*(1-
                    empty_overlap_discharge_lines)* (n_ch/n_modules_tot))

        E_5d += energy_conveyor('ICS', bags, (l_s4/n_modules_tot)/l_ICS,
            empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

    elif sortation_loop == 'Series':
        E_5a += energy_conveyor('ICS', bags, l_s1/l_ICS, empty_overlap_ICS,
            loaded_overlap_ICS)

        E_5b += energy_conveyor('ICS', bags, l_s2/l_ICS, empty_overlap_ICS,
            loaded_overlap_ICS)

        E_5c += bags * l_di/(v_di*3600) * (P_dit +\
            (P_dic*(1-loaded_overlap_discharge))* n_ch +\
                (2 * P_dic*(1-empty_overlap_discharge))* n_ch)

        E_5d += energy_conveyor('ICS', bags, l_s4/l_ICS, empty_overlap_ICS,
            loaded_overlap_ICS)

    E_sort = [E_5a, E_5b, E_5c, E_5d]
    return E_sort
```

```

#%%
def EBS(t_op, n_bags_tot, sortation_loop):

    n_modules_tot = num_modules()

    E_EBS = 0

    bags = n_bags_tot*rate_EBS

    empty_overlap_ICS_line, loaded_overlap_ICS_line = overlap(t_op, bags/n_modules_tot, v_ICS, l_ICS, w_tray)
    empty_overlap_ICS, loaded_overlap_ICS = overlap(t_op, bags, v_ICS, l_ICS, w_tray)

    E_EBS += bags*2*(P_li*t_li/3600 + P_me*t_me/3600 + P_re*t_re/3600) +\
        divert(bags)

    if sortation_loop == 'Parallel':
        E_EBS += energy_conveyor('ICS', bags, (l_te/n_modules_tot)/l_ICS, empty_overlap_ICS_line, loaded_overlap_ICS_line)  +\
                energy_conveyor('ICS', bags, (l_fe/n_modules_tot)/l_ICS, empty_overlap_ICS_line, loaded_overlap_ICS_line)

    elif sortation_loop == 'Series':
        E_EBS += energy_conveyor('ICS', bags, l_te/l_ICS, empty_overlap_ICS, loaded_overlap_ICS) +\
                energy_conveyor('ICS', bags, l_fe/l_ICS, empty_overlap_ICS, loaded_overlap_ICS)

    return E_EBS

#%%
def return_trays(t_op, n_bags_tot, sortation_loop, return_trays_red):

    n_modules_tot = num_modules()

    E_return = 0

    bags = n_bags_tot

    empty_overlap_ICS, loaded_overlap_ICS = overlap(t_op, bags, v_ICS, l_ICS, w_tray)
    empty_overlap_ICS_lines, loaded_overlap_ICS_lines = overlap(t_op, bags/n_modules_tot, v_ICS, l_ICS, w_tray)

    E_return += energy_conveyor('ICS', bags, l_rs/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines)

    if sortation_loop == 'Series' and return_trays_red == 'Series':
        E_return += energy_conveyor('ICS', bags, l_rb/l_ICS, empty_overlap_ICS, loaded_overlap_ICS) +\
            energy_conveyor('ICS', bags, l_ret/l_ICS, empty_overlap_ICS, loaded_overlap_ICS) +\
                divert(bags*(1-(1/n_modules_tot)))

    elif sortation_loop == 'Parallel' and return_trays_red == 'Series':
        E_return += energy_conveyor('ICS', bags, (l_rb/n_modules_tot)/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines) +\
            energy_conveyor('ICS', bags, l_ret/l_ICS, empty_overlap_ICS, loaded_overlap_ICS) +\
                divert(bags*(1-(1/n_modules_tot)))

    elif sortation_loop == 'Series' and return_trays_red == 'Parallel':
        E_return += energy_conveyor('ICS', bags, (l_rb/n_modules_tot)/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines) +\
            energy_conveyor('ICS', bags, (l_ret/n_modules_tot)/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines) +\
                divert(bags*(1-(1/n_modules_tot)))

    elif sortation_loop == 'Parallel' and return_trays_red == 'Parallel':
        E_return += energy_conveyor('ICS', bags, (l_rb/n_modules_tot)/l_ICS, empty_overlap_ICS_lines, loaded_overlap_ICS_lines)  +\
```

```
            energy_conveyor('ICS', bags, (l_ret/n_modules_tot)/l_ICS, empty_overlap_ICS_lines
                , loaded_overlap_ICS_lines)

    return E_return

#%%
def initialise_lists(start_hour):
    E_tot_day_zeros, E_tot_day_bag = start_hour * [0], start_hour * [0]

    E_drop_tot_day = start_hour * [0]
    E_transport_op_day = start_hour * [0]
    E_HBS_tot_day = start_hour * [0]
    E_transport_sort_day = start_hour * [0]
    E_sort_op_day = start_hour * [0]
    E_EBS_tot_day = start_hour * [0]
    E_return_tot_day = start_hour * [0]

    E_drop_tot_day_bag = start_hour * [0]
    E_transport_op_day_bag = start_hour * [0]
    E_HBS_tot_day_bag = start_hour * [0]
    E_transport_sort_day_bag = start_hour * [0]
    E_sort_op_day_bag = start_hour * [0]
    E_EBS_tot_day_bag = start_hour * [0]
    E_return_tot_day_bag = start_hour * [0]

    E_process_tot_day = 18 * [0]
    E_main_tot_day = 7 * [0]
    E_main_tot_bag_day = 7 * [0]

    return E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day, E_transport_op_day,\
        E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
        E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
        E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag
            ,\
        E_process_tot_day, E_main_tot_day, E_main_tot_bag_day

def calculate_t_op(per_hour, period, t_op_tot):
    if per_hour == True:
        if period == 22:
            t_op = 2/3
        else:
            t_op = 1
    else:
        t_op = 1/6

    t_op_tot += t_op

    return t_op, t_op_tot

def overlap(t_op, n_bags, speed, l_conveyor, window):
    interarrival_time = (t_op*3600)/n_bags
    interdistance = interarrival_time * speed
    windows = l_conveyor / window

    loaded_overlap = 0
    empty_overlap = 0

    if interdistance < l_conveyor:
        loaded_overlap = 0.25
        empty_overlap = 0.5
    elif interdistance >= l_conveyor and interdistance < 2*l_conveyor:
        empty_overlap = ((1/8)/windows)+(3/8)
    elif interdistance >= 2*l_conveyor and interdistance < 3*l_conveyor:
        empty_overlap = ((1/8)/windows)+(1/8)

    return empty_overlap, loaded_overlap

def Parallel(df_scenarios, scenario):
    values = [df_scenarios[col][scenario] for col in df_scenarios.columns]
    drop_off_trayload, trayload_EDS, EDS_sorter, sortation_loop, return_trays_red = values

```

```
    return drop_off_trayload, trayload_EDS, EDS_sorter, sortation_loop, return_trays_red

def run_processes(t_op, n_bags_tot, scenario, drop_off_trayload, trayload_EDS, EDS_sorter, sortation_loop, return_trays_red):
    E_drop = drop_off(t_op, n_bags_tot)
    E_transport = transport_trayload(t_op, n_bags_tot, drop_off_trayload, trayload_EDS)
    E_HBS = HBS(t_op, n_bags_tot, EDS_sorter)
    E_transport_sort = transport_sorter(t_op, n_bags_tot, EDS_sorter, sortation_loop)
    E_sort = sorter(t_op, n_bags_tot, sortation_loop)
    E_EBS = EBS(t_op, n_bags_tot, sortation_loop)
    E_return = return_trays(t_op, n_bags_tot, sortation_loop, return_trays_red)

    return E_drop, E_transport, E_HBS, E_transport_sort, E_sort, E_EBS, E_return

def print_result_per_process(E_drop, E_drop_sum, E_transport, E_transport_sum, E_HBS,
                             E_HBS_sum, E_transport_sort, E_sort, E_sort_sum, E_EBS, E_return):
     print('\nDrop_off:', E_drop, E_drop_sum)
     print('Transport:', E_transport, E_transport_sum)
     print('HBS:', E_HBS, E_HBS_sum)
     print('Transport to sortation:', E_transport_sort)
     print('Sorter:', E_sort, E_sort_sum)
     print('EBS:', E_EBS)
     print('Return:', E_return)

def plots_per_timestep(processes, Energy_per_process, main_processes, Energy_per_main_process,
                       Energy_per_main_process_per_bag, axis_name_legend, period):
    plt.bar(processes, Energy_per_process)
    plt.title(f'Energy per process in {axis_name_legend} {period}')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=80)
    plt.show()

    plt.bar(main_processes, Energy_per_main_process)
    plt.title(f'Energy per process in {axis_name_legend} {period}')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=70)
    plt.show()

    plt.bar(main_processes, Energy_per_main_process_per_bag)
    plt.title(f'Energy per process per bag in {axis_name_legend} {period}')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=70)
    plt.show()

def calculate_E_sum(E_drop, E_transport, E_HBS, E_transport_sort, E_sort, E_EBS, E_return, n_bags_tot):
    E_drop_sum = sum(E_drop)
    E_transport_sum = sum(E_transport)
    E_HBS_sum = sum(E_HBS)
    E_sort_sum = sum(E_sort)

    E_drop_sum_bag = E_drop_sum/n_bags_tot
    E_transport_sum_bag = E_transport_sum/n_bags_tot
    E_HBS_sum_bag = E_HBS_sum/n_bags_tot
    E_transport_sort_bag = E_transport_sort/n_bags_tot
    E_sort_sum_bag = E_sort_sum/n_bags_tot
    E_EBS_bag = E_EBS/n_bags_tot
    E_return_bag = E_return/n_bags_tot

    return E_drop_sum, E_transport_sum, E_HBS_sum, E_sort_sum,\
        E_drop_sum_bag, E_transport_sum_bag, E_HBS_sum_bag,\
        E_transport_sort_bag, E_sort_sum_bag, E_EBS_bag, E_return_bag

```

```
def finalise_lists(end_day, end_hour, E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day,
    E_transport_op_day,\
    E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
    E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
    E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag):

    for i in range(end_day-end_hour):
        E_tot_day_zeros.append(0)
        E_tot_day_bag.append(0)
        E_drop_tot_day.append(0)
        E_transport_op_day.append(0)
        E_HBS_tot_day.append(0)
        E_transport_sort_day.append(0)
        E_sort_op_day.append(0)
        E_EBS_tot_day.append(0)
        E_return_tot_day.append(0)
        E_drop_tot_day_bag.append(0)
        E_transport_op_day_bag.append(0)
        E_HBS_tot_day_bag.append(0)
        E_transport_sort_day_bag.append(0)
        E_sort_op_day_bag.append(0)
        E_EBS_tot_day_bag.append(0)
        E_return_tot_day_bag.append(0)

    return E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day, E_transport_op_day,\
        E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
        E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
        E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag

def plot_output(scenario, processes, E_tot_day, E_process_tot_day, main_processes,
    E_main_tot_day,
                E_main_tot_bag_day, E_tot_day_bag, E_tot_day_zeros, end_day, axis_name,
                E_drop_tot_day, E_transport_op_day, E_HBS_tot_day, E_transport_sort_day,
                E_sort_op_day, E_EBS_tot_day, E_return_tot_day, E_drop_tot_day_bag,
                E_transport_op_day_bag, E_HBS_tot_day_bag, E_transport_sort_day_bag,
                E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag, axis_name_legend,
                    n_bags_tot_day, time_0_23):

    # Get energy per process per hour and plot it
    plt.bar(processes, E_process_tot_day)
    plt.title(f'Energy per process per day (scenario {scenario})')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=80)
    plt.show()

    # Get energy per main process per hour and plot it
    plt.bar(main_processes, E_main_tot_day)
    plt.title(f'Energy per process per day (scenario {scenario})')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=70)
    plt.show()

    # Get energy per process per hour per bag and plot it
    plt.bar(main_processes, E_main_tot_bag_day)
    plt.title(f'Estimated energy consumption per process per bag per day (scenario {scenario
        })')
    plt.xlabel('Process')
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    plt.xticks(rotation=70)
    plt.show()

    # Plot energy consumption over the day
    plt.plot(time_0_23, E_tot_day_bag)
    plt.title(f'Estimated energy consumption over the day per bag (scenario {scenario})')
    plt.xlabel(axis_name)
    plt.ylabel('Estimated energy consumption (kWh)')
```

```
    plt.grid(True)
    if per_hour == True:
        plt.xticks(time_0_23)
    plt.show()

    plt.plot(time_0_23, E_tot_day_zeros)
    plt.title(f'Estimated energy consumption over the day (scenario {scenario})')
    plt.xlabel(axis_name)
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    if per_hour == True:
        plt.xticks(time_0_23)
    plt.show()

    # Plot energy consumption over the day per process
    plt.plot(time_0_23, E_drop_tot_day, label='Drop-off', color='orange')
    plt.plot(time_0_23, E_transport_op_day, label='Transport to HBS', color='red')
    plt.plot(time_0_23, E_HBS_tot_day, label='HBS', color='green')
    plt.plot(time_0_23, E_transport_sort_day, label='Transportation to sortation', color='deeppink')
    plt.plot(time_0_23, E_sort_op_day, label='Sortation', color='grey')
    plt.plot(time_0_23, E_EBS_tot_day, label='EBS', color='blue')
    plt.plot(time_0_23, E_return_tot_day, label='Return of trays', color='purple')
    plt.title(f'Estimated energy consumption per process over the day (scenario {scenario})')
    plt.xlabel(axis_name)
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    if per_hour == True:
        plt.xticks(time_0_23)
    plt.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')
    plt.show()

    plt.plot(time_0_23, E_drop_tot_day_bag, label='Drop-off', color='orange')
    plt.plot(time_0_23, E_transport_op_day_bag, label='Transport to HBS', color='red')
    plt.plot(time_0_23, E_HBS_tot_day_bag, label='HBS', color='green')
    plt.plot(time_0_23, E_transport_sort_day_bag, label='Transportation to sortation', color='deeppink')
    plt.plot(time_0_23, E_sort_op_day_bag, label='Sortation', color='grey')
    plt.plot(time_0_23, E_EBS_tot_day_bag, label='EBS', color='blue')
    plt.plot(time_0_23, E_return_tot_day_bag, label='Return of trays', color='purple')
    plt.title(f'Estimated energy consumption per process per bag over the day (scenario {scenario})')
    plt.xlabel(axis_name)
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    if per_hour == True:
        plt.xticks(time_0_23)
    plt.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')
    plt.show()

    plt.plot(time_0_23, E_tot_day_bag, label=f'Average energy \nper bag per {axis_name_legend}')
    plt.axhline(y=sum(E_tot_day)/n_bags_tot_day, color='r', label='Average energy \nper bag per day')
    plt.title(f'Estimeated energy consumption per bag over the day (scenario {scenario})')
    plt.xlabel(axis_name)
    plt.ylabel('Estimated energy consumption (kWh)')
    plt.grid(True)
    if per_hour == True:
        plt.xticks(time_0_23)
    plt.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')
    plt.show()

def plot_E_scenario(E_scenario, E_scenario_day, time_0_23, axis_name, per_hour,
            E_scenario_drop, E_scenario_transport, E_scenario_HBS,
            E_scenario_tosort, E_scenario_sort, E_scenario_EBS, E_scenario_return):
    # Plot energy per scenario
    plt.bar([sc for sc in range(1,len(E_scenario)+1)], E_scenario)
    plt.title('Estimated energy consumption per scenario per day')
    plt.xlabel('Scenario')
    plt.ylabel('Estimated energy consumption (kWh)')
```

```
    plt.grid(True)
    plt.xticks([sc for sc in range(1, len(E_scenario)+1)])
    plt.show()

    colors = ['blue', 'green', 'red', 'grey', 'deeppink', 'orange', 'purple']

    scenarios = [(E_scenario_drop, 'process 1'), (E_scenario_transport, 'process 2'),
                 (E_scenario_HBS, 'process 3'), (E_scenario_tosort, 'process 4'),
                 (E_scenario_sort, 'process 5'), (E_scenario_EBS, 'process 6'),
                 (E_scenario_return, 'process 7'), (E_scenario_day, 'the total BHS')]

    for scenario, process in scenarios:
        for i, E_day in enumerate(scenario):
            plt.plot(time_0_23, E_day, label=f'Scenario {i+1}', color=colors[i % len(colors)
                ])
        plt.title(f'Estimated energy consumption over the day for {process}')
        plt.xlabel(axis_name)
        plt.ylabel('Estimated energy consumption (kWh)')
        plt.grid(True)
        if per_hour:
            plt.xticks(time_0_23)
        plt.legend(bbox_to_anchor=(1.05, 1.0), loc='upper left')
        plt.show()

    import numpy as np
    for scenario, process in scenarios:
        total_values = [np.sum(E_day) for E_day in scenario]
        plt.bar(range(1, len(total_values) + 1), total_values, color=colors[:len(total_values
            )], tick_label=[f'{i+1}' for i in range(len(total_values))])
        plt.title(f'Estimated energy consumption for each scenario in {process}')
        plt.xlabel('Scenario')
        plt.ylabel('Estimated energy consumption (kWh)')
        plt.grid(True)
        plt.show()

    print('\n### Overall: ###')
    print(f'The scenario with the lowest total energy expected to be consumed per day is
        scenario {E_scenario.index(min(E_scenario))+1} with {round(min(E_scenario),4)} kWh')
    print(f'The scenario with the highest total energy expected to be consumed per day is
        scenario {E_scenario.index(max(E_scenario))+1} with {round(max(E_scenario),4)} kWh')

#%%

def calculating_scenarios(per_hour, plots_show, print_per_hour, print_per_process,
    give_output):

    df_scenarios = pd.read_csv('Scenarios input.csv')
    df_scenarios = df_scenarios.set_index('Scenario')

    E_scenario = []
    E_scenario_day = []

    E_scenario_drop = []
    E_scenario_transport = []
    E_scenario_HBS = []
    E_scenario_tosort = []
    E_scenario_sort = []
    E_scenario_EBS = []
    E_scenario_return = []

    for scenario in df_scenarios.index:
        drop_off_trayload, trayload_EDS, EDS_sorter, sortation_loop, return_trays = Parallel(
            df_scenarios, scenario)

        # Initialisation
        E_tot_day = []

        if per_hour == True:
            bags_per_hour = pd.read_csv('Average bags inserted per hour.csv')
            axis_name = 'Hour'
            axis_name_legend = 'hour'
```

```
        else:
            bags_per_hour = pd.read_csv('Average bags inserted per 10 minutes.csv')
            axis_name = 'Period (10 minutes)'
            axis_name_legend = 'period'

        start_hour = bags_per_hour['Hour'].loc[bags_per_hour['Average per operating hour'] != 0].iloc[0]
        end_hour = bags_per_hour.loc[bags_per_hour['Average per operating hour'].to_numpy().nonzero()[0][-1], 'Hour'] + 1
        end_day = len(bags_per_hour)

        E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day, E_transport_op_day,\
            E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
            E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
            E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag,\
            E_process_tot_day, E_main_tot_day, E_main_tot_bag_day = initialise_lists(start_hour)

        n_bags_max = 0
        n_bags_min = 10000000

        t_op_tot = 0

        n_bags_tot_day = 0

        for period in range(start_hour, end_hour):
            t_op, t_op_tot = calculate_t_op(per_hour, period, t_op_tot)

            n_bags_tot = bags_per_hour.loc[bags_per_hour['Hour'] == period, 'Average per operating hour'].iloc[0]
            n_bags_tot_day += n_bags_tot

            E_drop, E_transport, E_HBS, E_transport_sort, E_sort, E_EBS, E_return =\
                run_processes(t_op, n_bags_tot, scenario, drop_off_trayload, trayload_EDS, EDS_sorter, sortation_loop, return_trays)

            E_drop_sum, E_transport_sum, E_HBS_sum, E_sort_sum, E_drop_sum_bag, E_transport_sum_bag,\
                E_HBS_sum_bag, E_transport_sort_bag, E_sort_sum_bag, E_EBS_bag,\
                E_return_bag = calculate_E_sum(E_drop, E_transport, E_HBS, E_transport_sort, E_sort, E_EBS, E_return, n_bags_tot)

            if print_per_process == True:
                print(f'\n### The {axis_name_legend} is:', period, '###')
                print_result_per_process(E_drop, E_drop_sum, E_transport, E_transport_sum, E_HBS,
                                         E_HBS_sum, E_transport_sort, E_sort, E_sort_sum, E_EBS, E_return)

            # Get energy per hour
            E_tot_hour = E_drop_sum + E_transport_sum + E_HBS_sum + E_transport_sort + E_sort_sum + E_EBS + E_return
            E_tot_day.append(E_tot_hour)
            E_tot_day_zeros.append(E_tot_hour)
            E_tot_day_bag.append(E_tot_hour/n_bags_tot)

            if n_bags_tot > n_bags_max:
                E_busiest_bag = E_tot_hour/n_bags_tot
                n_bags_max = n_bags_tot
            if n_bags_tot < n_bags_min:
                E_least_busy_bag = E_tot_hour/n_bags_tot
                n_bags_min = n_bags_tot

            if print_per_hour == True:
                print(f'\n### The {axis_name_legend} is:', period, '###')
                print(f'The total energy expected to be consumed per {axis_name_legend} is: {round(E_tot_hour,4)} kWh')
                print(f'The total energy expected to be consumed per bag in {axis_name_legend} {period} is: {round(E_tot_hour/n_bags_tot,4)} kWh')
```

```

            E_drop_tot_day.append(E_drop_sum)
            E_transport_op_day.append(E_transport_sum)
            E_HBS_tot_day.append(E_HBS_sum)
            E_transport_sort_day.append(E_transport_sort)
            E_sort_op_day.append(E_sort_sum)
            E_EBS_tot_day.append(E_EBS)
            E_return_tot_day.append(E_return)

            E_drop_tot_day_bag.append(E_drop_sum_bag)
            E_transport_op_day_bag.append(E_transport_sum_bag)
            E_HBS_tot_day_bag.append(E_HBS_sum_bag)
            E_transport_sort_day_bag.append(E_transport_sort_bag)
            E_sort_op_day_bag.append(E_sort_sum_bag)
            E_EBS_tot_day_bag.append(E_EBS_bag)
            E_return_tot_day_bag.append(E_return_bag)

            # Get energy per process per hour
            Energy_per_process = [E_drop[0], E_drop[1], E_drop[2], E_drop[3], E_drop[4], E_transport[0], E_transport[1], E_transport[2], E_HBS[0],
                                  E_HBS[1], E_transport_sort, E_sort[0], E_sort[1], E_sort[2], E_sort[3], E_EBS, E_return]

            E_process_tot_day = [a + b for a, b in zip(E_process_tot_day, Energy_per_process)]
            processes = ['E_kiosks', 'E_dod', 'E_dropbelt', 'E_collectorbelt_1bag', 'E_collectorbelt_empty', 'E_2a', 'E_2b', 'E_2c', 'E_L1',
                         'E_L3', 'E_transport_sort', 'E_5a', 'E_5b', 'E_5c', 'E_5d', 'E_EBS', 'E_return']

            # Get energy per main process per hour
            Energy_per_main_process = [E_drop_sum, E_transport_sum, E_HBS_sum, E_transport_sort, E_sort_sum, E_EBS, E_return]
            E_main_tot_day = [a + b for a, b in zip(E_main_tot_day, Energy_per_main_process)]
            main_processes = ['Drop-off', 'Transport to HBS', 'HBS', 'Transport to sortation', 'Sorter', 'EBS', 'Return']

            # Get energy per process per hour per bag
            Energy_per_main_process_per_bag = [E_drop_sum_bag, E_transport_sum_bag, E_HBS_sum_bag,
                                               E_transport_sort_bag, E_sort_sum_bag, E_EBS_bag, E_return_bag]
            E_main_tot_bag_day = [a + b for a, b in zip(E_main_tot_bag_day, Energy_per_main_process_per_bag)]

            if plots_show == True:
                plots_per_timestep(processes, Energy_per_process, main_processes, Energy_per_main_process,
                    Energy_per_main_process_per_bag, axis_name_legend, period)

        E_scenario.append(sum(E_tot_day))

        E_scenario_drop.append(E_drop_tot_day)
        E_scenario_transport.append(E_transport_op_day)
        E_scenario_HBS.append(E_HBS_tot_day)
        E_scenario_tosort.append(E_transport_sort_day)
        E_scenario_sort.append(E_sort_op_day)
        E_scenario_EBS.append(E_EBS_tot_day)
        E_scenario_return.append(E_return_tot_day)

        E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day, E_transport_op_day,\
            E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
            E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
            E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag =\
                finalise_lists(end_day, end_hour, E_tot_day_zeros, E_tot_day_bag, E_drop_tot_day, E_transport_op_day,\
                E_HBS_tot_day, E_transport_sort_day, E_sort_op_day, E_EBS_tot_day,\
                E_return_tot_day, E_drop_tot_day_bag, E_transport_op_day_bag, E_HBS_tot_day_bag,\
                E_transport_sort_day_bag, E_sort_op_day_bag, E_EBS_tot_day_bag,
```

```
                    E_return_tot_day_bag)

        E_scenario_day.append(E_tot_day_zeros)

        if give_output == True:
            print(f'\n### Energy per day (scenario {scenario}): ###')
            print('The total energy expected to be consumed per day is: {} kWh'.format(round(sum(E_tot_day),4)))
            print('The average energy expected to be consumed per operating hour is: {} kWh'.format(round(sum(E_tot_day)/t_op_tot,4)))
            print('The average energy expected to be consumed per hour is: {} kWh'.format(round(sum(E_tot_day)/24,4)))
            print('The average energy expected to be consumed per bag in the busiest {} is: {} kWh'.format(axis_name_legend, round(E_busiest_bag,4)))
            print('The average energy expected to be consumed per bag in the least busy {} is: {} kWh'.format(axis_name_legend, round(E_least_busy_bag,4)))
            print('The average energy expected to be consumed per bag per day is: {} kWh'.format(round(sum(E_tot_day)/n_bags_tot_day,4)))

            time_0_23 = [hour for hour in range(end_day)]

            plot_output(scenario, processes, E_tot_day, E_process_tot_day, main_processes, E_main_tot_day,
                        E_main_tot_bag_day, E_tot_day_bag, E_tot_day_zeros, end_day, axis_name,
                        E_drop_tot_day, E_transport_op_day, E_HBS_tot_day, E_transport_sort_day,
                        E_sort_op_day, E_EBS_tot_day, E_return_tot_day, E_drop_tot_day_bag,
                        E_transport_op_day_bag, E_HBS_tot_day_bag, E_transport_sort_day_bag,
                        E_sort_op_day_bag, E_EBS_tot_day_bag, E_return_tot_day_bag, axis_name_legend, n_bags_tot_day, time_0_23)

    plot_E_scenario(E_scenario, E_scenario_day, time_0_23, axis_name, per_hour,
                    E_scenario_drop, E_scenario_transport, E_scenario_HBS,
                    E_scenario_tosort, E_scenario_sort, E_scenario_EBS, E_scenario_return)

#%%

per_hour = False

plots_show = False
print_per_hour = False
print_per_process = False
give_output = True

calculating_scenarios(per_hour, plots_show, print_per_hour, print_per_process, give_output)
```

C

Derivation of time factors

C.1. $itd < l_d$

The time factor for operating loaded conveyor devices, given that the interdistance of bags is smaller than a device length, is calculated in this section. The situation is illustrated in Figures C.1, C.2, and C.3 for cases with bag windows n_w ranging from 2 to 4. The positions of the bags are discretised and indicated with crosses. A conveyor device is always operating when loaded with at least 1 bag, as indicated with 'L'. The conveyor devices indicated with 'Em' are operating while empty to increase or decrease the device's speed.

Figure C.1: Overlap of device usage with $itd < l_d$ and $n_w = 2$

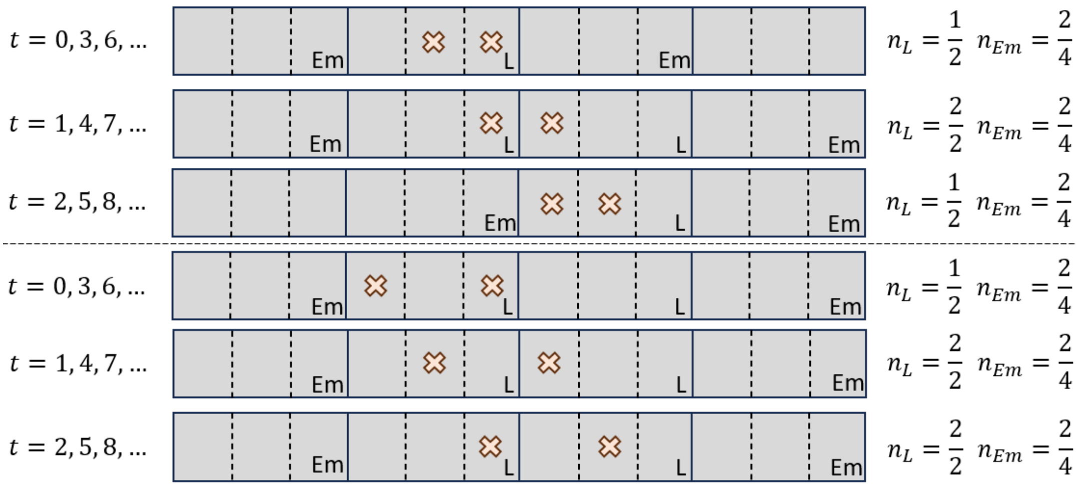

Figure C.2: Overlap of device usage with $itd < l_d$ and $n_w = 3$

When the interdistance is larger than or equal to a device length ($itd \geq l_d$), exactly 1 bag is loaded on a conveyor device. In the current situation, the interdistance is smaller than a device length, i.e. $itd < l_d$, such that it could occur that multiple bags are on the same conveyor device simultaneously. This overlap of loaded device usage results in a decreased energy consumption, as fewer devices should operate for the same number of bags. From Figures C.1, C.2, and C.3, the number of cases in which overlap of loaded device usage occurs can be found. Namely, n_L indicates the fraction of devices that is operated while loaded for two bags. In Equation C.1, the number of cases in which a decreased energy consumption occurs, i.e. $n_L < \frac{2}{2}$, is presented.

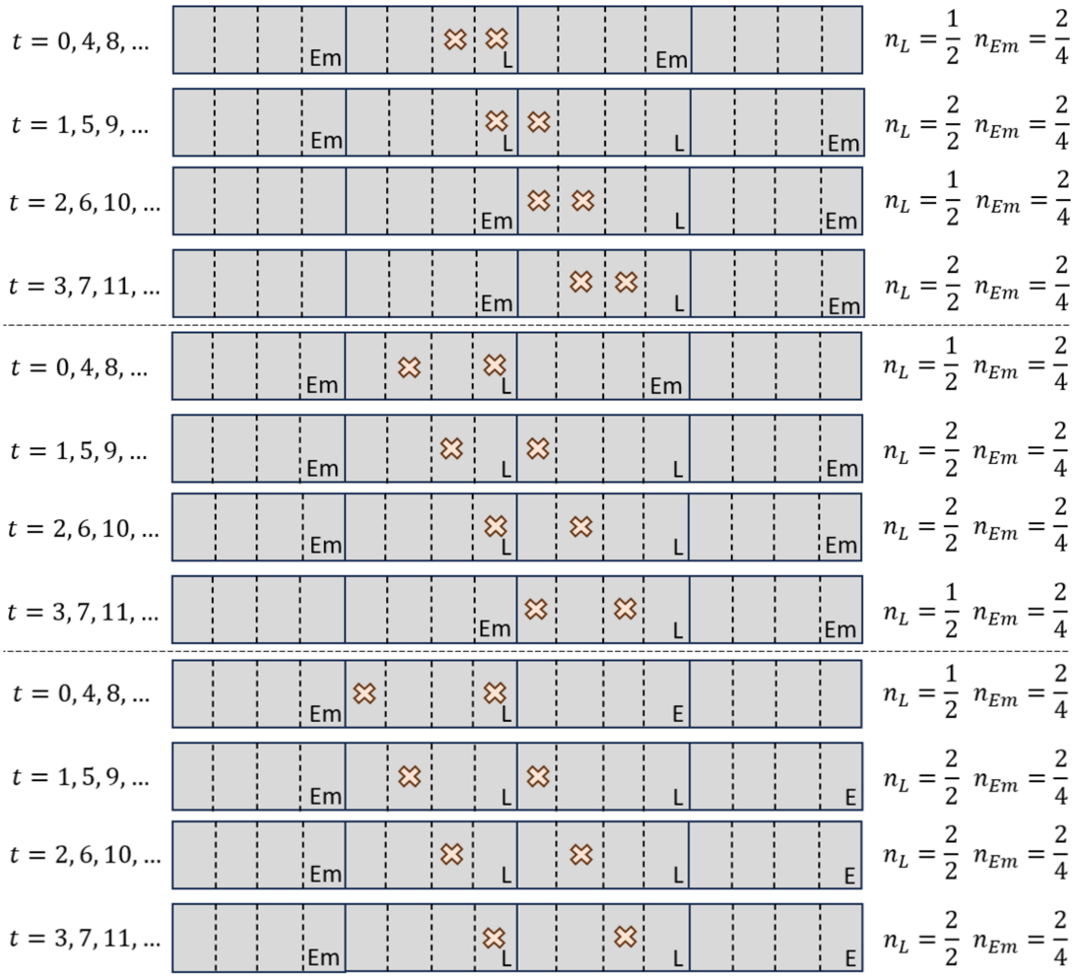

Figure C.3: Overlap of device usage with $itd < l_d$ and $n_w = 4$

$$n_{cases} = \sum_{x=1}^{n_w-1} n_w - x = \frac{(n_w-1)+1}{2} \cdot (n_w - 1) = \frac{n_w}{2} \cdot (n_w - 1) = \frac{1}{2}(n_w^2 - n_w) \quad \text{(C.1)}$$

Where n_w is the number of bags, as calculated in Equation 3.9. The summation is a sequence in which the difference is constant. This is known as a finite arithmetic sequence (Ross, 2017). It is rewritten using the formula for the sum of an arithmetic series, see Equation C.2.

$$sum_{series} = \frac{a_1 + a_2}{2} \cdot n \quad \text{(C.2)}$$

With a_1 being the first term of the series, which is $n_w - 1$, a_2 being the last term of the series, which is 1, and n being the number of terms, which is $n_w - 1$ (Khan Academy, 2024).

The total number of relative positions the bags can have, can be calculated with Equation C.3.

$$n_{tot} = n_w^2 - n_w \quad \text{(C.3)}$$

To find the probability that overlap of loaded device usage occurs, given that the interdistance of bags is smaller than the device's length $P(overlap_L|itd < l_d)$, Equation C.4 is employed. The probability can be found by comparing the number of cases in which overlap of loaded device usage occurs n_{cases} (Equation C.1) and the total number of relative positions the bags can have n_{tot} (Equation C.3).

$$P(overlap_L|itd < l_d) = \frac{n_{cases}}{n_{tot}} = \frac{\frac{1}{2}(n_w^2 - n_w)}{n_w^2 - n_w} = \frac{1}{2} \quad \text{(C.4)}$$

The expected value of the number of decreased loaded device operations can be calculated as in Equation C.5. Please note that E is referred to as the expected value in this appendix, although referred to as electrical energy in the remainder of the report.

$$E_{reduction} = P(overlap_L | itd < l_d) \cdot n_{overlap_L} = \frac{1}{2} \cdot \frac{1}{2} = \frac{1}{4} \tag{C.5}$$

Where $n_{overlap_L} = \frac{1}{2}$ is the rate of decreased loaded device operations given that there is overlap.

The time factor for the usage of loaded conveyor devices given that the interdistance of bags is smaller than a device's length, can be found using Equation C.6.

$$f_{L,itd<l_d} = 1 - E_{reduction} = 1 - \frac{1}{4} = \frac{3}{4} \tag{C.6}$$

The time factor for operating empty devices is equal to $\frac{1}{2}$ when $itd < l_d$. Namely, the number of empty devices simultaneously operated per bag is 2 if the interdistance of bags does not cause any overlap of device usage. When the interdistance of bags is smaller than a device's length, it does not happen that there is an empty device in between two bags by definition. This follows from Figures C.1, C.2, and C.3, as well. As such, the number of empty devices operated in any case is 2 (instead of 4) for 2 bags.

C.2. $l_d \leq itd < 2l_d$

The value for the time factor for operating loaded and empty conveyor devices, given that the interdistance of bags is greater than or equal to a device length and smaller than two device lengths ($l_d \leq itd < 2l_d$), is explained in this section. The situation is illustrated in Figures C.4, C.5, and C.6. The interpretations of the figures are similar to those of Figures C.1, C.2, and C.3.

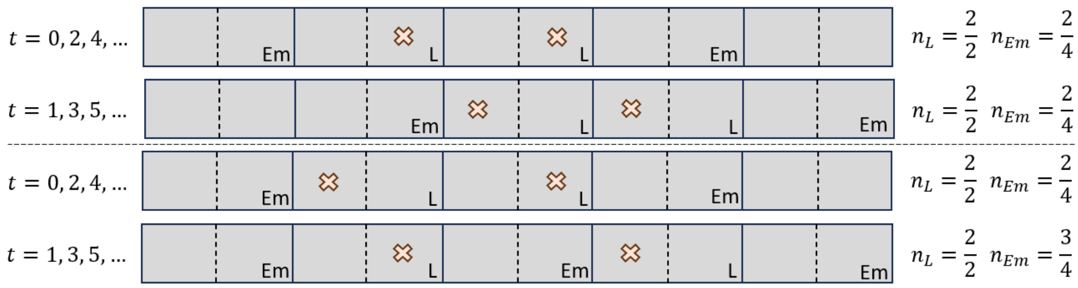

Figure C.4: Overlap of device usage with $l_d \leq itd < 2l_d$ and $n_w = 2$

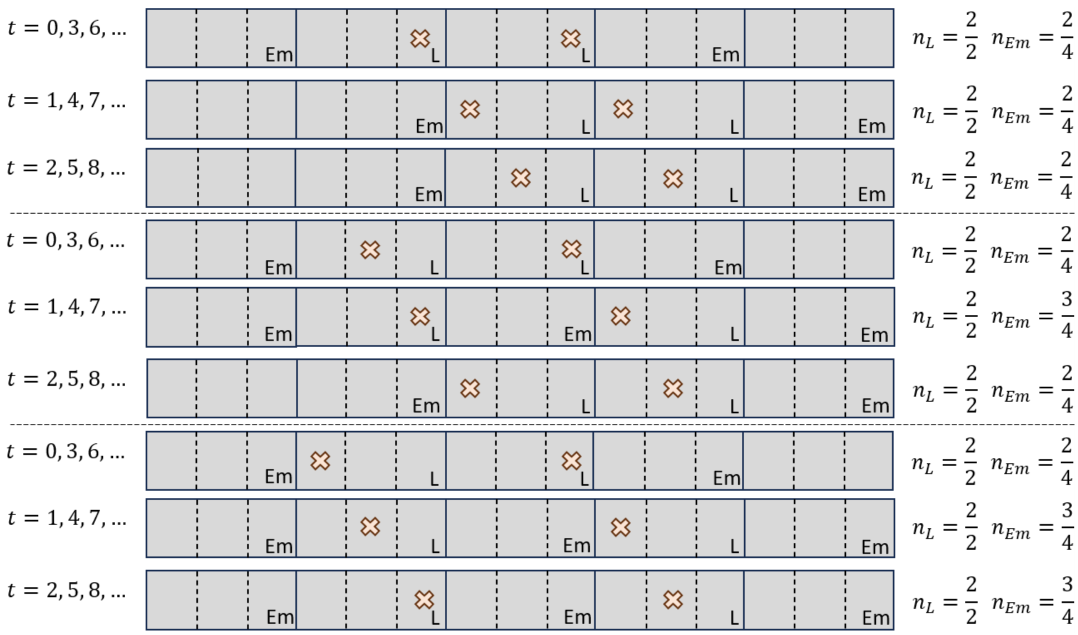

Figure C.5: Overlap of device usage with $l_d \leq itd < 2l_d$ and $n_w = 3$

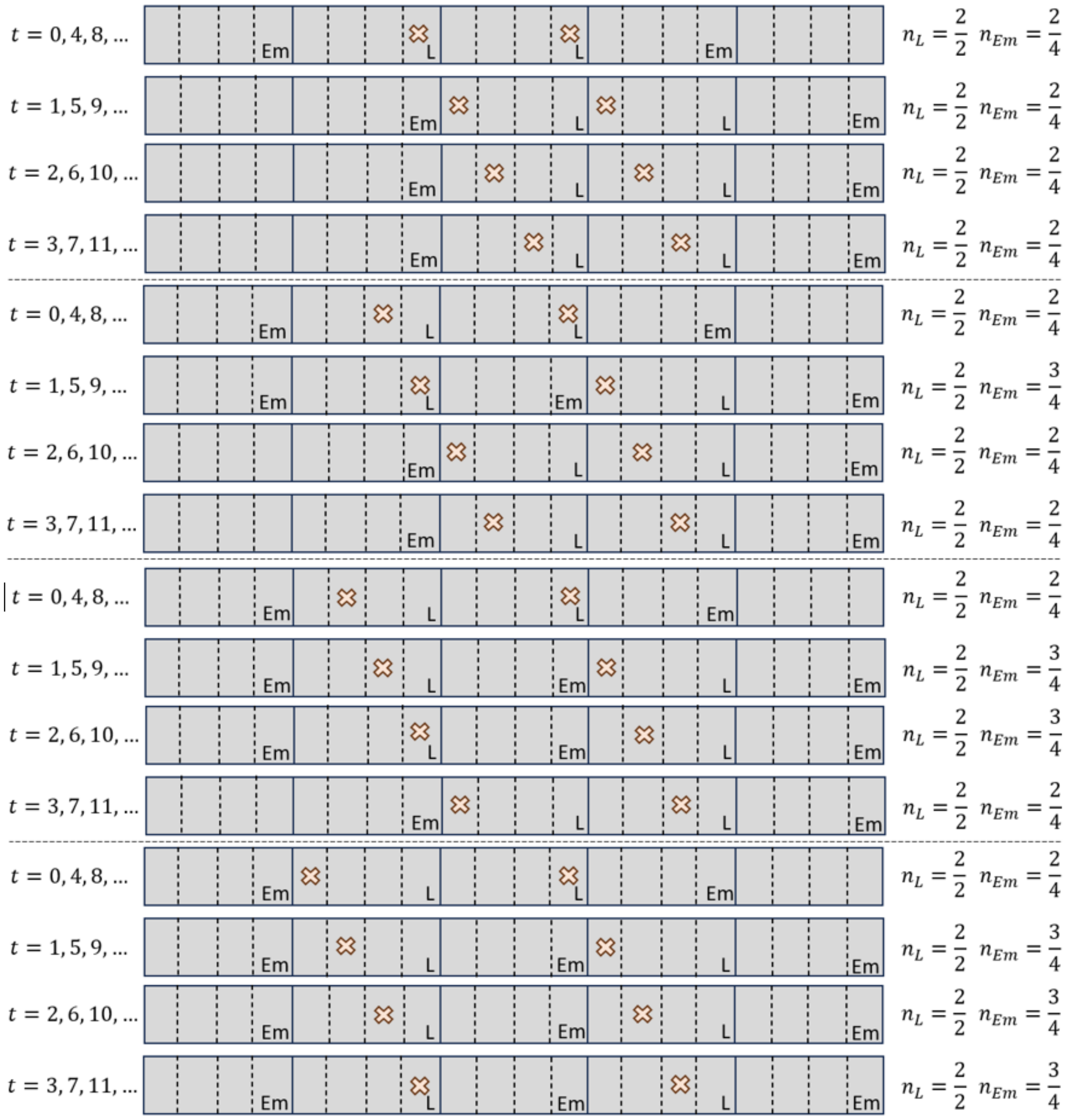

Figure C.6: Overlap of device usage with $l_d \leq itd < 2l_d$ and $n_w = 4$

When the interdistance is larger than or equal to a device length ($itd \geq l_d$), a conveyor device carries at most 1 bag simultaneously. This means that the time factor for loaded devices is equal to 1. In other words, no overlap in loaded device usage occurs and thus no energy is saved here.

The number of empty devices simultaneously operated per bag is 2 if the interdistance of bags does not cause any overlap of device usage. When the interdistance of bags is between 1 and 2 device lengths, either no or one empty device is in between two bags. This overlap of empty device usage results in decreased energy consumption, as fewer devices should operate for the same number of bags. From Figures C.4, C.5, and C.6, the number of cases in which overlap of empty device usage occurs can be found. Namely, n_{Em} indicates the fraction of devices that are operated for two bags while empty.

For calculating the time factor covering this reduction in device usage, the probabilities of overlap of 1 and 2 devices should be calculated separately first.

In Equation C.7, the number of cases in which there is an overlap of device usage of two devices, i.e. $n_{Em} = \frac{2}{4}$, is presented.

$$n_{cases,\frac{2}{4}} = \sum_{x=0}^{n_w-1} n_w - x = \frac{n_w+1}{2} \cdot n_w = \frac{1}{2}(n_w^2 + n_w) \tag{C.7}$$

Where n_w is the number of bags, as calculated in Equation 3.9. As the summation is a sequence in which the difference is constant, it is again a finite arithmetic sequence (Ross, 2017). It is rewritten using the formula for the sum of an arithmetic series, see Equation C.2, with a_1 being the first term of the series, which is n_w, a_2 being the last term of the series, which is 1, and n being the number of terms, which is n_w.

The total number of relative positions the bags can have, can be calculated with Equation C.8.

$$n_{tot} = n_w^2 \tag{C.8}$$

To find the probability that overlap of 2 empty device usage occurs, given that the interdistance of bags is greater than or equal to a device length and smaller than two device lengths $P(n_{Em} = \frac{2}{4}|l_d \leq itd < 2l_d)$, Equation C.9 is employed. The probability can be found by comparing the number of cases in which overlap of loaded device usage occurs $n_{cases,\frac{2}{4}}$ (Equation C.7) and the total number of relative positions the bags can have n_{tot} (Equation C.8).

$$P(n_{Em} = \frac{2}{4}|l_d \leq itd < 2l_d) = \frac{n_{cases}}{n_{tot}} = \frac{\frac{1}{2}(n_w^2 + n_w)}{n_w^2} = \frac{n_w^2 + n_w}{2n_w^2} = \frac{n_w^2}{2n_w^2} + \frac{n_w}{2n_w^2} = \frac{1}{2} + \frac{1}{2n_w} = \frac{1}{2}(1 + \frac{1}{n_w}) \tag{C.9}$$

The number of cases in which there is an overlap of device usage of one device, i.e. $n_{Em} = \frac{3}{4}$, can be calculated as in Equation C.1. This is referred to as $n_{cases,\frac{3}{4}}$ in this section. The total number of relative positions n_{tot} is similar to Equation C.8.

To find the probability that overlap of 1 empty device usage occurs, given that the interdistance of bags is greater than or equal to a device length and smaller than two device lengths $P(n_{Em} = \frac{3}{4}|l_d \leq itd < 2l_d)$, Equation C.10 is employed. The probability can be found by comparing the number of cases in which overlap of loaded device usage occurs $n_{cases,\frac{2}{4}}$ (Equation C.7) and the total number of relative positions the bags can have n_{tot} (Equation C.8).

$$P(n_{Em} = \frac{3}{4}|l_d \leq itd < 2l_d) = \frac{n_{cases}}{n_{tot}} = \frac{\frac{1}{2}(n_w^2 - n_w)}{n_w^2} = \frac{n_w^2 - n_w}{2n_w^2} = \frac{n_w^2}{2n_w^2} - \frac{n_w}{2n_w^2} = \frac{1}{2} - \frac{1}{2n_w} = \frac{1}{2}(1 - \frac{1}{n_w}) \tag{C.10}$$

The expected value of the number of decreased empty device operations can be calculated as in Equation C.11.

$$\begin{aligned} E_{reduction} &= P(n_{Em} = \frac{2}{4}|l_d \leq itd < 2l_d) \cdot n_{overlap_{Em,2}} + P(n_{Em} = \frac{3}{4}|l_d \leq itd < 2l_d) \cdot n_{overlap_{Em,1}} \\ &= (\frac{1}{2}(1 + \frac{1}{n_w})) \cdot \frac{2}{4} + (\frac{1}{2}(1 - \frac{1}{n_w})) \cdot \frac{1}{4} = \frac{1}{4}(1 + \frac{1}{n_w}) + \frac{1}{8}(1 - \frac{1}{n_w}) = \frac{1}{4} + \frac{1}{4n_w} + \frac{1}{8} - \frac{1}{8n_w} \\ &= \frac{3}{8} + \frac{1}{8n_w} \end{aligned} \tag{C.11}$$

Where $n_{overlap_{Em,1}} = \frac{2}{4}$ is the rate of decreased empty device operations given that there is an overlap of empty device usage of 2 devices. Similarly, $n_{overlap_{Em,2}} = \frac{1}{4}$ is the rate of decreased empty device operations given that there is an overlap of empty device usage of 1 device.

The time factor for the usage of loaded conveyor devices given that the interdistance of bags is smaller than twice a device's length and greater than or equal to one device length, can be found using Equation C.12.

$$f_{Em,l_d \leq itd < 2l_d} = 1 - E_{reduction} = 1 - (\frac{3}{8} + \frac{1}{8n_w}) = 1 - \frac{3}{8} - \frac{1}{8n_w} = \frac{5}{8} - \frac{1}{8n_w} = \frac{1}{8}(5 - \frac{1}{n_w}) \tag{C.12}$$

C.3. $2l_d \leq itd < 3l_d$

The value for the time factor for operating loaded and empty conveyor devices, given that the interdistance of bags is greater than or equal to twice a device length and smaller than three device lengths ($2l_d \leq itd < 3l_d$), is explained in this section. The situation is illustrated in Figures C.7, C.8, and C.9. The interpretations of the figures are similar to those of Figures C.1, C.2, C.3, C.4, C.5, and C.6.

Figure C.7: Overlap of device usage with $2l_d \leq itd < 3l_d$ and $n_w = 2$

When the interdistance is larger than or equal to a device length ($itd \geq l_d$), exactly 1 bag is loaded on a conveyor device. This means that the time factor for loaded devices is equal to 1. In other words, no overlap in loaded device usage occurs and thus no energy is saved here.

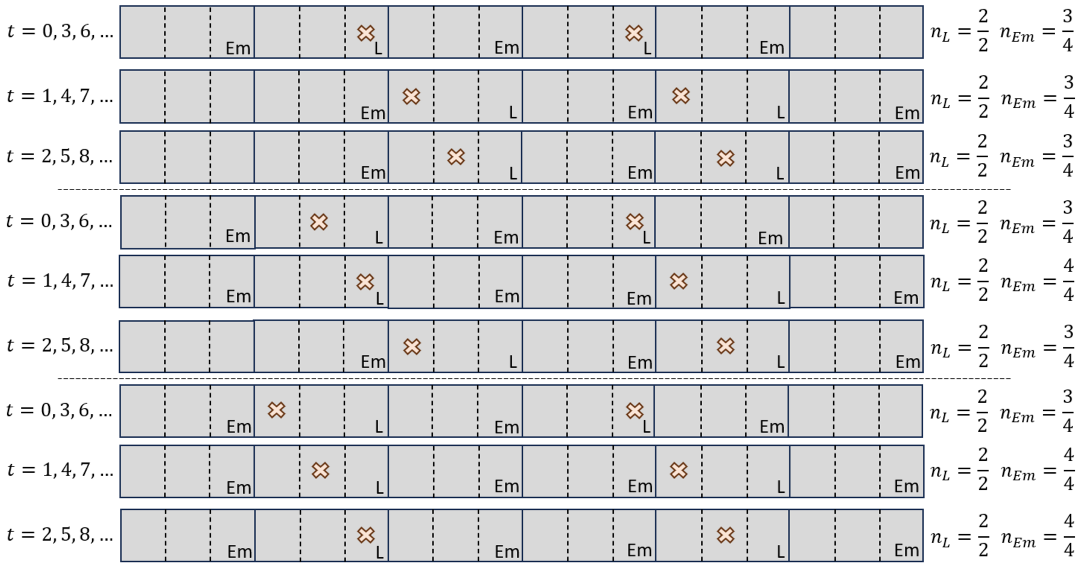

Figure C.8: Overlap of device usage with $2l_d \leq itd < 3l_d$ and $n_w = 3$

The number of empty devices simultaneously operated per bag is 2 if the interdistance of bags does not cause any overlap of device usage. When the interdistance of bags is between 1 and 2 device lengths, either 1 or 2 empty devices are in between two bags. When there is an overlap of one empty device usage, a decreased energy consumption is the result, as fewer devices should operate for the same number of bags. From Figures C.7, C.8, and C.9, the number of cases in which overlap of empty device usage occurs can be found. Namely, n_{Em} indicates the fraction of devices that are operated for two bags while empty. From the figures, it becomes clear that the savings in empty device operations are at most 1 device in each instance.

In Equation C.13, the number of cases in which there is an overlap of device usage, i.e. $n_{Em} < \frac{4}{4}$, is presented.

$$n_{cases} = \sum_{x=0}^{n_w-1} n_w - x = \frac{n_w+1}{2} \cdot n_w = \frac{1}{2}(n_w^2 + n_w) \tag{C.13}$$

Where n_w is the number of bags, as calculated in Equation 3.9. As the summation is a sequence in which the difference is constant, it is again a finite arithmetic sequence (Ross, 2017). It is rewritten using the formula for the sum of an arithmetic series, see Equation C.2, with a_1 being the first term of the series, which is n_w, a_2 being the last term of the series, which is 1, and n being the number of terms, which is n_w.

The total number of relative positions the bags can have, can be calculated with Equation C.8.

To find the probability that overlap of empty device usage occurs, given that the interdistance of bags is greater than or equal to two device lengths and smaller than three device lengths $P(n_{Em} = \frac{3}{4} | 2l_d \leq itd < 3l_d)$, Equation C.14 is employed. The probability can be found by comparing the number of cases in which overlap of loaded device usage occurs n_{cases} (as in Equation C.13) and the total number of relative positions the bags can have n_{tot} (Equation C.8).

$$\begin{aligned} P(n_{Em} = \frac{3}{4} | 2l_d \leq itd < 3l_d) &= \frac{n_{cases}}{n_{tot}} = \frac{\frac{1}{2}(n_w^2+n_w)}{n_w^2} = \frac{n_w^2+n_w}{2n_w^2} = \frac{n_w^2}{2n_w^2} + \frac{n_w}{2n_w^2} = \frac{1}{2} + \frac{1}{2n_w} \\ &= \frac{1}{2}(1 + \frac{1}{n_w}) \end{aligned} \tag{C.14}$$

The expected value of the number of decreased empty device operations can be calculated as in Equation C.15.

$$E_{reduction} = P(n_{Em} = \frac{3}{4} | 2l_d \leq itd < 3l_d) \cdot n_{overlap_{Em}} = (\frac{1}{2}(1 + \frac{1}{n_w})) \cdot \frac{1}{4} = \frac{1}{8}(1 + \frac{1}{n_w}) = \frac{1}{8} + \frac{1}{8n_w} \tag{C.15}$$

Where $n_{overlap_{Em}} = \frac{1}{4}$ is the rate of decreased empty device operations given that there is an overlap of empty device usage of one device.

The time factor for the usage of loaded conveyor devices given that the interdistance of bags is smaller than trice a device's length and larger than or equal to twice a device's length, can be found using Equation C.16.

$$f_{Em,2l_d \leq itd < 3l_d} = 1 - E_{reduction} = 1 - (\frac{1}{8} + \frac{1}{8n_w}) = 1 - \frac{1}{8} - \frac{1}{8n_w} = \frac{7}{8} - \frac{1}{8n_w} = \frac{1}{8}(7 - \frac{1}{n_w}) \tag{C.16}$$

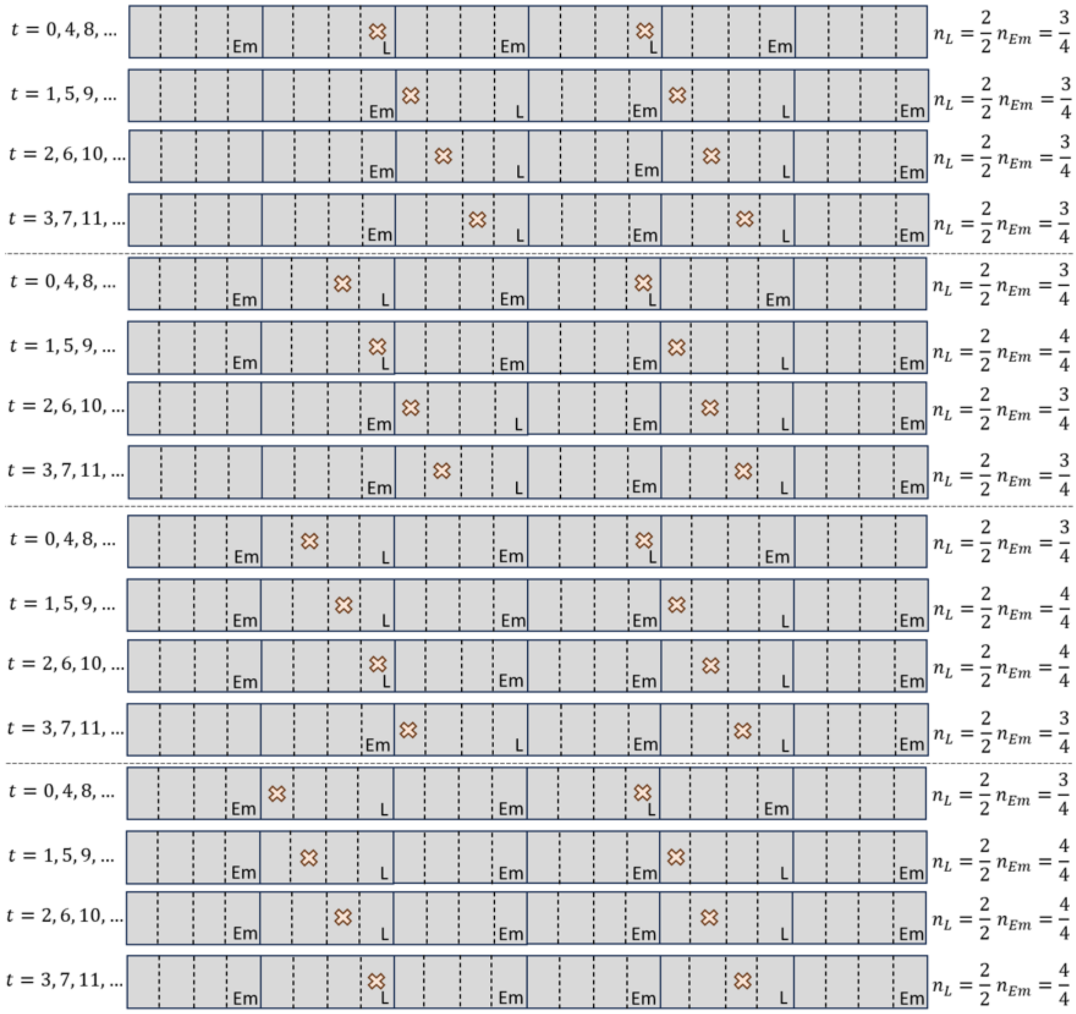

Figure C.9: Overlap of device usage with $2l_d \leq itd < 3l_d$ and $n_w = 4$