TÉCNICO LISBOA

Stochastic Modelling of an Airport Baggage Handling System

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

The main task of air transport is to safely transport both passengers and their baggage to their destinations. Nowadays, one of the most crucial tasks airports have to take on is baggage handling, since a failure of a Baggage Handling System (BHS) often causes a blockage in the airport, which greatly impacts its quality of service.

The main goal of this dissertation is to model a BHS, capable of withstanding changes in the pattern of arrivals and unforeseen machine breakdowns, and describe improvement proposals based on the removal of certain system components. The analysis of the BHS was developed in a more generalised approach, to ensure that its takeaways can be applicable to airports with similar characteristics, including the size, features and equipment. The baggage handling model was described on a Discrete Event Simulation (DES) tool, SIMUL8, where the bottlenecks could be identified and the system performance could be evaluated for particular scenarios.

Modifications to the system can be suggested after analysing the simulation results. For an increase in the baggage injection rate, results reveal that additional conveyor belts are necessary before the first security stage; whereas in the event of a decline in checked baggage volume, it was demonstrated that certain security stages resources could be excluded from the system and still report low queueing times.

Keywords

Baggage Handling System, Discrete Event Simulation, Stochastic Process

Resumo

A principal tarefa do transporte aéreo é transportar os passageiros e suas respectivas bagagens para um determinado destino. Atualmente, uma das tarefas mais cruciais dos aeroportos é o processamento de bagagens, dado que uma falha num sistema de processamento de bagagens (BHS) leva a congestionamento no aeroporto, o que afeta a qualidade do serviço prestado.

O principal objetivo da presente dissertação é modelar um BHS, capaz de suportar mudanças no padrão de chegadas e falhas esporádicas de equipamento, e descrever propostas de melhoria com base na remoção de determinados componentes do sistema. A análise do BHS foi desenvolvida tendo por base uma abordagem mais generalizada, para garantir que os seus resultados possam ser aplicáveis a aeroportos com características semelhantes, incluindo o tamanho e o tipo de equipamentos. O modelo de processamento de bagagens foi descrito tendo por base uma ferramenta de simulação de eventos discretos (DES), SIMUL8, onde os locais de congestionamento podem ser identificados e o desempenho do sistema pode ser avaliado para cenários específicos.

Após a análise dos resultados da simulação, foram evidenciadas possíveis melhorias ao sistema. Enquanto que para um aumento da taxa de injeção de bagagem, os resultados revelam ser necessários tapetes rolantes adicionais antes da primeira etapa de segurança; para uma redução do volume de bagagens de porão, conclui-se que certos recursos podem ser excluídos do sistema, mantendo tempos de espera aceitáveis.

Palavras Chave

Sistema de Processamento de Bagagens, Simulação de Eventos Discretos, Processo Estocástico

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Acronyms

ANA	Aeroportos e Navegação Aérea
ATR	Automatic Tag Reader
AWT	Average Waiting Time
BHS	Baggage Handling System
CT	Cycle Time
DES	Discrete Event Simulation
DCV	Destination Coded Vehicle
EDS	Explosive Detection System
ETD	Explosive Trace Detectors
FIFO	First In First Out
HBS	Hold Baggage Screening
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
INE	Instituto Nacional de Estatística
KPI	Key Performance Indicator
LCC	Low Cost Carrier
LIFO	Last In Fist Out
MA	Moving Average
MTR	Manual Tag Reader
MTTR	Mean Time to Repair
MWT	Maximum Waiting Time
SIRO	Service In Random Order
PDF	Probability Density Function

PQ	Priority Queueing
PS	Processor Sharing
th	throughput
WIP	Work-in-Progress
WS	Workstation

1

Introduction

Contents

1.1 Motivation

Air travel is a mode of transportation with many advantages which makes it a popular choice among its alternatives. As of 2019, more than 30 million passengers arrived in Portugal, a number that has almost doubled since 2010 [12], mainly as a result of the rise in popularity of low-cost airlines. This increase in passenger traffic was not only common to Portugal but also to most countries in the world and is directly correlated with an increase in the quantity of checked-in baggage [13]. In fact, it was reported that 4.54 billion passengers and their baggage boarded a flight in 2019 [2].

Despite the overall increase in the number of passengers in the last years, in the second quarter of 2020, only 434 thousand passengers were transported at national airports, representing a decrease of 97.4%, as a result of the impact of the COVID-19 pandemic and the restrictive measures adopted in airspace [1].

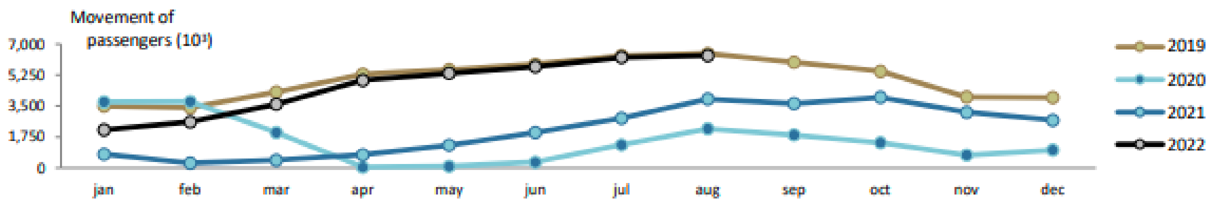

Figure 1.1: Passengers movement at Portuguese airports [1].

Figure 1.1 depicts movement of the passengers at Portuguese airports, where it is visible that the number of passengers in 2022 is already approaching the levels recorded in the pre-pandemic period (2019). It is expected that by the end of 2023, most regions will have reached or surpassed pre-pandemic levels of demand [14].

Nowadays, airports use modern Baggage Handling Systems (BHSs) to transport baggage through the terminals. Baggage handling consists of numerous subtasks involving the collection, sorting and distribution of baggage, and can be distinguished in three main processes related to the departures, transfers and arrivals to airports. The number of baggage items, passenger arrival rate, barcode misreads, early and late bags, and security checks are all factors that contribute to the performance of a BHS [15]. The management of baggage systems has become a more and more challenging task in the past years and its efficiency directly impacts the airport's performance as well as passenger and airline satisfaction, since misdirected and lost baggage influences the airport's public image [16].

With the recent increase in automation and smart technology, airlines are able to not only improve baggage handling capabilities but also lower the bag mishandling rate. Figure 1.2 gathers data from 2007 until 2019, illustrating the overall decrease in the number of mishandled bags. Despite this decrease, airports and airlines are still subjected to substantial costs which greatly impact their operations. Delayed baggage stands as the primary cause for mishandled baggage and, analysing Figure 1.3, it is evident that the transfer bags account for the vast majority of delayed bags.

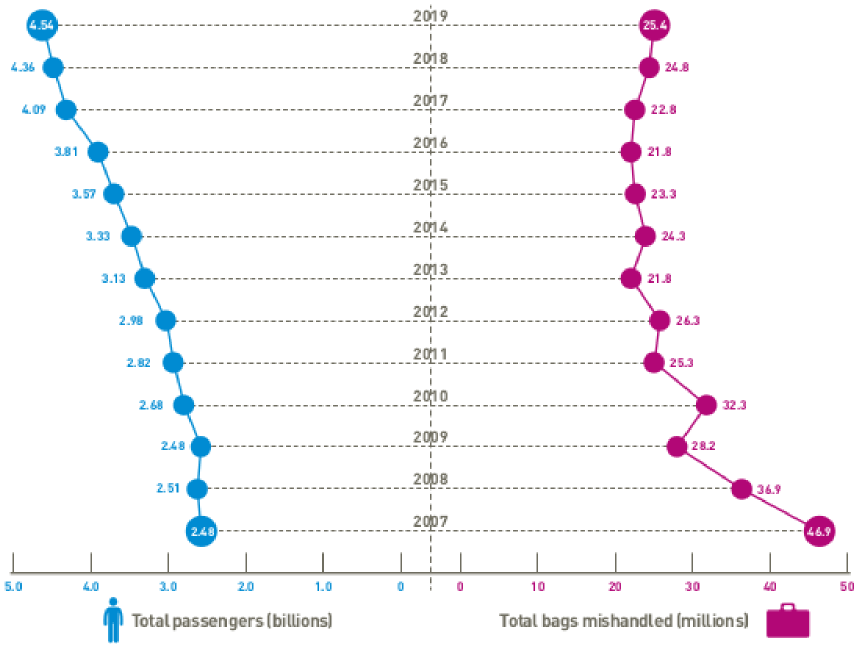

Figure 1.2: Long term decrease in baggage mishandling [2].

Due to the growth of passenger traffic, BHSs occasionally operate at system capacity and need improvements and/or expansions [13]. However, before applying any improvement strategy to a given BHS, an extensive analysis of the whole process should be done, since implementing changes in the physical system can be very costly. This analysis, which may include the testing and evaluation of various scenarios, requires suitable modelling and simulation tools in order to model and simulate the real system with the utmost rigour, and test and evaluate the performance of the possible modifications to the physical system.

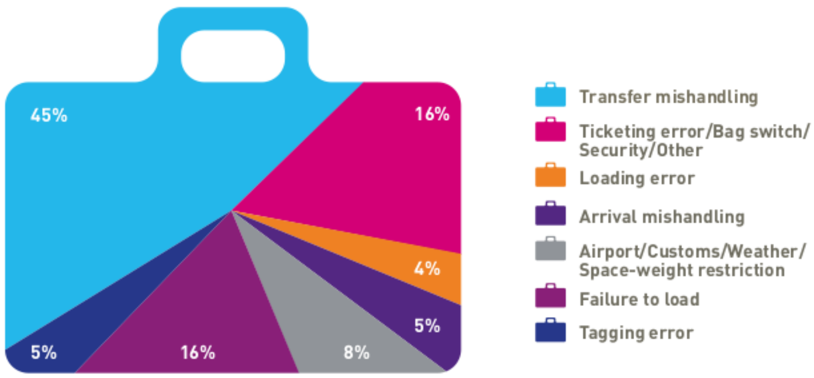

Figure 1.3: Reasons for delayed bags [2].

1.2 Objectives and Contributions

The main goal of this dissertation is to model a BHS that is capable of withstanding changes in the pattern of arrivals, unforeseen machine breakdowns and other relevant scenarios. Any of these modifications will always have effects on the performance of the system. Using simulation, it is possible to quantify these effects and explore potential solutions that can lessen them without intervening directly in the actual system.

The following steps have to be established in order to achieve the main objective of the thesis:

- Build a simulation model of the system using a simulation software.
- Identify bottlenecks and describe their impact on the system.
- Create scenarios that improve the overall performance of the system.

This dissertation produced the following contributions: the analysis of a BHS in a generalised approach to facilitate the study of other similar systems; the detection of bottlenecks; and the suggestion of improvement strategies.

1.3 Document Structure

The remainder of the dissertation is organized as follows:

- **Chapter 2 - State of the Art**: Overview of the state of the art for the subject of the dissertation, encompassing a description of an airport environment and an overview of relevant concepts from queuing theory and discrete event simulation.
- **Chapter 3 - Model Implementation**: Thorough presentation of the methodology used to model the system, along with details of the implementation of the simulation model in SIMUL8.
- **Chapter 4 - Scenario Definition**: Description of the proposed scenarios developed for the simulation model.
- **Chapter 5 - Results and Discussion**: Display of the simulation results and comparison of the different scenarios developed.
- **Chapter 6 - Conclusions and Future Work**: Conclusions extrapolated from the developed work and discussion of potential future improvements.

2

State of the Art

Contents

2.1 Airport Environment

Air transport requires a separation between passengers and their baggage, which sets it apart from the vast majority of other modes of transportation. As a consequence, it becomes more challenging and complex to design passenger terminals and BHSs, since the separation and subsequent reunion of the passenger with its baggage must be carried out without jeopardizing the efficiency of the system and the quality of service that must be provided [17].

2.1.1 Overall description

Every airport can be divided in two parts: landside and airside. The landside includes the check-in counters, access roads, public transportation, parking lots and the airside is composed by the areas with access to airplanes including ramps and runways. The BHS allows the flow of baggage between the airside and landside. Figure 2.1 shows the several baggage inflow and outflow streams at an airport, where it is possible to see that both check-in baggage and transfer baggage are forwarded to a departing flight by the outbound baggage handling, while inbound baggage is forwarded to the baggage claim area.

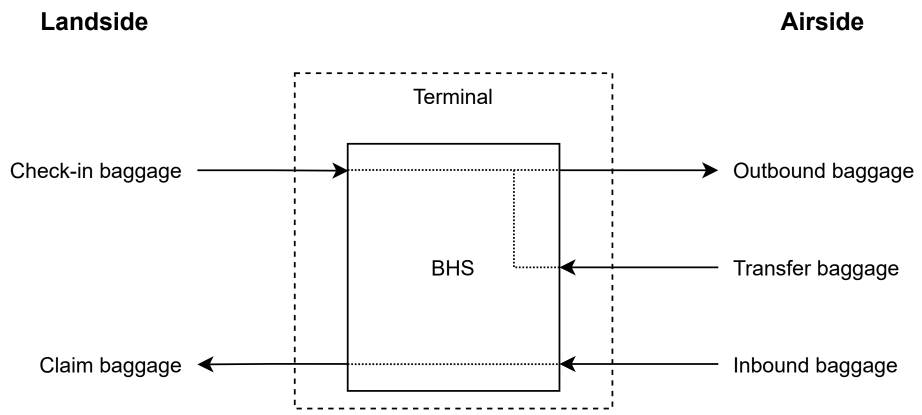

Figure 2.1: Baggage inflow and outflow streams.

A BHS has three fundamental tasks, to move bags from:

- the check-in counters to the departure gate;
- the arrival gate to the baggage claim zone;
- one gate to another during transfers.

These three jobs can also be referred to as departures, arrivals and transfers, respectively.

Departures Outbound baggage handling includes baggage coming from arriving passengers through check-in counters and baggage from incoming flights. The handling of outbound baggage involves all the necessary steps to forward baggage from the BHS to a departing flight. In the case of an early check-in, the BHS has to momentarily store the baggage in a buffer zone, until it is time to be loaded into the departing airplane.

Arrivals Inbound baggage handling comprises the transport of the baggage from arriving flights to the baggage claim area, via the BHS, to be picked up by the passenger.

Transfers Transfer baggage handling involves the process of forwarding baggage from an arriving flight to a departing flight. From the moment the baggage from an arriving flight enters the BHS, the outbound baggage handling controls the process. In the event of an overnight layover, the baggage may need to be picked up in the baggage claim area and then rechecked for the outgoing flight. As a general rule, airlines will not consider these cases as transfers but instead as arrivals.

According to Young *et al.* [18], passengers can be characterized by the type of baggage they carry:

- Passengers without baggage;
- Passengers with hand baggage;
- Passengers with hold baggage;
- Passengers with oversized/oddly shaped baggage.

This thesis will focus on the passengers carrying hold baggage. The hold compartment of airplanes is limited, so airlines place requirements when it comes to what passengers can bring to their flight. For example, TAP airline defines 158 cm as the maximum dimension for checked baggage. This dimension comprises height, length and width of the baggage. The number of items passengers can carry free of charge in the hold depend on the type of fare and on the destination. Table 2.1 shows the requirements for intercontinental flights with TAP airline.

Fare	Amount	Weight
Basic	1 bag	23kg
Classic	2 bags	23kg per bag
Plus	3 bags	23kg per bag
Executive	2 bags	32kg per bag
Top Executive	3 bags	32kg per bag

Table 2.1: Hold baggage requirements [9].

2.1.2 Airport resources

One of the most important infrastructures of an airport is the BHS. Its components include check-in counters, baggage screening, baggage sorting, baggage carousels, storage system and baggage claim. Figure 2.2 presents an overview of the components of a BHS, for the handling of outbound baggage.

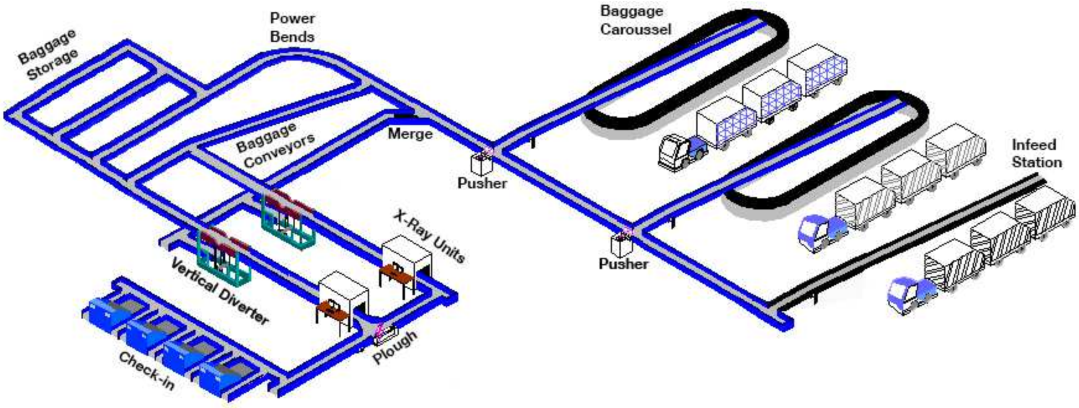

Figure 2.2: Components of a BHS [3].

Subsequently, the components of the BHS are explained in more detail.

- Infeed stations: bags enter the system through infeed stations, or access points, which are either the check-in counters or the inbound/transfer baggage infeed stations.
- Baggage screening: prior to entering the BHS, the bags go through a screening process and a unique tag is attached to every bag. Afterwards, the BHS is able to track the movement of every bag, thus knowing its location at every time instant.
- Baggage sorting: different transportation devices can be selected to transport the baggage in the BHS, including conveyor belts, plastic boxes, tilt trays or Destination Coded Vehicle (DCV). The DCVs transport the bags at high speed on a railway network, routing them to their destination.
- Baggage storage: a BHS has to include a buffer zone for storage of baggage, visible on the upper left side of Figure 2.2. This storage is mainly used in the event of early check-ins, in which bags have to be temporarily stored until it is time to be loaded into a departing airplane.
- Handling facility: the location of handling facilities can be centralized or decentralized. Centralized facilities are located in one central baggage hall as opposed to decentralized facilities which are stationed very close to the departing airplane. Handling facilities are conveyor belts shaped either as a baggage carousel or as a chute.
- Baggage claim: in an airport, the baggage claim halls are comprised of multiple baggage claim

carousels. Inbound baggage infeed stations can be directly connected to a specific carousel or connected to more than one carousel, via the BHS.

The processing of checked baggage begins in the check-in counters and there are three ticket counter configurations currently in use: linear, flow-through counters and island counters [4]. Linear configuration is the most commonly used in airports, where the airline agent is responsible for several tasks including ticketing and baggage check-in. High-volume locations prefer flow-through counters because it allows the passenger to check-in their baggage before concluding the ticket transaction. Lastly, island counter configuration incorporates features from the linear and the flow-through configurations. Figure 2.3 shows the different ticket counter configurations.

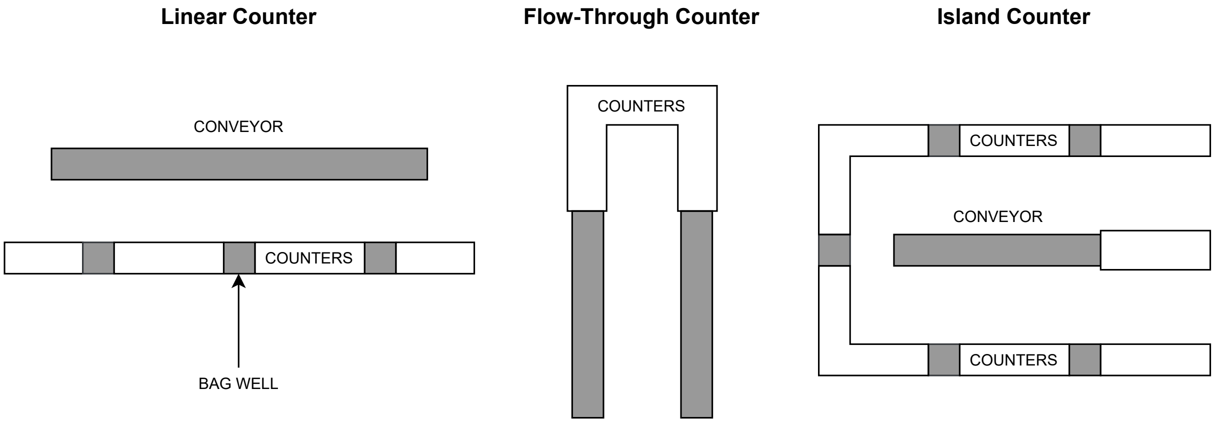

Figure 2.3: Check-in counter configurations [4].

Some findings by Takakuwa *et al.* [19] include the amount of time passengers spend waiting (roughly 25%) and they also stated that a reduction of passengers missing flights could be possible by making use of business-class check-ins for processing of economy passengers. Multiple scenarios have been analysed by Appelt *et al.* [20] regarding the different check-in procedures available at Buffalo Niagara International Airport. The data was collected on peak hours for the curbside, kiosk, counter and online check-in process. The scenario that yielded the best results (lowest queuing times and lowest average time in system) was the removal of the counter as a check-in option, operating only for weighing bags, printing bag tags, as well as for other procedures. The authors came to the conclusion that Buffalo Niagara International Airport check-in would be handled at the curbside, kiosk, and online, thereby eliminating the need for the counter check-in.

In the past few years, common use facilities/equipment have been adopted as a way to use existing space more efficiently and therefore, expanding the capacity of the airport without having to undergo through structural changes. These common use facilities include ticketing areas, gates, curbside areas and baggage claim areas. Belliotti [21] discussed the advantages of the implementation of common use in airports and stated that not only airport operators benefit from this implementation, airlines and passengers also recognize advantages. While airport operators profit by being more flexible in the use of the space, airlines gain by having more flexibility in changing schedules and passengers stated they feel less rushed since they can quickly complete the check-in process at the kiosks.

On the other hand, Heinz *et al.* [22] investigated transfer baggage performance of British Airways as they became the sole airline using Terminal 5 of Heathrow Airport. The improvement in transfer baggage performance and the consolidation of operations in the terminal are found to be significantly correlated, suggesting a causal relationship.

The Airport Cooperative Research Program [5] defines four types of baggage sortation systems:

- **Centralized sortation:** the BHS is localized to the terminal, meaning that the system gathers outbound and transfer baggage into a single location and then proceeds to sort the bags to the respective flight departing area.
- **Decentralized sortation:** the BHS is localized to the gates, which means that the baggage is sorted at two or more locations and can also be sorted near the airplane gates.
- **Common-use sortation:** the BHS integrates the baggage from all airlines in a single sortation system and then sorts the bags by flights.
- **Manual sortation:** airline workers manually sort each individual bag and place it in the appropriate cart.

Figure 2.4 shows the differences between centralized and decentralized sortation systems.

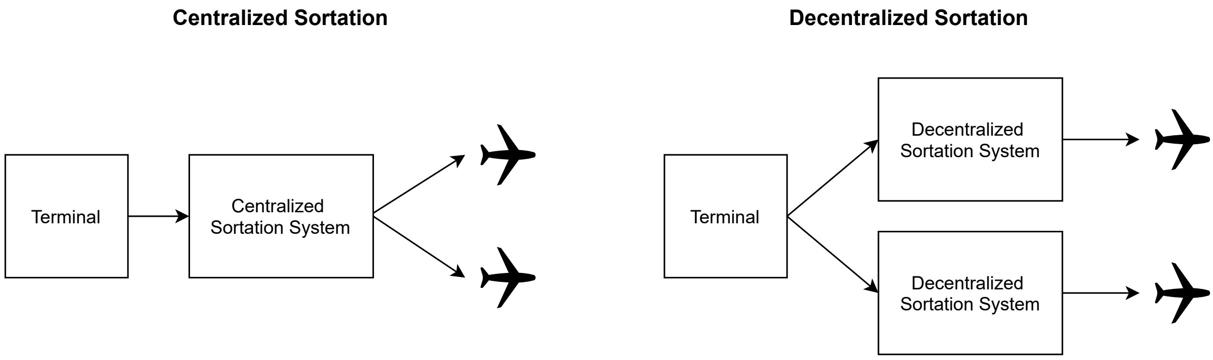

Figure 2.4: Centralized and decentralized sortation systems [5].

2.1.3 Working principle of a Baggage Handling System

Figure 2.5 shows a more complete diagram of the processes of a BHS, from the moment the passenger arrives to the check-in counter to the moment the passenger goes through customs in the destination airport.

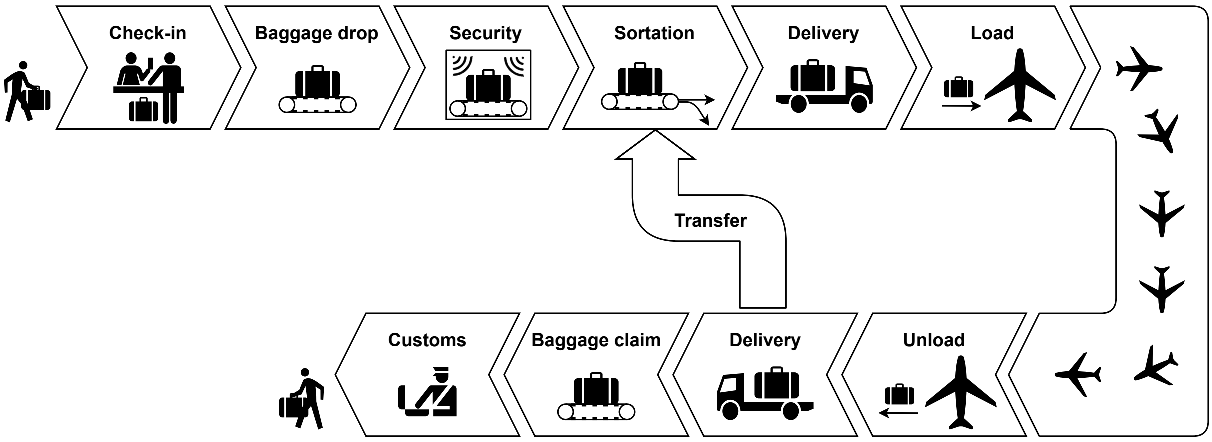

Figure 2.5: Different processes of the BHS.

The first process is the check-in counter, where the passenger gets its ticket and checks its bag, followed by the baggage drop where the bag goes through the first conveyor belt into the BHS. In the security process, the bag goes through as many steps of security as necessary until the bag is deemed as safe for embarking the airplane. The sortation process is responsible for separating the bags in different piles according to their departing flight, while the delivery process is responsible for directing bags to their destination. The load process is the final step of the handling of outbound baggage, since after the airplane lands in their destination, the handling of inbound baggage begins with the unloading of the baggage to baggage carts. Transfer baggage handling involves the process of forwarding baggage back into the outbound BHS to embark into a departing flight. The delivery process of the inbound BHS can send baggage to the sortation (transfer baggage) or to the baggage claim, to be picked up by the passenger. To conclude the processes of the BHS, the passengers have to go through customs and immigration before being able to leave the airport, where officials check their documents and ask questions about the items they are carrying in the baggage.

Hold Baggage Screening (HBS) involves several security screening processes which, in European airports, are usually integrated in the BHS. Figure 2.6 illustrates a BHS with an integrated HBS.

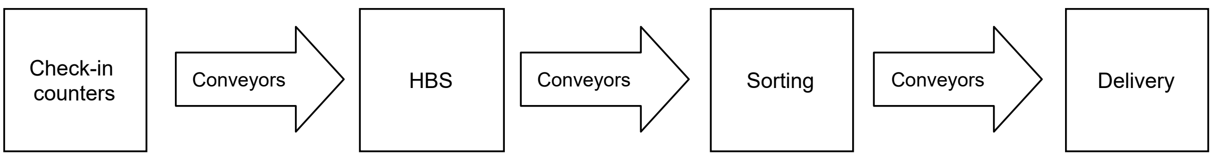

Figure 2.6: BHS with an integrated HBS.

According to the European Union legislation [23], there are five tracking methods used to assess if hold baggage is considered safe to embark in a plane. These methods are the following:

- Hand search;

- X-ray equipment;
- Explosive Detection System (EDS);
- Explosive detection dogs;
- Explosive Trace Detectors (ETD).

There are four levels of security inspection for the departing flights [24]:

1. In the first stage of security, bags go through a EDS machine that captures an X-ray scan of their content and sends it to the security operators to be analysed.
2. In the second security screening stage, operators have access to the image captured in the previous level of security and decide if the contents of the bag are, in fact, explosives or any other forbidden objects that can compromise the security of the airplane.
3. In the third stage, the bag is sent through another EDS machine, this time manually controlled by a operator, allowing for a more precise analysis of the bag.
4. If the bag fails to pass the previous security levels, it is taken to the last level of security, the fourth stage, where the bag is sent to an isolated place to be checked by a security operator. The passenger responsible for the bag has to be present during the bag search. In the extreme case that the bag is deemed a threat, it is removed from the BHS and handled by the authorities.

As every airport has a unique layout and traffic patterns, the screening process adopted should be specific to local conditions, while also adhering to International Civil Aviation Organization (ICAO) regulations [25]. When devising acceptable solutions for the location of screening and the procedures to be followed, each airport must take into account the impact of cost, capacity, and local operating conditions.

Locations of baggage screening systems can include [26]:

- Off-airport check-in
- Sterile terminal complexes
- Sterile security area before check-in
- Screening in front of check-in
- Screening devices at or behind check-in
- Screening downstream or in-line within the baggage system

The final configuration, which involves incorporating the HBS into the BHS, is the most frequently employed. This approach implies that the security processes are not easily accessible to the passengers, which can be a drawback for example, in the fourth stage of security screening when the passenger is required to be present during the bag search. Nevertheless, there are many advantages to this configuration including the fact that current check-in procedures are not affected, only hold baggage is screened, security operators are under less pressure to screen bags and the HBS can be used to screen *Transfer baggage* too.

2.2 Queueing Theory

In 1904, Danish engineer A.K. Erlang published the first paper about queueing theory [27], presenting a model to describe the number of telephone calls arriving at the Copenhagen Telephone Exchange, where he worked at the time. However, it was when David Kendall introduced the modern notation for queues, currently known as *Kendall's notation*, that queueing theory began to attract the attention of mathematicians and soon becoming an area of research interest.

2.2.1 Characteristics

Queueing models are used to predict queue lengths and queueing time. Figure 2.7 shows a typical queueing system, composed of a single queue and several servers. Jobs are entities that arrive to the system wanting to be processed. The small circles, which represent the jobs, arrive to the queue where they wait for service, receive service in the servers (large circles) and then leave the service facility. In the context of this thesis, a service facility like the one presented in Figure 2.7 is called a Workstation (WS).

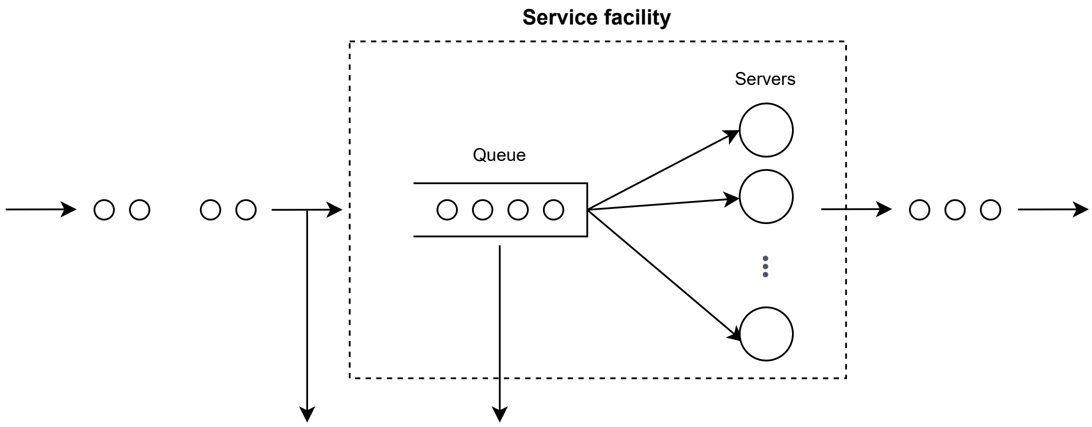

Figure 2.7: Typical queueing system [6].

A queueing system can be described with the following characteristics [6]:

- **Arrival pattern of jobs**: seeing that the process of arrivals is typically stochastic, a probability distribution describing the times between successive arrivals is needed to model the arrival pattern of jobs.
- **Service pattern of servers**: similarly to the arrival pattern, a probability distribution describing the sequence of service times is also needed.
- **Number of servers**: represents the numbers of servers available to process a job. This characteristic of queueing systems represents a trade-off considering that adding servers can decrease the job queueing times but increases the cost to the company.
- **Queue discipline**: this characteristic details the priority in which the jobs in the queue are served. Some examples include First In First Out (FIFO) where jobs are served in the order they arrived in, Last In Fist Out (LIFO) where jobs are served in the reverse order to the order they arrived in, Service In Random Order (SIRO) where jobs are selected randomly from the queue independent of their arrival times, Processor Sharing (PS) where the server processes all jobs simultaneously and Priority Queueing (PQ) where jobs with a higher priority are selected for service before those with a lower priority.
- **System capacity**: represents the maximum number of jobs allowed in the queue and therefore, when the system reaches its full capacity, new arrivals are turned away. If the system capacity is omitted, the capacity is said to be infinite.

Nowadays, Kendall's notation [28] is the standard notation used to describe and classify queueing processes. Kendall described a queueing process by series of symbols A/B/X/Y/Z, where A is the inter-arrival time distribution, B denotes the service time distribution, X corresponds to the number of parallel servers, Y denotes the system capacity and Z is the queue discipline. For instance, M/G/2/∞/FIFO refers to a queueing system with exponential inter arrival times (M stands for Markovian [6]), general service times, two parallel servers, infinite buffer capacity and FIFO queue discipline.

A shorter notation for describing queueing processes has evolved where only the first three symbols are used (A/B/X) [6] and this notation is followed in this dissertation.

2.2.2 Network Models

Single WS models (like the one illustrated in Figure 2.7) can be linked together to mimic more realistic systems that use general G/G/c system approximations as the building blocks for multiple WS models. The approach used to model these networks of WSs is to decompose the system into small components, model the components individually and then rebuild the system. Figure 2.8 presents a serial network queueing model comprised of three G/G/c queues, with external inflow into WS1 and no branching.

Figure 2.8: Example of a serial network model with three WSs.

However, serial network models do not address various situations that most production systems frequently have to deal with, including the merging of streams entering a WS and the splitting of a WS output to several WSs. Figure 2.9 illustrates a non serial network queueing model with three G/G/c queues and an external inflow into WS1 and job feedback from WS3 to both WS1 and WS2.

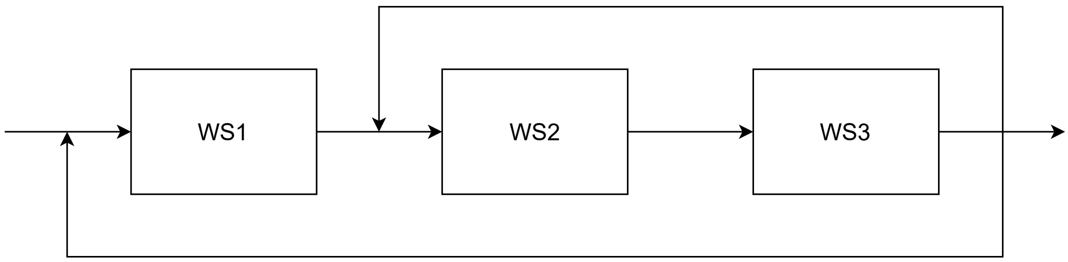

Figure 2.9: Example of a non serial network model with three WSs.

A complex system such as a BHS needs to be modelled as a non serial network of WSs and in what follows, some important WS parameters will be thoroughly explained.

Mean Arrival Rates According to the definition [29], the switching rule for the network is defined by a $n \times n$ matrix $P = [p_{ij}]$, where n is the number of WSs and p_{ij} is the probability that an arbitrary job leaving WSi will be routed directly to WSj. The matrix P is the routing matrix for the network. The total rate into WSi (for $i = 1, \ldots, n$) must satisfy

$$\lambda_i = \gamma_i + \sum_{k=1}^{n} p_{ki} \lambda_k, \tag{2.1}$$

where λ_i is the mean arrival rate into WSi and γ_i is the external inflow rate into WSi. (2.2) is equivalent to (2.1) in standard matrix form, where $\Lambda = [\lambda_1, \ldots, \lambda_n]$ is the unknown vector consisting of the mean arrival rates of jobs to the WS and $\Gamma = [\gamma_1, \ldots, \gamma_n]$ is the vector of the mean arrival rates from an external source.

$$\Lambda = P^T \Lambda + \Gamma \tag{2.2}$$

The vector Λ can be determined using

$$\Lambda = (I - P^T)^{-1}\Gamma. \tag{2.3}$$

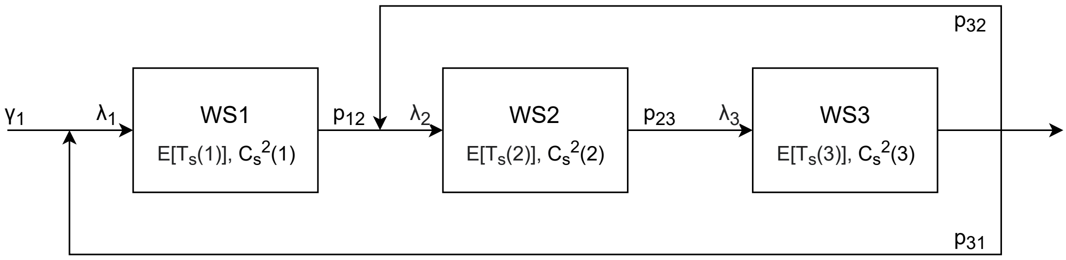

Figure 2.10: Example of a non serial network model with three WSs.

As an example, an analysis of the network of WSs presented in Figure 2.9 which contains three WSs, an external inflow into WS1 and job feedback from WS3 to WS1 and WS2. Figure 2.10 illustrates a replica of Figure 2.9, containing the mean arrival rates λ_i and the squared coefficient of variation for arrivals $C_a^2(i)$ for each WS, as well as the mean processing times $E[T_s(i)]$ and the routing probabilities p_{ij}. Since there is only one external inflow, one can say that the vector of the mean arrival rates coming from an external source is $\Gamma = [\gamma_1, 0, 0]$. The routing matrix can be filled in, as seen in

$$P = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ p_{31} & p_{32} & 0 \end{bmatrix}. \tag{2.4}$$

After computing the vector Γ and the routing matrix P, one can compute the vector of the mean arrival rates of jobs to each WS, using (2.3).

Utilization factors Now that the mean arrival rate of jobs to each WS is known, each WS's utilization factor can be computed. The probability that the WS is currently processing a job is given by this parameter and can be computed using

$$u_k = \frac{\lambda_k \cdot E[T_s(k)]}{c_k} \tag{2.5}$$

where λ_k is mean arrival rate of jobs to WSk, $E[T_s(k)]$ is the mean processing time of WSk and c_k is the number of servers of WSk.

Squared Coefficients of Variation for Arrivals This unitless parameter measures the dispersion of a variable and it is the ratio of the variance to the mean squared. The variable with the smaller C^2 is less dispersed than the variable with the larger C^2. C_a^2 denotes the squared coefficient of variation for arrivals while C_s^2 denotes the squared coefficient of variation for service. The squared coefficient of variation for arrivals can be computed using

$$C_a^2(j) = \frac{\gamma_i}{\lambda_i} \cdot C_a^2(0,j) + \sum_{k=1}^{n} \frac{\lambda_k p_{kj}}{\lambda_j} \left[p_{kj}(1-u_k^2) \cdot C_a^2(k) + p_{kj} u_k^2 \left(\frac{C_s^2(k) + \sqrt{c_k} - 1}{\sqrt{c_k}} \right) + 1 - p_{kj} \right]. \tag{2.6}$$

More detailed information regarding this previous expression can be found in [29]. The parameter $C_a^2(0,j)$ represents the squared coefficient of variation for the inter-arrival times for jobs coming from an external source.

Expression (2.6) represents a system of equations and can be approximated using an iterative process known as the method of successive substitution, where $C_a^2(i)$ is initialized at any value and then after each step of the algorithm $C_a^2(i)$ will have different values until it begins to converge.

Expression $c_a^2 = [C_a^2(1), \ldots, C_a^2(n)]$ represents the vector of squared coefficients of variation for the arrivals stream and can be computed using

$$c_a^2 \approx (I - Q^T)^{-1} b. \tag{2.7}$$

The elements of Q are computed by

$$q_{kj} = \frac{\lambda_k p_{kj}^2 (1-u_k^2)}{\lambda_j} \tag{2.8}$$

and the elements of b are given by

$$b_j = \frac{\gamma_i}{\lambda_i} \cdot C_a^2(0,j) + \sum_{k=1}^{n} \frac{\lambda_k p_{kj}}{\lambda_j} \left(p_{kj} u_k^2 \frac{C_s^2(k) + \sqrt{c_k} - 1}{\sqrt{c_k}} + 1 - p_{kj} \right). \tag{2.9}$$

Cycle times and Work-in-progress The Cycle Time (CT) represents the time that a job spends inside a system and therefore, comprises both the processing time and the queueing time. Kingman's Approximation [30] is used to compute the mean waiting time W_q

$$W_q(i)(G/G/c) \approx \left(\frac{C_a^2(i) + C_s^2(i)}{2} \right) \left(\frac{u_i^{\sqrt{2c_i+2}-1}}{c_i(1-u_i)} \right) E[T_s(i)] \tag{2.10}$$

and the mean cycle time W for each WS

$$W(i)(G/G/c) = W_q(i)(G/G/c) + E[T_s(i)]. \tag{2.11}$$

The Work-in-Progress (WIP) represents the number of jobs within a system, either processing or waiting in the queue. Using Little's Law [31], the WIP can be obtained

$$L = \lambda \cdot W, \tag{2.12}$$

where L is the WIP, λ is the arrival rate and W is the average time a job spends in a system.

2.3 Simulation

A simulation is the imitation of the operation of a real-world process or system over time [7]. Simulation can help to get a better understanding of the system, compare different system designs as well as aid in improving the system's efficiency by resolving their problems. In this section, simulation is presented as the suitable choice to model the current problem.

2.3.1 Advantages and disadvantages of using simulation

Simulation is intuitively appealing to a client because it mimics what happens in a real system or what is perceived for a system that is in the design stage. There are many advantages of using simulation [7], such as:

- New operating procedures, decision rules and so on can be explored without disrupting ongoing operations of the real system.
- Hypotheses about how or why certain phenomena occur can be tested for feasibility.
- Time can be compressed or expanded to allow for a speed-up or slow-down of the phenomena under investigation.
- Insight can be obtained about the interaction of variables.
- Bottleneck analysis can be performed to discover where work in process, materials, and so on are being delayed.
- *What if* questions can be answered. This is particularly useful in the design of new systems.

Some disadvantages include:

- Model building requires special training. It is an art that is learned over time and through experience.
- Simulation results can be difficult to interpret. Most simulation outputs are essentially random variables (they are usually based on random inputs), so it can be hard to distinguish whether an observation is the result of system interrelationships or of randomness.
- Simulation modelling and analysis can be time consuming and expensive. Skimping on resources for modelling and analysis could result in a simulation model or analysis that is not sufficient to the task.

2.3.2 Components of a system

A group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of a purpose is the definition of a system [7]. A model, in the other hand, is an abstract representation of a system, generally consisting of structural, logical, or mathematical relationships which describe a system in terms of state, entities and their attributes, sets, processes, events and activities. The main components of a system are:

- Entity: any object or component in the system which requires explicit representation in the model.
- Attribute: a property of an entity.
- Activity: a time period of specified length.
- State: the collection of variables necessary to describe the system at any time, relative to the objectives of the study.
- Event: an instantaneous occurrence that may change the state of the system.

Table 2.2 illustrates some examples of systems and their components, where the subject of this dissertation is represented by the last row.

System	Entities	Attributes	Activities	Events	State Variables
Banking	Customers	Account balance	Making deposits	Arrival, departure	Number of customers waiting
Inventory	Warehouse	Capacity	Withdrawing	Demand	Levels of inventory
Baggage handling	*Bags*	*Destination*	*Security screening*	*Arrival, departure*	*Number of bags waiting*

Table 2.2: Examples of systems and their respective components [7].

2.3.3 Steps in a typical simulation study

According to the authors in [7], a proper simulation study should follow a set of steps, as shown in Figure 2.11 and thoroughly detailed in what follows.

1 **Problem formulation** Firstly, a statement of the problem must be done, either by the organization wanting to resolve the problem or by the external entity developing the model.

2 Setting objectives and overall project plan The objectives specify the questions to be answered from the results of simulation. The overall project plan should include details about the simulation study, such as the number of days required to accomplish every phase of the study and the corresponding expected results.

3 Model conceptualization There are some general guidelines that one can follow when building successful and appropriate models. It is advised to begin with a simple model and then build from there, without exceeding the required complexity to accomplish the purposes of the model. Contrary to what one may believe, a literal copy of the real system is not necessary to model the system, only its fundamentals are needed.

4 Data collection One of the most time consuming tasks of a simulation study is precisely data collection. Thus, it is necessary to start working on that task as early as possible.

5 Model translation The majority of real world systems end up requiring a lot of information storage and computation when they are being modelled. Simulation software helps reduce the model development time and elevate their flexibility, as a result of their added features.

6 Verified? Verification of the computer program is necessary to assure that it is performing properly. Parameters such as the input data and the logical structure of the model have to be correctly represented in the computer program.

7 Validated? To validate a model, a comparison of the actual system behaviour against the model is performed. Then, the model can be improved using the discrepancies and the insights gathered from the comparison.

8 Experimental design The length of simulation runs, the number of replications of each run and the length of the initialization period have to be studied and determined for every system design that is simulated.

9 Production runs and analysis One should use the analysis of the production runs to estimate performance measures for the system designs that are simulated.

10 More runs? Following the completed runs that were performed, one should determine if additional runs are required as well as the design these new runs should follow, if it should differ.

11 Documentation and reporting The documentation produced should be of two types: program and progress. Program documentation is crucial in the cases where a different person is going to use the program, if the program needs to be modified or even so that model users can change parameters in order to better understand the input/output relationships. Furthermore, progress documentation presents the written history of a simulation project, along with a chronology of work done and decisions made.

12 Implementation Successful implementation will be determined by the continual involvement of the model user during the simulation process and the successful performance of all the steps in the process.

2.3.4 Discrete event simulation

This dissertation will follow a Discrete Event Simulation (DES) approach since the BHS can be characterised by:

- being a discrete system, where the state variables (number of bags in the system) change at a discrete set of points in time, contrary to a continuous system, where the state variables change continuously (for example, the amount of water flow over a dam);
- being stochastic, opposed to deterministic, incorporating random variables, for instance the inter-arrival times and the service times.
- being a dynamic system that changes through time in contrast to a static system which represents a system at a particular point in time.

Currently, there is a variety of DES software packages available on the market which differ on the level of specificity, the price, the available features and the modelling approaches. It is necessary to evaluate their strengths and weaknesses in order to select the one that best fits the needs.

Tewoldeberhan *et al.* [32] propose a two-phase evaluation and selection methodology for DES software: in the first phase, simulation packages that include important features and criteria are selected and in the second phase, a detailed evaluation and analysis is performed to those selected packages.

Dias *et al.* [33] perform a comparison of DES tools based on the measure called ”popularity”, since they found that comparisons based on features/characteristics are often non-conclusive, as the majority of them are equipped with a similar feature list. The authors measure the intensity or level of presence of simulation tools on several categories, such as Winter Simulation Conference scientific publications, document database oriented sites, reviews and surveys, among many others. SIMUL8 scored in the Top 4 among the other 19 DES tools.

The authors in [34] attempt to identify answers for numerous logically raised and thought out questions that are stumbled upon when using any given simulations package, including the use of spreadsheets as reporting tools, simulation approaches, programming languages and *what if* scenarios. The work developed argues that SIMUL8 is a simulation software suitable to deal with bottlenecks as well as *what if* scenarios. For these reasons, the chosen software for this dissertation is SIMUL8.

SIMUL8 was developed in 1994 in Scotland's Strathclyde University with the intent of being a teaching aid. In light of its great success, SIMUL8 Corporation decided to commercialize the product as a professional simulation tool [35]. A simulation model in SIMUL8 revolves around processing *Work Items* and is comprised of objects and the routes between them, modelled as a directed graph.

A big advantage of this software is its *Scenario Manager* [36], where one can test multiple configurations in a very easy and efficient way in order to assess which scenario best fits the specific needs of the project. Furthermore, SIMUL8 provides its own simulation language, known as *Visual Logic*, optimized for simulation processing which allows the user to implement detailed logic of the simulation. Single or multiple runs of the simulation can be performed with SIMUL8. Every simulation object generates results that can be exported to various tools, such as Microsoft Excel or Google Sheets.

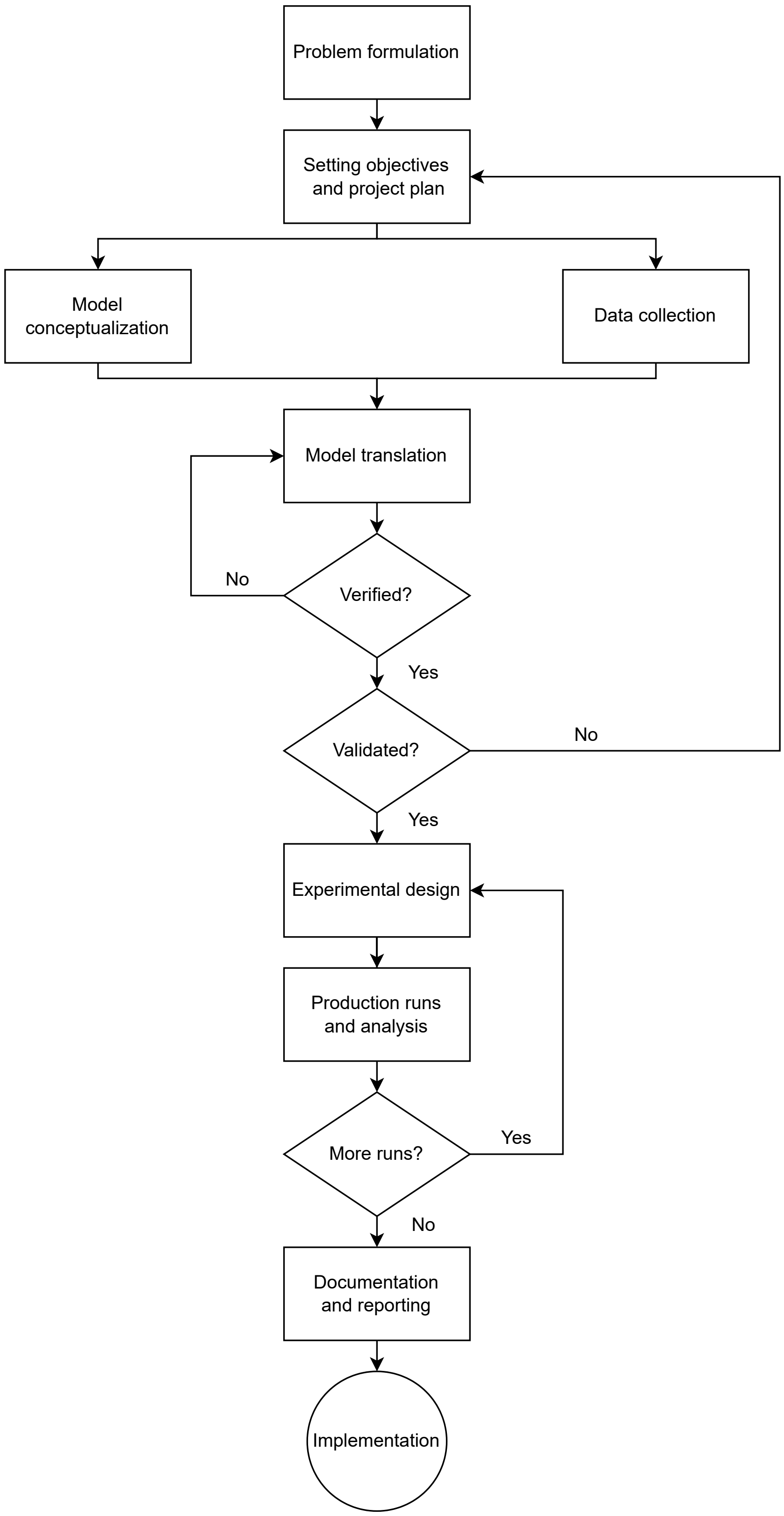

Figure 2.11: Steps in a simulation study [7].

3

Model Implementation

Contents

3.1 Problem Description

In the early stages of this project, *Siemens Logistics* provided a draft of the BHS installed in the Lisbon airport, in order to serve as a building block for the development of the simulation model of a general BHS. Afterwards, the first step was to identify the system components to be modelled, which included check-in counters, conveyors, X-ray security screening machines and an Automatic Tag Reader (ATR). With the identification of the components concluded, a network connecting the components was defined (Figure 3.1).

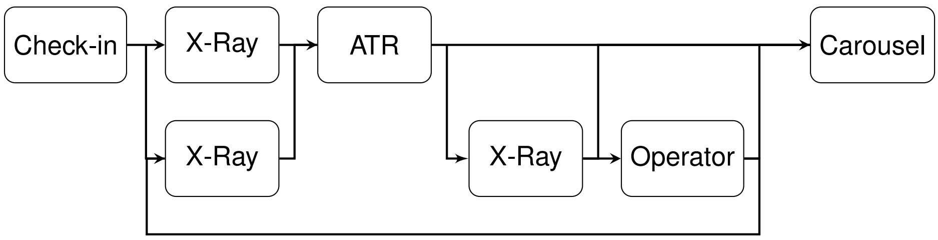

Figure 3.1: Draft of the airport's BHS.

Furthermore, a detailed explanation of each component is presented below.

Conveyors The vast majority of a BHS is comprised of conveyor belts, whose goal is to transport the baggage to the destination. In Figure 3.1, conveyors are represented by the arrows. These conveyors are equipped with junctions and sorting machines.

Check-in Baggage injection to the system is defined by applying probability distributions to the check-in subsystem, which corresponds to a group of check-in counters. These probability distributions are used to emulate the real arrivals to the system.

X-Ray The bag goes through a security screening process, denoted by the X-Ray block. In this simplified draft of the system, there are three X-ray blocks: two just after the check-in block and the third after the ATR block. For each check-in group, there is a corresponding X-ray screening machine. In the event of a breakdown of this machine, there is a second X-ray available. If after the bag goes through the ATR and is flagged as *unclear*, it has to be submitted to an additional security check and thus goes to another X-ray machine.

Automatic Tag Reader The ATR is a scanning machine that reads the unique tag attached to each bag, in order to know its destination as well as its location anywhere in the BHS. From there on, the bag is forwarded to conveyor belts according to its destination. Occasionally, ATR machines are not able to correctly scan the tag and there is a need for the tag to be scanned manually, a process that is also known as Manual Tag Reader (MTR).

Operator The last security screening stage involves an operator checking the bag manually. The chances of this happening are very slim, roughly 0.5 %. Subsequently, the operator decides if the bag is clear and can move to the carousel, or is unclear and goes to back to the initial X-ray (which in this draft is the bottom X-ray).

Carousel Lastly, the carousel aggregates all bags that were cleared after going through the necessary security stages. Bags are then separated depending on the flight and sent to the respective shoot. The behaviour of the shoots is not relevant to this dissertation as the analysis of the BHS was focused on the prior systems.

Four key modules compose the BHS simulation model, as illustrated in Figure 3.2: baggage injection, baggage transportation, security screening stages and baggage unloading.

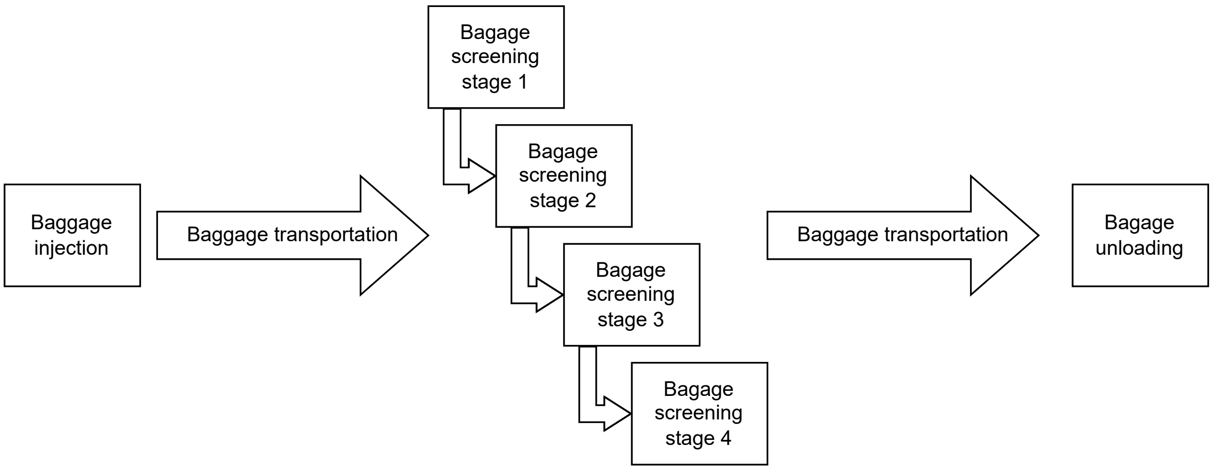

Figure 3.2: Main processes in the BHS simulation model.

3.1.1 Arrival of entities

The arrival of entities is composed by the check-in baggage as well as the baggage coming from arriving flights (*transfer baggage*). Transfer baggage can be divided in two types: the bags that went through the security in the previous airport and need no further screening (*Screened transfer baggage*) and the ones that need another security screening in the current airport (*Unscreened transfer baggage*).

Taking into account that the majority of airports have their earliest flight of the day at 6:00 and their latest flight near midnight, the operating hours of the BHS were set to start at 5:00 and end at midnight.

Hence, based on the input received from *Siemens Logistics*, bags start arriving to check-in counters at 5:00 with a mean arrival rate of 3600 bags per hour.

The outbound baggage volume throughout the day is influenced by the originating passenger arrival profile combined with a flight schedule [5]. The data provided was an average of bags per hour and since in every airport there are rush hours, it would not be accurate to model the system using that average value for each time slot. In order to model the variations of baggage entry rate over the course of an operating day, the data from the outbound bag volume [5] was used (Figure A.1). Time slots of $30\,\mathrm{min}$ were used and the data obtained from the chart had to be adjusted in order to match the average 3600 per hour during the day. The resulting mean arrival rates for outbound baggage are displayed in Figure 3.3.

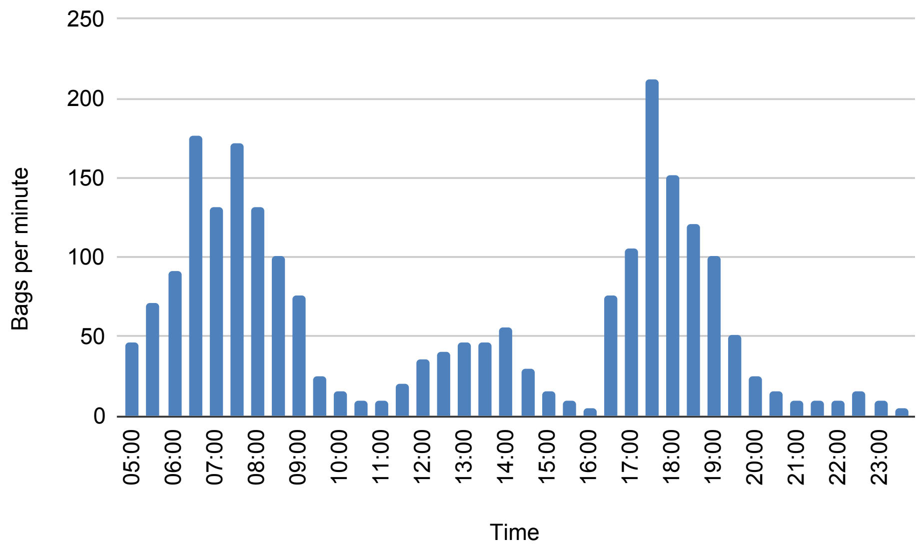

Figure 3.3: Outbound bag volume in bags per minute.

Since data regarding the transfer baggage volume was not provided by *Siemens Logistics*, that information had to be extracted from articles about the topic. According to a case study performed in Dusseldorf airport [37], the calculated transfer rate is 12.6%, which corresponds to 454 bags per hour. The same approach was used for the calculation of the arrival rates for the transfer baggage, using data from Figure A.2 and adjusting the data to the mean arrival rate (Figure A.4).

The mean inter-arrival rates for outbound and transfer baggage are displayed in Figure A.3.

3.1.2 Processing times

EDSs have a mean processing time of $3\,\mathrm{s}$, while ATR machines take $40\,\mathrm{s}$ to process a bag. Operators have $15\,\mathrm{s}$ to review one image and to decide whether an X-ray image of baggage contains a target or not by clicking on an *OK* button (target absent) or *NOT OK* button (target present) [38]. Furthermore, it is important to note that the European regulation [23] mandates that after each period of $20\,\mathrm{min}$ continuously reviewing X-ray images, operators have to take a break of at least $10\,\mathrm{min}$. That is implemented in the model through the definition of the availability of the resources working on this activity.

Additionally, it was defined a mean processing time of $5\,\mathrm{min}$ for the fourth stage of security screening and a mean processing time of $1\,\mathrm{min}$ for the MTR activity.

The Gamma distribution is a typical distribution used to describe processing times, lead time and time to failure. The Probability Density Function (PDF) of the random variable X and the Gamma function $\Gamma(x)$ are represented by

$$f(s) = \frac{s^{\alpha-1}e^{-(\frac{s}{\beta})}}{\beta^{\alpha}\Gamma(\alpha)} \quad \text{for} \quad s \geq 0, \quad \text{where} \quad \Gamma(x) = \int_0^{\infty} s^{x-1}e^{-s}ds. \tag{3.1}$$

If an activity has a known mean ($E[X]$ or μ) and variance ($V[X]$ or σ^2), the shape α and scale β factors for a Gamma distribution can be calculated using

$$\alpha = \frac{E[X]^2}{V[X]} \quad \text{and} \quad \beta = \frac{E[X]}{\alpha}. \tag{3.2}$$

For the conveyors responsible for the baggage transportation in the system, a fixed length of $50\,\mathrm{m}$ and speed $0.7\,\mathrm{m/s}$ were defined. On the other hand, as the Carousel moves faster than regular conveyors, it was characterised with a length of $50\,\mathrm{m}$ and speed $2\,\mathrm{m/s}$.

In Table 3.1, there is a summary of the processing times of the activities included in the model.

Activity	**Distribution**	**Processing Time**		**Parameters**	
		Mean	Variance	α	β
First Stage	Gamma	$3\,\mathrm{s}$	$1\,\mathrm{s}$	0.15	0.333
Second Stage	Gamma	$15\,\mathrm{s}$	$5\,\mathrm{s}$	0.75	0.333
Third Stage	Gamma	$30\,\mathrm{s}$	$10\,\mathrm{s}$	1.5	0.333
Fourth Stage	Gamma	$5\,\mathrm{min}$	$5\,\mathrm{min}$	5	1
ATR	Gamma	$40\,\mathrm{s}$	$5\,\mathrm{s}$	5.333	0.125
MTR	Gamma	$1\,\mathrm{min}$	$15\,\mathrm{s}$	4	0.25
Conveyors	Fixed	$1.67\,\mathrm{min}$		-	
Carousel	Fixed	$0.42\,\mathrm{min}$		-	

Table 3.1: Processing times characterisation.

3.1.3 Breakdowns

The components of a BHS are subject to sudden or inadvertent breakdown, necessitating repair or replacement before normal working can be restored. In order to better monitor machine breakdowns, their causes need to be defined.

In a BHS, some frequent breakdown causes include conveyor breakdowns, machine resets and planned maintenance, while an infrequent breakdown cause can be a power failure that turns off all equipment. In the best case scenario, a machine failure has no impact on the job at all. However, it is more common that the job under processing is lost or it requires further processing before returning to regular working.

The time between failures and the repair time need to be defined for each machine in the system. Common distributions used for modelling the mean time between failures and the mean time to repair are the Exponential and the Erlang, respectively.

3.1.4 Definition of KPIs

The Key Performance Indicators (KPIs) were the last feature of the framework that needed to be set to verify and validate the behaviour of the system (Table 3.2).

The first step was to establish two high-level metrics to measure the total number of jobs entering the system as well as their average time in the system (CT). Later, for each WS, the number of completed jobs and their utilization (u) was set. For each label, the number of completed jobs and the Average Waiting Time (AWT), the Maximum Waiting Time (MWT) were defined as KPIs.

From the number of completed jobs, it is then possible to calculate the throughput (th) not only of the system but also of each WS and of each label, using

$$\text{Throughput} = \frac{\text{Number of completed jobs}}{\text{Simulation Time}}. \tag{3.3}$$

Scope of the Metric	Performance Measure	Terminology in SIMUL8
System	Number of completed jobs Average time in system	Work completed Average time in system
Workstation	Number of completed jobs Utilization	Completed jobs Utilization
Baggage per level of security	Number of completed jobs Average waiting time Maximum waiting time	Completed jobs Average queuing time Maximum queuing time

Table 3.2: Metrics defined to record the performance of the simulation model.

The performance of the new scenarios could be quickly evaluated and contrasted with the current performance by capturing and gathering all these metrics. To do this, it would first be necessary to analyse the variation of the pertinent KPIs. A desirable scenario would see the AWT decrease and the number of completed jobs, or the th, increase.

3.2 Implementation in SIMUL8

The simulation model constructed in this dissertation is illustrated in Figure 3.4. In order to thoroughly explain the construction of the simulation model, it can be divided in 5 sections (Figure 3.5):

- Baggage injection
- Baggage transportation
- Security screening stages
- Baggage identification
- Baggage unloading

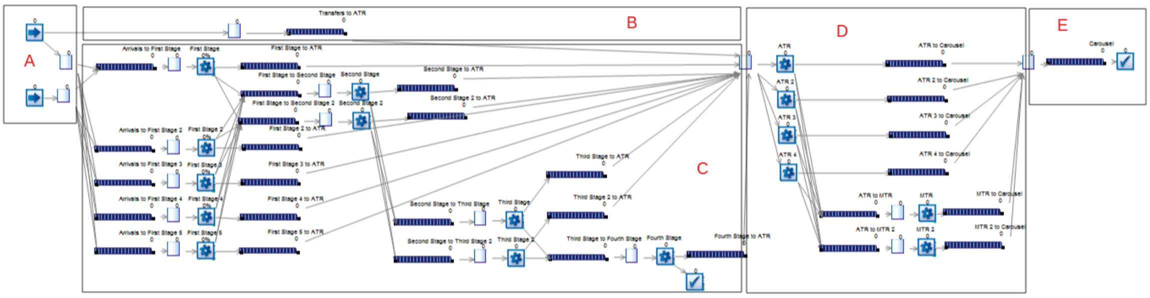

Figure 3.5: BHS simulation model divided in sections.

3.2.1 Initial configurations

At first, it was necessary to define the operating hours for the simulation model. To do so, the start time of each day, the duration of the day and the days per week can be configured in *Clock Properties* (Figure 3.6).

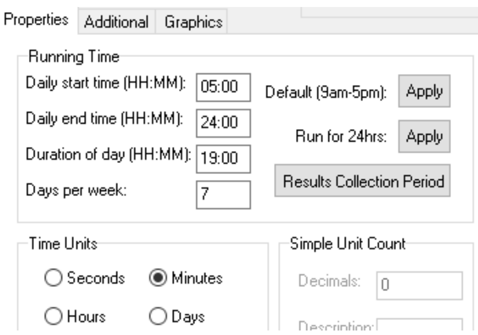

Figure 3.6: Clock Properties.

SIMUL8 lets the user set distinct *Travel times* (of the *Work Item*), or distances, between two components. By default, the distance displayed on the screen is proportional to the actual distance. This

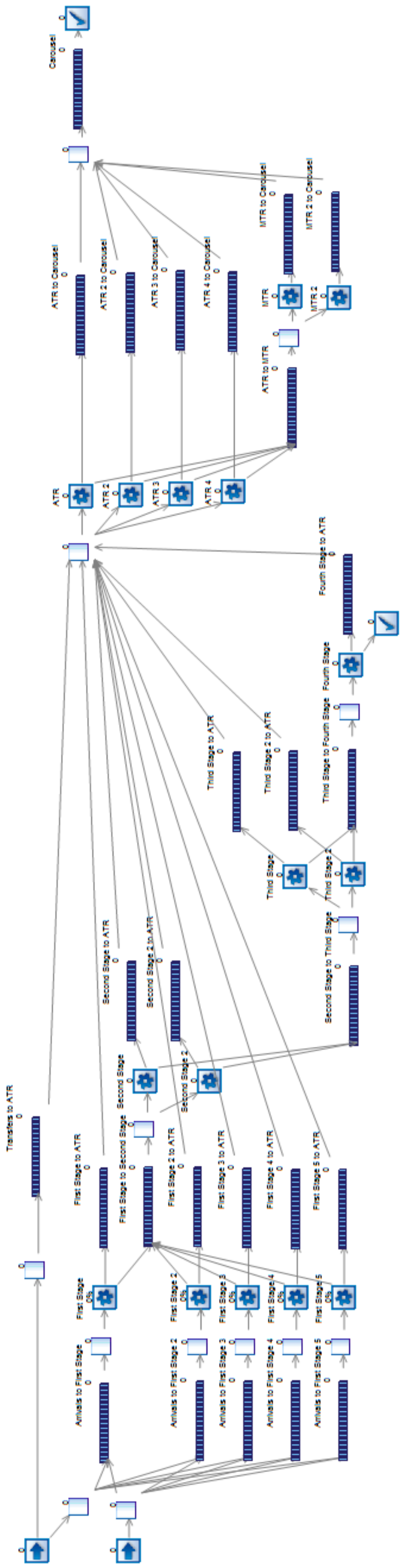

Figure 3.4: BHS simulation model.

distance, however, is not substantial, hence it is not considered for this simulation. As a result, the *Travel times* were set to zero on *Preferences*.

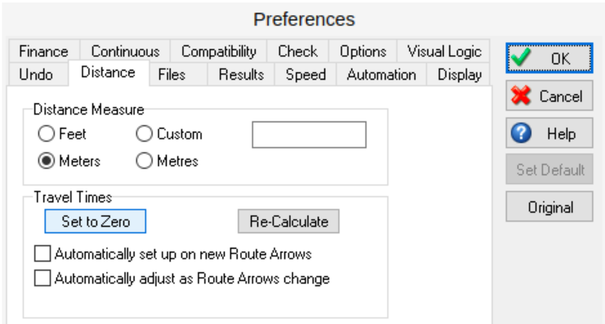

Figure 3.7: Travel times.

The several operators used in the development of the simulation model are listed in Table 3.3, along with their respective physical meaning.

Table 3.3: SIMUL8 operators used in the simulation model.

SIMUL8	Definition	Physical Meaning
Start Point	Baggage entry nodes	Check-in counters and transfer baggage entry point
Queue	Nodes where a queue forms	Baggage storage
Activity	Nodes where a service is performed	X-ray machines, CT scanner, ATR and MTR
Conveyor	Baggage transportation	Conveyor belts
End	Baggage exit nodes	Baggage unloading

3.2.2 Group A - Baggage injection

Bags enter the system through a *Start Point*, that can feed work into the simulation using a fixed rate or using different statistical distributions.

As previously discussed in section 3.1.1, bags enter the system through *Time Dependent* distributions, in both *Start Points* in the simulation model. For the Check-in, time slots of $30\,\mathrm{min}$ were chosen, whereas for the Transfer baggage the time slots were set to $1\,\mathrm{h}$. An exponential distribution with a mean arrival rate previously calculated is assigned to each time slot.

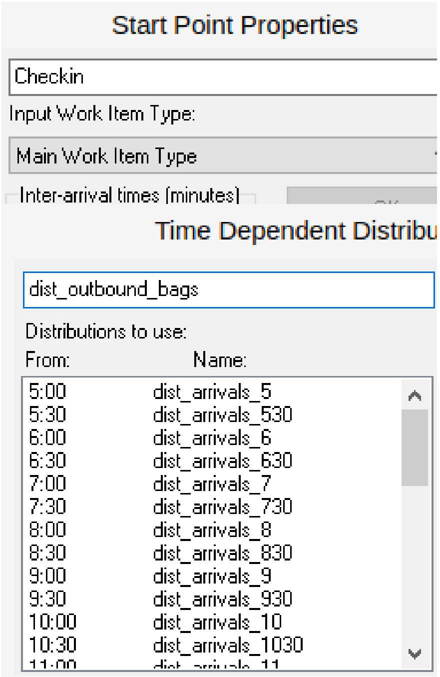

Figure 3.8: Check-in properties.

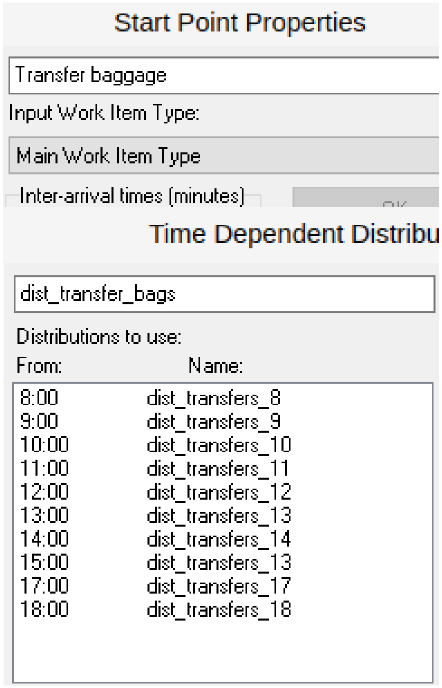

Figure 3.9: Transfer baggage properties.

The label *Origin* was created to distinguish the baggage coming from the check-in counters from the baggage coming from transfer flights. The label is populated with the text *Check-in* or *Transfers* depending on whether the bag entered the system through a check-in counter or transfer baggage *Start Point*, respectively.

3.2.3 Group B - Baggage transportation

In a BHS, baggage is transported in *Conveyors* from point A to point B at a specific fixed speed. *Siemens Logistics* provided data for the speed of a standard conveyor ($0.5\,\mathrm{m/s}$) as well as for the Carousel ($2\,\mathrm{m/s}$). As the units of the simulation are minutes, it corresponds to $30\,\mathrm{m/min}$ and $120\,\mathrm{m/min}$, respectively. The conveyor properties are displayed in Figures 3.10 and 3.11.

In addition, it was also defined the breakdown behaviour for the conveyors. By performing routine inspections and maintenance, the majority of conveyor belt failures can be prevented. However, it is not always possible to cover every contingency. Preventive maintenance is done once every 15 days for critical equipment, that is, equipment whose failure will directly affect the performance of the system [39].

3.2.4 Group C - Security screening stages

After entering the system, bags are subject to security checks, here illustrated as security stages 1 through 4. An *Activity* processes the bags for a certain amount of time, defined with statistical distribu-

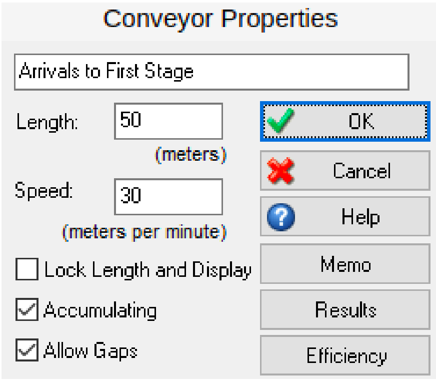

Figure 3.10: Conveyor properties.

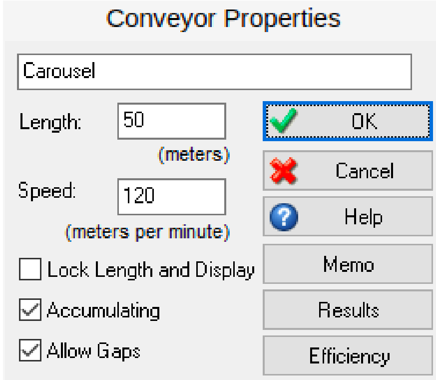

Figure 3.11: Carousel properties.

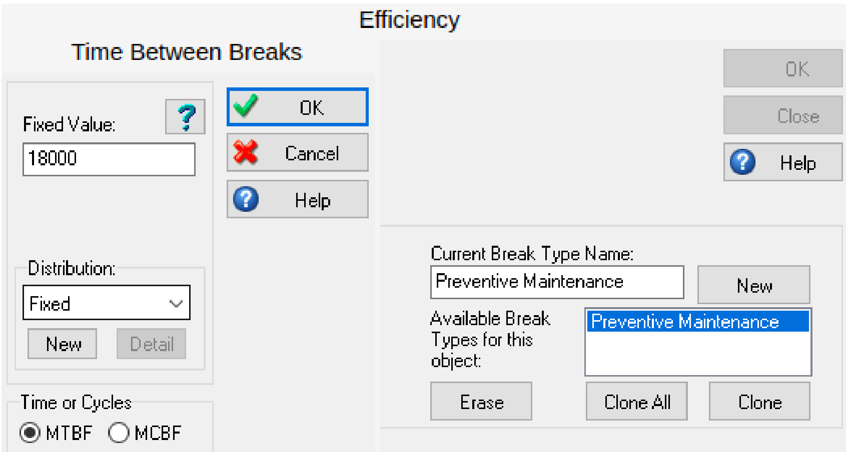

Figure 3.12: Mean time between failure.

tions. Every time a Work Item goes through a security stage, the label *Security* is populated with the number corresponding to the that specific security stage, so that at the end of the simulation, one can know how many Work Items went through each security stage.

According to data from a case study performed in a Portuguese airport [10], for an arrival rate of 1200 bags per hour, the system contains 9 EDS and 12 ATR machines. The arrival rate to this BHS is nearly 4 times the previous system and thus, this system can use a maximum of 36 EDS and 48 ATR machines.

The security screening stages are defined in the following sections.

First Stage The first stage of security screening is composed of EDS machines that capture a X-ray scan of the content of the bag. There are 5 WSs in this first stage of security, each one of them succeeding a conveyor belt and a FIFO queue and include 3 EDS machines, which makes for a total of 15 EDS machines in this stage. The first stage properties are illustrated in Figure 3.13, while in Figure 3.14 the label *Security* is set to 1 since this activity corresponds to the First Stage.

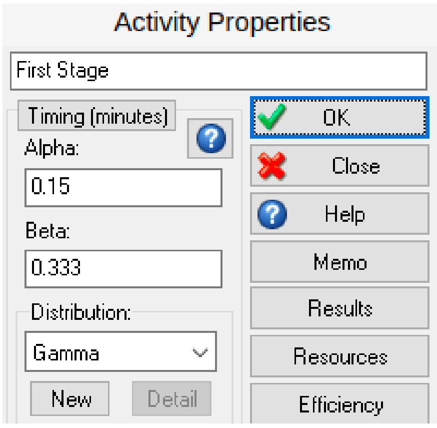

Figure 3.13: First stage properties.

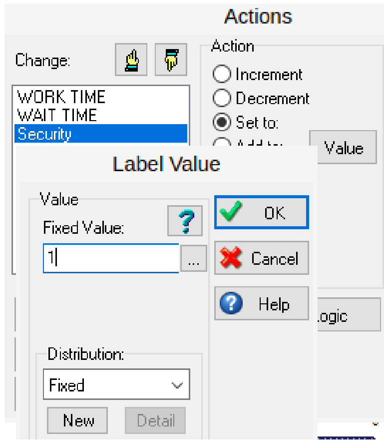

Figure 3.14: Definition of label *Security*.

Second Stage In this activity, an operator analyses the image captured in the first stage and determines if the bag is *OK* and therefore, needs no further screening or *NOT OK* and the bag must go to the next stage of security. The second stage properties are displayed in Figure 3.15.

A SIMUL8 *Resource* was created for this stage of security and populated with 10 available resources (Figure 3.16), to represent the security operators analysing the X-ray images. As mentioned in 3.1.2, after each period of $20\,\mathrm{min}$ continuously reviewing X-ray images, operators have to take a break of at least $10\,\mathrm{min}$. To implement this mandatory break, the resource availability was set to 0.7.

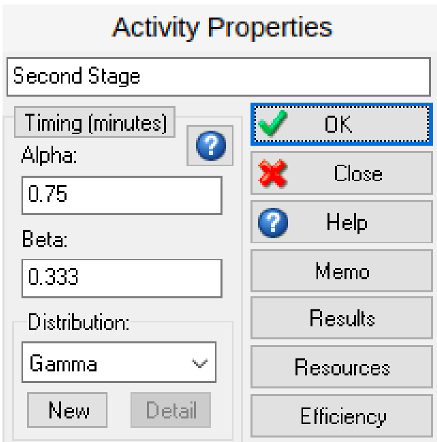

Figure 3.15: Second stage properties.

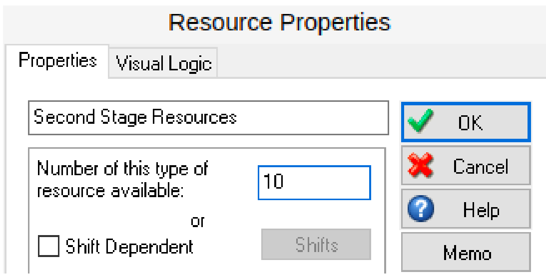

Figure 3.16: Second stage resource properties.

Third Stage In the third stage of security screening, there are 8 EDS machines controlled by operators. The properties of this activity are presented in Figure 3.17. Similar to the second stage, for this stage it was also created a resource with 8 persons available (Figure 3.18).

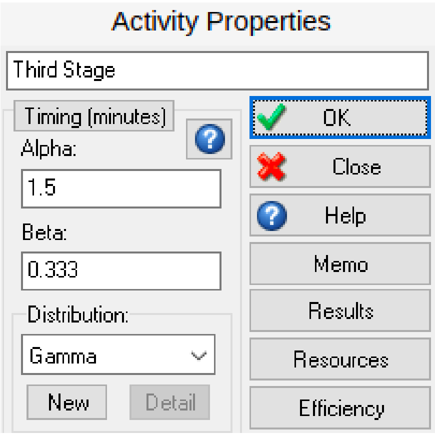

Figure 3.17: Third stage properties.

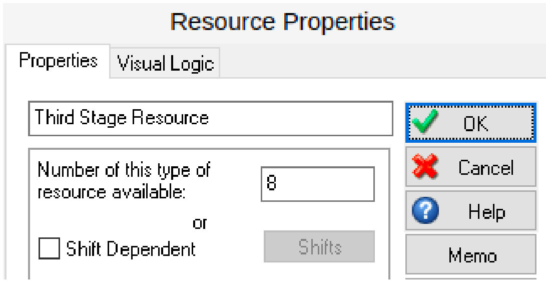

Figure 3.18: Third stage resource properties.

Fourth Stage In the last stage of security, operators open the bags in an isolated place and check for any forbidden objects that can compromise the security of the airport. The fourth stage properties are displayed in Figure 3.19. There are 8 resources available to work on this activity (Figure 3.20).

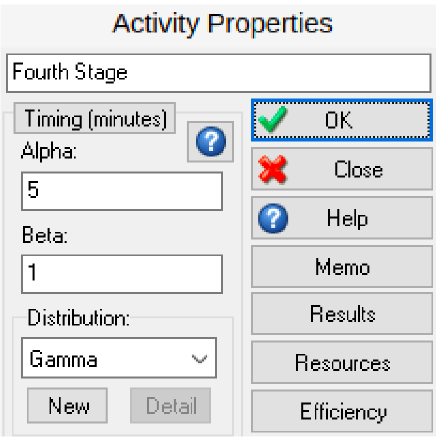

Figure 3.19: Fourth stage properties.

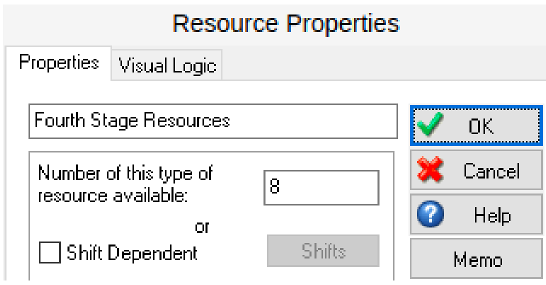

Figure 3.20: Fourth stage resource properties.

3.2.5 Group D - Baggage identification

After going through security and being authorized to board the aircraft, bags move to the baggage identification phase. This process in a BHS is responsible for the scanning of the unique tag attached to each bag and can be performed by an ATR machine or by a MTR. There are 48 ATR machines available and 6 operators are available to perform the manual scanning of the tag (Figures 3.23 and 3.24).

The label *Tag* was created to separate baggage by the type of baggage identification performed. It is populated with the text *Auto* as soon as entities enter the ATR and populated with the text *Manual* when bags enter the MTR activity.

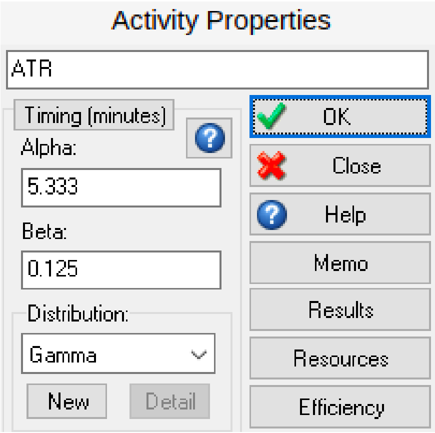

Figure 3.21: ATR properties.

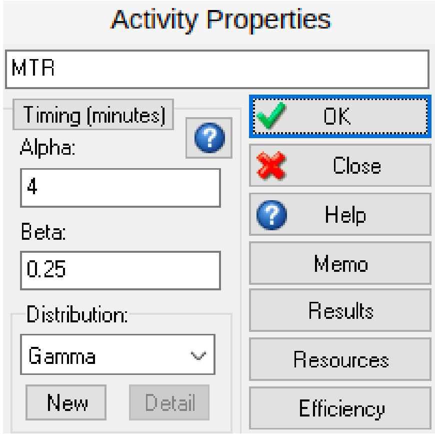

Figure 3.22: MTR properties.

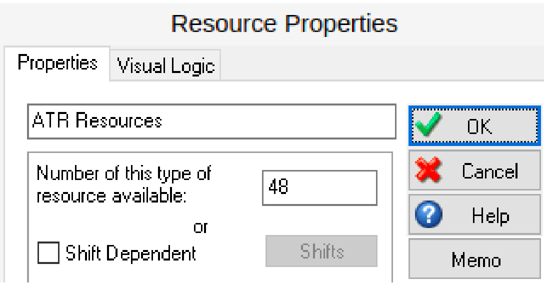

Figure 3.23: ATR resource properties.

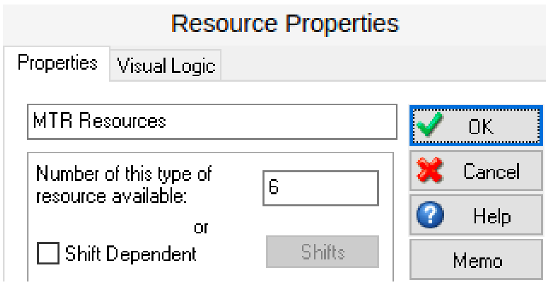

Figure 3.24: MTR resource properties.

3.2.6 Group E - Baggage unloading

The last section of the simulation model comprises the carousel (see 3.2.3) and an *End Point*, created to allow entities to leave the system. This end block is equipped with some important results: the number of completed jobs, the minimum, the average and the maximum time in system. As a result of entities having the label *Security* attached, now the results can be segregated by the label value for a more detailed analysis.

3.3 Verification and validation of the model

This section covers a crucial phase in the construction of a simulation model. Despite its simplicity, using a simplified version of the real model also yields findings that approximate reality. The model cannot be simplified in a way that makes it portray a situation other than what is experienced in the real system. It is essential to validate and verify the developed model in order for these results to be coherent and reflect the actual operation of the system. The primary goal of verification is to make sure the implementation of the model is faultless. Validation ensures that the model presents the rigour required to mimic reality.

3.3.1 Baggage injection in the system

Making sure the baggage is properly entered into the system is one of the important model checks. It was possible to verify that bags enter the system correctly by analysing the results of the first conveyors that receive Work Items from the corresponding *Start Points*. In Figure 3.25, entities with different values of the label *Origin* can be observed, confirming that both *Start Points* are feeding entities into the system.

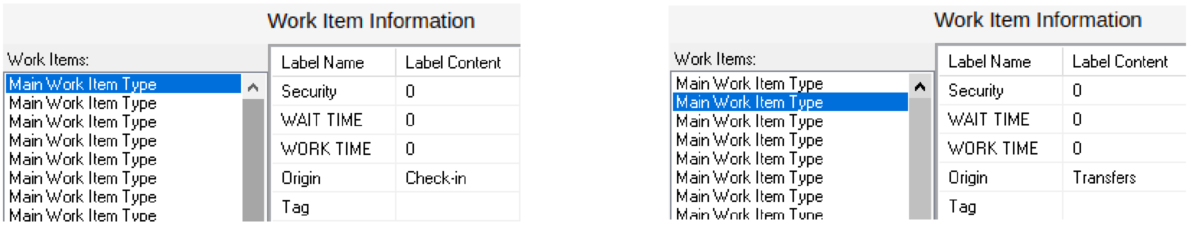

Figure 3.25: Conveyor contents with the label *Origin* populated.

3.3.2 Probability of baggage approval in the security stages

The performance of the different security stages is portrayed through baggage approval rates. After each bag is processed in a security stage, the bag's next step is dependent on the *Routing Out* parameter, that allows for the definition of a probability for the bag to be appointed as *clear* on that security stage.

This data was provided by Aeroportos e Navegação Aérea (ANA) and retrieved from a Masters thesis regarding a case study performed in a Portuguese airport [10]. These probabilities are calculated based on statistical data collected on the BHS along the years. It is safe to assume that there is not a significant change between these rates and other airport's baggage approval rates, as long as the security screening stages are equipped with the same machines.

Stage	**Percentage of approval**
First	60.04%
Second	97.78%
Third	98.61%
Fourth	99.99%

Table 3.4: Baggage approval percentages [10].

3.3.3 Probability of baggage not being correctly scanned

Immediately after the security screening stages, bags are forwarded to the baggage identification area. Now, it is crucial to assess the probability that there would be errors with the automatic reading of a bag's destination code, or the probability that a bag would need to be scanned by a MTR.

A probability value for the manual scanning of the bags common to every piece of baggage could be admitted (5.99%) [10] and this probability value was defined in the simulation model through the *Routing Out* parameter in *ATR* activity. Since there are two separate areas for the MTR, the probability for the manual scanning of the bags is divided by two as illustrated in Figure 3.26.

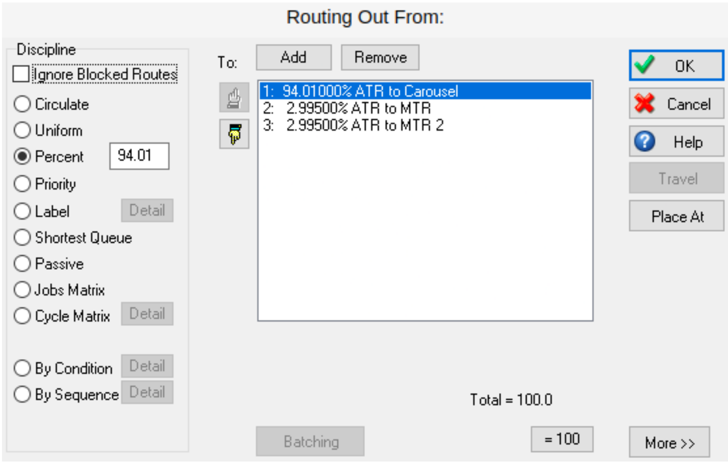

Figure 3.26: ATR *Routing Out*.

3.3.4 Labels *origin*, *security* and *tag*

The success of the developed model depends on the proper operation of the labels since faulty label use can produce inaccurate results.

In order to verify this, the simulation was paused and the *Current contents* of one of the security stage activities was analysed. As observed in Figure 3.27, the Work Items contain the label *Security* populated with the number 3, corresponding to the Third Stage of security. The same approach was done in MTR, as observed in Figure 3.28, where the *Tag* is correctly set to *Manual*. The correct use of the label *Origin* was already discussed in section 3.3.1.

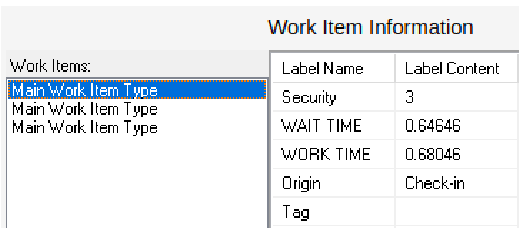

Figure 3.27: Third Stage contents with the label *Security* populated.

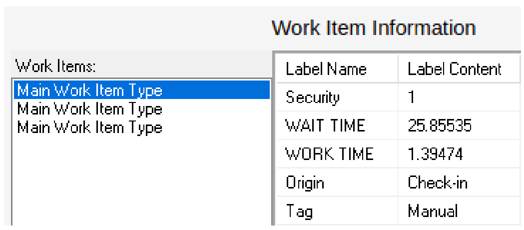

Figure 3.28: MTR contents with the label *Tag* populated.

3.3.5 Simulation time and *warm-up* period

In order to avoid running lengthy simulations, it was chosen to define a simulation period of one day. As previously mentioned on subsection 3.2.1, the daily start time was set to 5:00 and the end time was set to 24:00. Nevertheless, numerous simulations were run for the same period, through the *Run Trial* feature, and averages of these different runs were derived when collecting the results.

The *Warm-up* is the period of time during which the software does not collect any performance metrics. Since, in reality, airports' BHSs begin their operation without any bags in the system from the previous day, it was decided not to define a *Warm-up* period.

3.3.6 Number of runs

In order to ensure results with narrower confidence intervals, it is important to conduct an experiment with multiple runs, adopting a series of pseudo random numbers and independent of one another. A trial is a collection of simulation runs that are all done with the same parameter values, with the exception of the *random numbers* used. It is crucial to run a simulation multiple times in order to mimic the variability of real-world systems.

Trials Calculator is a SIMUL8 feature that recommends a number of runs to use for trials, based on required precision of the confidence limits around the estimate of the mean for the KPIs. Adopting a confidence interval of 5%, the recommended number of runs is 4 (Figure 3.29).

Trials Calculator - Recommendations

KPI	Recommended Runs
(Recommended runs for 5% precision)	
gbl_throughput: Value	4
End: Average Time in System	4
Group MTR: Average Use	4
Group ATR: Average Use	4

Figure 3.29: Recommended runs by the *Trials Calculator*.

3.3.7 Validation of the simulation model

In this section, it will be determined whether the values obtained from the simulation model developed are accurate and whether there are any visible bottlenecks in the system. The simulation model is currently implemented and already has the necessary data inserted. An important aspect to note is that bags cannot stay in the system after the simulation stops running or, in other words, the WIP has to be zero, since all baggage has to be dispatched to the respective airplane during the work day. That is why it was decided to have a simulation time of one day.

While the model was running, it was possible to identify the periods in which the system was working beyond its capacity. For instance at 7:30 the system was already experiencing significant queueing times in the first and second stages and in the ATR (Figures 3.30, 3.31 and 3.32), as can be explained by the arrival rate of baggage displayed in Figure 3.3.

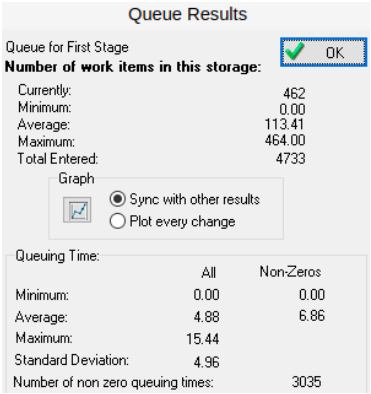

Figure 3.30: First stage queue.

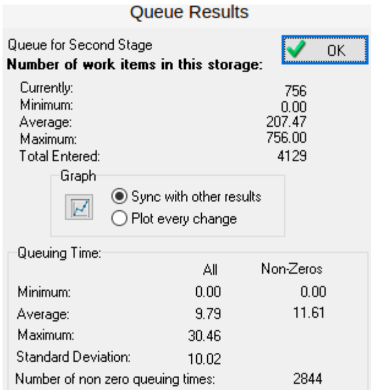

Figure 3.31: Second stage queue.

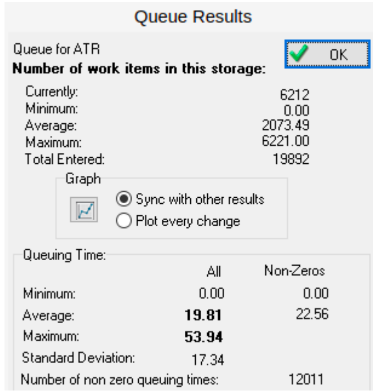

Figure 3.32: ATR queue.

It is possible to draw the conclusion that the simulation model developed accurately identifies bottlenecks in the following activities: the first and second stages of security and the ATR. However, it was noticeable the decrease in the queue size from around 10:00 until 16:30, since that is when the baggage arrival rate is at its lowest during the day. During that period, the queues in the system were essentially empty and there were no bottlenecks visible. Table 3.5 shows the average and maximum queueing time for each security stage in addition to the number of completed jobs.

Security stages	**Queueing Time (min)**		**Completed jobs**
	Average	Maximum	
1	59.06	127.83	43442
2	142.22	275.11	28259
3	140.94	270.26	651
4	169.45	256.45	9
No screening	59.27	113.46	3107

Table 3.5: Queueing times by security stage.

Hereafter, the number of servers currently available in those three critical activities need to increase in order to decrease the queueing time in the system. Another simulation was run with 30 servers available in first stage, 16 in the second and 80 in the ATR. Following this modification, queue times significantly decreased, as displayed in Table 3.6.

This simulation yielded an average CT of 29.83 minutes, while the maximum CT was 85.40 minutes. The throughput of the system was 65.9 bags per minute and the WIP recorded at the end of the simulation was 28 jobs.

To address the fact that the WIP is not zero, a constraint was set on Check-in *Start Point* to impose

Security stages	Queueing Time (min)		Completed jobs
	Average	Maximum	
1	21.35	58.82	43231
2	25.96	71.47	28282
3	26.16	69.62	645
4	29.69	64.02	13
No screening	9.49	32.82	3060

Table 3.6: Queueing times by security stage, after increasing the number of servers.

a time limit on the arrival time of work items. This way, the injection of baggage into the system ceases at 23:45.

4

Scenario Definition

Contents

4.1 Predictions for future passenger volume

Passenger data was collected with the goal of predicting the mean arrival rate for the upcoming years in order to determine whether the model can withstand variations in the input, namely an increase in the arrival of baggage, while maintaining the levels of throughput and average time in system.

4.1.1 Passenger traffic data from INE

Based on information gathered from Instituto Nacional de Estatística (INE) [11] displayed in Table A.1, the number of passengers departing from Lisbon airport from January 2012 to August 2022 can be observed in Figure 4.1. Additionally, there is a periodicity between the extreme values which undoubtedly correlates to 12-month cycles, along with a trend towards an increase in the number of passengers over the years.

The COVID-19 pandemic and the restrictive airspace restrictions resulted in a major reduction in passenger movement, and it wasn't until August of this year that it started to return to pre-pandemic levels.

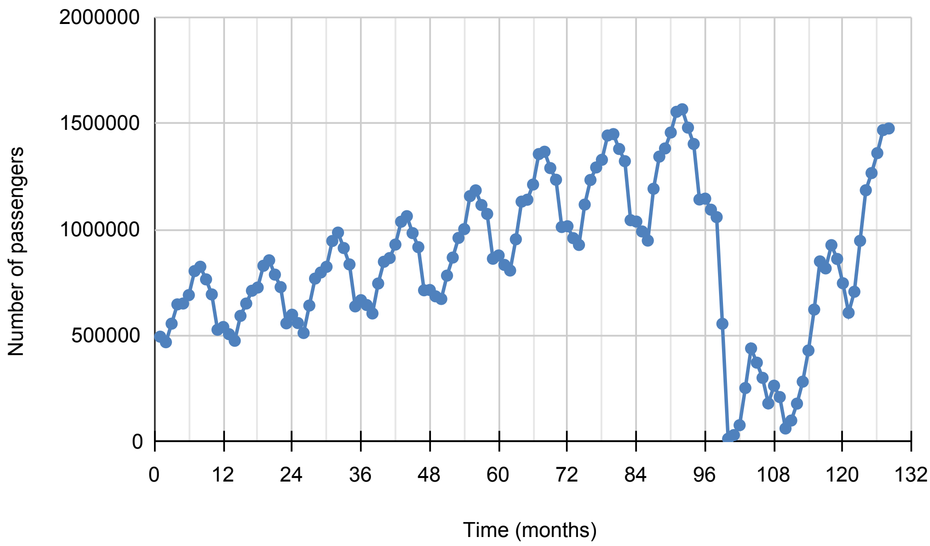

Figure 4.1: Embarked passengers at Lisbon airport from 2012 to 2022.

Equation 4.1 illustrates the formula for the centered Moving Average (MA) of length $k = 12$ months.

$$MA_t = \frac{1}{k}\left(\frac{1}{2}y_{t-k} + y_{t-k+1} + \cdots + y_t + \cdots + y_{t+k-1} + \frac{1}{2}y_{t+k}\right) \tag{4.1}$$

The arithmetic mean of the observations of the variable in a neighborhood of instant t is referred to as the moving average. The resulting MA, for the time frame prior to the COVID-19 pandemic (from

2012 to 2019), is displayed in Figure 4.2.

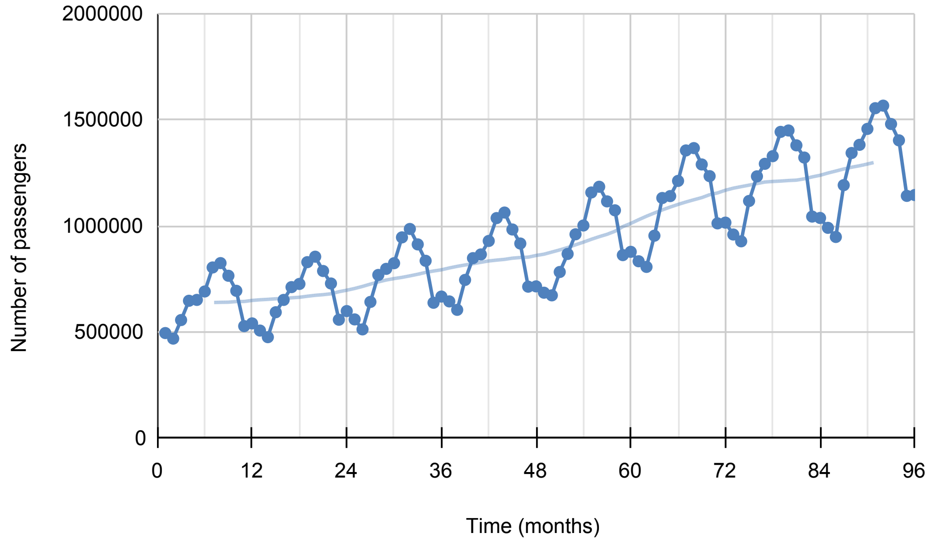

Figure 4.2: Embarked passengers at Lisbon airport from 2012 to 2019, with the respective centered moving average of $k = 12$.

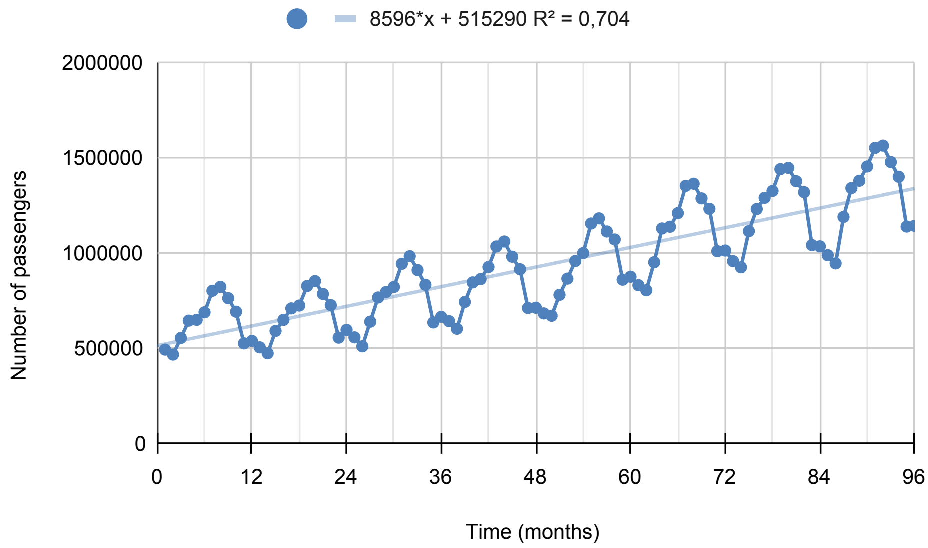

Figure 4.3: Embarked passengers at Lisbon airport from 2012 to 2019, with the respective trendline.

Figure 4.3 illustrates the number of embarked passengers at Lisbon airport as well as the linear regression trend line. The estimated coefficient of determination R^2 is 0.704, which indicates that 70.4% of the observed data is explained by this regression model. The resulting equation for the linear regression line is given by

$$\text{Number of passengers (month)} = 8596 \times \text{month} + 515290. \quad (4.2)$$

Hence, in the year 2032, the predictions for the number of passengers are presented in Table 4.1, where the month of February corresponds to the lowest volume of passengers and August to the highest.

	February 2032	**August 2032**
Number of expected passengers	2 389 218	2 440 794

Table 4.1: Predicted number of passengers for the year 2032, based on INE data.

4.1.2 Growth rates from IATA and Eurocontrol

In order to obtain additional predictions for the number of passengers in the upcoming years, data from other sources related to the air transport was gathered, namely from International Air Transport Association (IATA) and Eurocontrol.

In their 20 year passenger forecast [40], IATA reported a 2.5% growth rate for the Europe region. Earlier this year, Eurocontrol published the Aviation Outlook 2050, pertaining the air traffic development until the year 2050. An annual average growth rate of 0.8% is expected for Portugal, one of the lowest rates in the European region, as Figure A.5 illustrates. Using the aforementioned annual growth rates, the predictions for the number of passengers can be obtained (Table 4.2).

	February 2032	**August 2032**
Number of expected passengers (IATA)	1 242 546	2 054 072
Number of expected passengers (Eurocontrol)	1 033 751	1 708 909

Table 4.2: Predicted number of passengers for the year 2032, based on IATA and Eurocontrol forecasts.

.

4.2 Baggage to passenger ratio

Due to the lack of statistical information provided on the number of checked bags carried per passenger, the authors of [5] suggest that 1.0 to 1.25 bags per domestic passenger and 1.25 to 2.0 bags per international passenger be used. Since this data relates to the American continent it does not accurately reflect the behaviour observed in European airports. A ratio of 0.97 bags per passenger was calculated in [41], specifically for the European continent.

Low Cost Carriers (LCCs) are an integral part of modern-day European aviation, accounting for 27% of the market share in Europe [42]. Nowadays, due to the added fees imposed to checked baggage by LCCs, the ratio is most likely lower than 1 checked bag per passenger. Moreover, a ratio of 0.69

bags per passenger was calculated in a case study performed in the Faro airport, where the majority of carriers are low cost [10].

4.3 Scenarios

In the next sections, scenarios were created using combinations of the predictions previously calculated. Every scenario includes simulations for the month of February and August. The adjustments to the data to model the arrival of entities were performed for every scenario, similarly to what was previously detailed in 3.1.1. The auxiliary calculations are displayed in Appendix B.

A – First scenario Firstly, the predictions calculated from INE data for the number of expected passengers in 2032 are used in combination with a baggage to passenger ratio of 0.97. It is possible to note that the average number of bags per day expected for February is higher than the predictions for the month of August. This occurrence in data from INE is due to the fact that the monthly number of passengers is similar for both months and, to compute the number of bags per day, that value was divided by the number of days of every month, 29 for February (leap year in 2032) and 31 for August.

	February 2032	**August 2032**
Number of passengers	2 389 218	2 440 794
Bag to passenger ratio	0.97	0.97
Number of bags per day	79 915	76 373

Table 4.3: First scenario: number of bags per day.

.

B – Second scenario In the second scenario, a baggage to passenger ratio of 0.69 is used in combination with the predictions calculated from INE data for the number of expected passengers in 2032.

	February 2032	**August 2032**
Number of passengers	2 389 218	2 440 794
Bag to passenger ratio	0.69	0.69
Number of bags per day	56 847	54 327

Table 4.4: Second scenario: number of bags per day.

.

C – Third scenario Using the predictions calculated from the annual growth rate reported by IATA with a baggage to passenger ratio of 0.97, the third scenario is created.

	February 2032	August 2032
Number of passengers	1 242 546	2 054 072
Bag to passenger ratio	0.97	0.97
Number of bags per day	43 045	64 273

Table 4.5: Third scenario: number of bags per day.

.

D – Fourth scenario The fourth scenario uses the predictions calculated from the annual growth rate reported by IATA with a baggage to passenger ratio of 0.69.

	February 2032	August 2032
Number of passengers	1 242 546	2 054 072
Bag to passenger ratio	0.69	0.69
Number of bags per day	30 620	45 720

Table 4.6: Fourth scenario: number of bags per day.

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E – Fifth scenario In this scenario, the predictions calculated from the annual growth rate reported by Eurocontrol for Portugal are used in combination with a baggage to passenger ratio of 0.97.

	February 2032	August 2032
Number of passengers	1 033 751	1 708 909
Bag to passenger ratio	0.97	0.97
Number of bags per day	35 812	53 472

Table 4.7: Fifth scenario: number of bags per day.

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F – Sixth scenario The sixth scenario uses the predictions calculated from the annual growth rate reported by Eurocontrol for Portugal in combination with a baggage to passenger ratio of 0.69.

	February 2032	August 2032
Number of passengers	1 033 751	1 708 909
Bag to passenger ratio	0.69	0.69
Number of bags per day	25 475	38 037

Table 4.8: Sixth scenario: number of bags per day.

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G – Seventh scenario This scenario aims to simulate a day in which the BHS experiences a machine breakdown, namely in a component that directly impacts the normal operation of the system, such as the carousel. Two simulations are run in this scenario, one for the lowest number of bags per day and the other for the highest number of bags per day.

A breakdown is set to happen to the carousel at the peak time of day (17:30) and the Mean Time to Repair (MTTR) is defined by a Erlang distribution with a mean processing time of $30\,\mathrm{min}$.

H – Eighth scenario As previously discussed in 3.1.2, operators have to take a break of at least $10\,\mathrm{min}$ after each period of $20\,\mathrm{min}$ continuously reviewing X-ray images. In the simulation model, this break was implemented by setting the available resources to 12, for the entire day.

The objective of this scenario is to simulate a day in which the available second stage resources change to 14 as well as to the resources previously defined in the model validation phase (16).

5

Results and Discussion

Contents

5.1 Future baggage volume

Initially, six scenarios were performed to model the number of expected bags entering a BHS in the year 2032. In Table 5.1, an overview of the scenarios is presented, where it is possible to note that the number of expected bags per day in scenario 1 is higher than the current bag volume used in the simulation model. The remaining scenarios project that there will be less checked baggage in ten years, which is very likely, given the rise of LCCs and the costs they charge for checked baggage.

Scenarios	**Month**	**Expected bags per day**
Scenario 1	February	79 915
	August	76 373
Scenario 2	February	56 847
	August	54 327
Scenario 3	February	43 045
	August	64 273
Scenario 4	February	30 620
	August	45 720
Scenario 5	February	35 812
	August	53 472
Scenario 6	February	25 475
	August	38 037

Table 5.1: Future baggage volume scenarios.

First scenario This scenario simulates the highest baggage injection rate into the BHS and the respective simulation results are displayed in Table 5.2.

Although this simulation reported a th rate of 76.28 bags per minute, the queueing times significantly increased, reaching levels that were not actually feasible for the system to operate at on a regular basis. Given that passengers typically drop off their baggage between $1.5\,\mathrm{h}$ and $2\,\mathrm{h}$ prior to the departure of their flight, BHSs need to report cycle times under $1.5\,\mathrm{h}$ to guarantee that all bags board the respective airplane.

KPI	**Total**	**No screening**	**1**	**2**	**3**	**4**
Completed jobs	87338	3474	50286	32831	735	12
Minimum CT	3.84	3.84	5.46	7.20	9.33	14.76
Average CT	43.16	17.35	36.73	55.39	58.55	52.82
Maximum CT	139.10	43.00	90.67	139.10	136.71	131.54
AWT	36.01	12.72	30.29	46.97	48.03	36.59
MWT	127.81	35.83	80.82	127.81	125.77	115.65

Table 5.2: KPI results for scenario 1 (February).

In this scenario, only bags that do not undergo security screening and bags that go through stage 1 report CTs within $1.5\,\mathrm{h}$, suggesting that the system is operating beyond its maximum capacity due to the high rate of baggage injection.

The bottlenecks detected during model validation still persist, observed in the first and second stages of security and the ATR, with the queue for second stage being the most problematic, reporting a MWT of $51.87\,\mathrm{min}$ (Table B.1). Additionally, the queue immediately after the check-in also reports a considerable MWT of $29.85\,\mathrm{min}$.

When examining the resources available for the activities in the system in Table B.2, it becomes clear that the maximum use of the first stage resources does not even approach the 30 threshold that was established during model validation. The resources available for the third and fourth stages of security were similarly overestimated, since their maximum use was 4 and 1, respectively. The ATR and MTR, on the other hand, make full use of all resources despite having slightly lower average use.

Table 5.3 exposes the simulation results for the month of August, which shows a reduction of 3000 bags per day when compared to February. The th rate recorded for this simulation was 72.94 bags per minute.

KPI	Total	No screening	1	2	3	4
Completed jobs	83113	3369	48050	30989	697	8
Minimum CT	3.86	3.86	5.50	7.24	9.22	14.52
Average CT	37.73	14.04	31.11	50.14	56.05	39.46
Maximum CT	120.26	37.27	71.27	120.26	119.74	112.49
AWT	30.59	9.44	24.67	41.73	45.47	23.25
MWT	108.58	30.52	61.64	108.58	107.59	95.80

Table 5.3: KPI results for scenario 1 (August).

This scenario reports a reduction of $6\,\mathrm{min}$ in the AWT as well as $20\,\mathrm{min}$ in the MWT when compared to February. Nonetheless, it still indicates that only bags that do not undergo security screening and bags that go through stage 1 report CTs within $1.5\,\mathrm{h}$. According to Table B.1, the bottlenecks remain in the first conveyors after the check-in, in the first and second stages and in the ATR, with the queue for second stage recording the highest MWT in the system. As per Figure 3.3, the baggage injection rate is higher in the morning and in the late afternoon, which results in large queue sizes.

Second scenario The following scenario assumes a lower baggage to passenger ratio, leading to a decrease in the number of bags in a BHS per day. Due to the similarity in the baggage injection rates for both months, the simulation results for the month of August are displayed in Table B.3 in Appendix B. Table 5.4 features the simulation results for the month of February, which reported a th rate of 54.29 bags per minute.

KPI	Total	No screening	1	2	3	4
Completed jobs	61866	2436	35599	23296	530	5
Minimum CT	3.84	3.84	5.49	7.18	9.23	19.04
Average CT	17.04	7.81	13.39	23.39	25.37	31.39
Maximum CT	56.97	22.51	31.62	56.97	53.89	47.87
AWT	9.92	3.19	6.98	15.01	14.91	14.50
MWT	44.98	14.88	22.12	44.98	42.99	33.95

Table 5.4: KPI results for scenario 2 (February).

Due to a lower arrival rate, the data demonstrates a reduction in the queueing times throughout all security stages. Moreover, the system CT is below the $1.5\,\mathrm{h}$ threshold discussed in the previous scenario.

Notwithstanding, the bottlenecks of the system persist in the first conveyors, in the second stage and in the ATR, since their queues continue to show substantial queue sizes (Table B.4). Table B.5 shows a considerable reduction in the average use of the resources as the injection rates drop, with only two activities reporting to use the maximum available (ATR and MTR).

Third scenario The forecasts derived from the annual growth rate provided by IATA are used in the current scenario. In regard to the month of February, the results displayed in Table 5.5 reveal a significant drop in the average and maximum CTs, while also reporting minor queueing times. In this case, the system experiences bottlenecks in the second stage and in the ATR, since the queues for those activities are the only ones showing pertinent MWTs, as illustrated in Table B.6.

KPI	Total	No screening	1	2	3	4
Completed jobs	45265	1859	25979	17027	394	6
Minimum CT	3.85	3.85	5.47	7.25	9.05	14.23
Average CT	7.67	4.83	6.66	9.43	11.62	19.43
Maximum CT	24.08	11.74	14.21	22.78	21.94	24.08
AWT	0.64	0.26	0.34	1.15	1.27	1.11
MWT	10.72	4.80	5.05	10.72	9.39	6.64

Table 5.5: KPI results for scenario 3 (February).

Table 5.6 displays the simulation results for the month of August, where the baggage injection rate is much higher compared to February.

KPI	Total	No screening	1	2	3	4
Completed jobs	70080	2872	40409	26214	579	6
Minimum CT	3.85	3.85	5.49	7.20	9.17	15.65
Average CT	24.65	10.51	20.02	33.10	35.74	34.10
Maximum CT	80.15	29.94	47.44	80.15	77.62	47.76
AWT	17.53	5.92	13.59	24.70	25.25	15.64
MWT	68.08	23.06	37.71	68.08	66.39	27.63

Table 5.6: KPI results for scenario 3 (August).

This simulation reports a increase of $17\,\mathrm{min}$ in the AWT as well as $60\,\mathrm{min}$ in the MWT when compared to February. The first conveyors, the first and second stages and the ATR continue to be the bottlenecks of the system, reporting significant queueing times as observed in Table B.6.

Fourth scenario A smaller baggage arrival rate to the BHS is simulated in this scenario, for the month of February, and its results are displayed in Table 5.7. Since the baggage injection rate for the month of August is similar to the rate for February from scenario 3, the results are illustrated in Table B.8 in Appendix B.

KPI	Total	No screening	1	2	3	4
Completed jobs	31985	1335	18400	11972	275	3
Minimum CT	3.87	3.87	5.47	7.21	9.08	13.77
Average CT	7.01	4.60	6.31	8.27	10.41	14.71
Maximum CT	15.81	9.33	11.10	13.74	15.02	15.81
AWT	0.012	0.010	0.007	0.020	0.019	0.0009
MWT	2.10	1.76	2.10	1.99	0.50	0.0028

Table 5.7: KPI results for scenario 4 (February).

The current injection rate simulated in the system yielded a th rate of 28.07 bags per minute and almost no queueing time for the whole system. When analysing Table B.10, it becomes clear that the reported average use of the resources is very low for the first and third stages, whereas for the remaining activities it amounts to around a fourth of the total number of resources available.

Fifth scenario The simulation results for the month of February are presented in Table 5.8. Since the baggage injection rate for the month of August is similar to the rate for August from scenario 2, the results are illustrated in Table B.11 in Appendix B.

KPI	Total	No screening	1	2	3	4
Completed jobs	37679	1626	21629	14122	295	7
Minimum CT	3.89	3.89	5.50	7.23	9.23	15.56
Average CT	7.09	4.57	6.33	8.47	10.70	17.30
Maximum CT	20.30	9.59	13.81	16.95	17.99	20.30
AWT	0.088	0.007	0.016	0.208	0.217	0.059
MWT	4.93	2.33	3.01	4.93	4.78	0.196

Table 5.8: KPI results for scenario 5 (February).

For this scenario, the maximum amount of bags stored in queues is only significant in the queue preceding the second stage, reporting a total of 64 bags during rush hours. Thus, it is possible to claim that there are no bottlenecks in the system, for this specific baggage injection rate.

Sixth scenario Considering the similarities in the baggage arrival rates for the month of August and the month of February from scenario 5, the simulation results for the month of August are displayed in Table B.14 in Appendix B. The simulation results for the month of February are depicted in Table 5.9.

KPI	Total	No screening	1	2	3	4
Completed jobs	28505	1113	16371	10772	246	3
Minimum CT	3.85	3.85	5.49	7.22	9.23	17.97
Average CT	7.01	4.59	6.31	8.25	10.46	18.10
Maximum CT	18.28	9.15	11.20	12.86	14.33	18.28
AWT	0.008	0.004	0.003	0.015	0.012	0.005
MWT	0.91	0.54	0.97	0.91	0.53	0.008

Table 5.9: KPI results for scenario 6 (February).

The lowest injection rate simulated in the system generated an average CT of $7.01\,\mathrm{min}$, a maximum CT of $18.28\,\mathrm{min}$ and a th rate of 25.01 bags per minute. As observed in Table B.16, this is the first instance that the ATR does not utilize the total number of available resources (80); in this scenario, the activity uses 71.

5.2 Simulating a machine breakdown

Afterwards, a scenario was created to model a machine breakdown in a component that directly impacts the normal functioning of the system. In Table 5.10, an overview of the simulations is presented, where *Low rate* corresponds to the lowest number of bags per day and *High rate* corresponds to the highest number of bags per day.

Simulations	Scenario	Expected bags per day
Low rate	Scenario 6 - February	25 475
High rate	Scenario 1 - February	79 915

Table 5.10: Machine breakdown scenarios.

Seventh scenario Table 5.11 showcases the results for the *Low rate* simulation from the seventh scenario.

KPI	Total	No screening	1	2	3	4
Completed jobs	28306	1122	16329	10627	226	2
Minimum CT	3.78	3.78	5.51	7.23	9.22	16.30
Average CT	13.66	10.33	12.97	14.99	17.93	36.90
Maximum CT	61.75	56.81	61.58	60.77	61.75	57.51
AWT	6.64	5.79	6.63	6.74	7.38	19.70
MWT	51.99	51.67	51.99	51.94	50.86	39.40

Table 5.11: KPI results for scenario 7 (Low rate).

In contrast to the simulation of February from scenario 6, which produced a th rate of 25.01 bags per minute, this simulation yielded a th rate of 24.84 bags per minute, indicating a slight decline. Yet, a significant increase in the maximum CT can be observed in the present simulation, as well as in the AWTs and MWTs for all security stages. Looking at Table B.17, it becomes clear that all queues recorded negligible wait times with the exception of the queue preceding the carousel, reporting an AWT of $2.51\,\mathrm{min}$ and a MWT of $30.21\,\mathrm{min}$.

Table 5.12 illustrates the results for the *High rate* simulation from the seventh scenario.

KPI	**Total**	**No screening**	**1**	**2**	**3**	**4**
Completed jobs	86933	3530	49747	32925	724	7
Minimum CT	3.85	3.85	5.52	7.19	9.29	32.26
Average CT	47.39	19.94	40.87	59.86	61.72	82.21
Maximum CT	139.49	43.38	89.78	139.37	139.49	128.73
AWT	40.22	15.33	34.42	51.41	51.22	65.25
MWT	128.07	36.26	80.22	128.07	126.92	113.32

Table 5.12: KPI results for scenario 7 (High rate).

Due to the high baggage injection rate, there are small differences between KPIs from the simulation of February from scenario 1 and the current one, since the system is already working beyong its capabilities. Even though the MWT of the carousel's queue increased from 0 to $41.08\,\mathrm{min}$, the majority of the KPIs remained similar, with the exception of the average CT and the AWT that increased by $4\,\mathrm{min}$.

It is undeniable that a carousel breakdown significantly affects the normal behaviour of a BHS. Due to its dimension and cost, the majority of BHSs only has one carousel, making it impossible to route the bags to an alternate component in the event of a breakdown. However, for other components of the system, having an alternate component becomes a clear solution to bypass possible malfunctions.

5.3 Changing the availability of the second stage resources

The second stage resources are required to take a $10\,\mathrm{min}$ break after every $20\,\mathrm{min}$ of continuous labour. This aspect substantially increases the average queueing times and can create a bottleneck for the BHS. It was chosen to simulate the model by varying the number of available resources in order to reduce this waiting time. The *Low rate* and *High rate* simulations depicted in Table 5.10 are used in this scenario.

Eighth scenario Table 5.13 showcases the main KPI results for the eighth scenario simulations. The remaining simulation results are displayed in Appendix B.

KPI	Resources					
	12		14		16	
	Low	*High*	*Low*	*High*	*Low*	*High*
Average CT	7.01	43.16	7.02	42.09	6.99	42.44
Maximum CT	18.28	139.10	18.01	118.50	15.84	111.01
AWT	0.008	36.01	0.005	34.95	0.004	35.29
MWT	0.91	127.81	0.99	106.15	1.42	96.44

Table 5.13: KPI results for scenario 8.

Increasing the available resources to 14, it is visible that, for the *High rate* simulations, there is an overall reduction in the KPIs, especially in the maximum CTs and MWT. It can be noted that only the maximum CTs and MWT decreased significantly when 16 resources are available, while the other KPIs remained unchanged. For the *Low rate* simulations, it becomes clear that the second stage activity does not represent a bottleneck in the system, since an increase in the resources did not affect the KPIs.

Combining the queue results from Tables B.21 and B.25, Figure 5.1 illustrates the variation in the AWT and MWT of the second stage queue when the second stage resources change from 12 to 14 and 16. As predicted, the AWT and MWT decrease as the number of available resources increase. The average and maximum CTs experience the same behaviour for both the *High rate* and *Low rate* simulations.

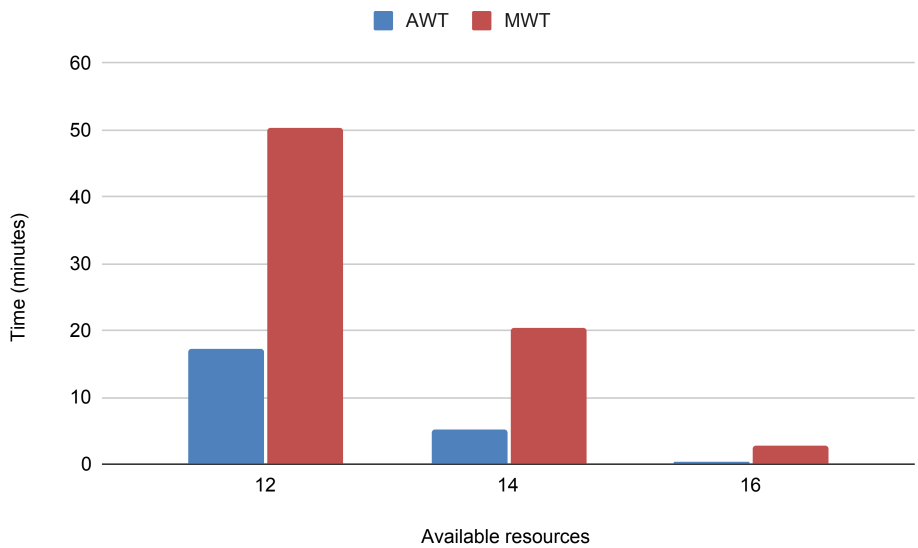

Figure 5.1: Queue for the second stage: AWT and MWT variation (*High rate*).

Even though the implementation of this scenario in a BHS would benefit its KPIs, it might not be possible to implement due to the European regulation requirements that airports and baggage handlers have to comply, as previously discussed in 3.1.2.

5.4 Discussion

One aspect that was shared by every scenario was the fact that the number of available resources for the third and fourth stages was overestimated. A system improvement would be to set a restriction on the amount of available resources, with 5 for the third stage and 1 for the fourth.

On a similar note, the first stage resources were also slightly overestimated during the model validation phase. The simulation results from the scenarios recorded that the maximum number of resources used was 22, even though the number of available resources was 30.

Nonetheless, it becomes clear that for high baggage arrival rates, the system operates beyond its capacity which results in bigger queueing times and CT of the system. To prevent the first queue after the check-in from storing too many bags, more conveyors would need to be placed before the first security screening stage. Additionally, increasing the resource availability in the second stage would highly improve the overall performance of the system.

6

Conclusions and Future Work

Contents

6.1 Conclusions

The proposed objectives for this dissertation consisted on performing an analysis of a BHS and elaborating improvement suggestions that would lower waiting times and incur in future cost savings, related to less machinery requirements and operating time. In addition, future predictions for the baggage volume in airports were calculated, using data from INE, IATA and Eurocontrol.

To expand the knowledge on this subject and comprehend the scientific advances already made in this field, a literature review was the first step to be taken. Subsequently, the outlined methodology consisted on adopting a DES approach to model the problem. This approach was chosen due to the discrete, stochastic and dynamic characteristics of the system. During the model validation phase, bottlenecks in the initial components of the system were identified, resulting in an increase in the number of available resources in those respective components.

By creating and performing studies for each scenario, the impact of variations in baggage injection volume and its effects on the airport's performance metrics could be demonstrated. On the one hand, a 16 % increase in bag volume was predicted for the year 2032, resulting in a congestion in critical components of the system, which suggests that modifications to the infrastructure of the airport are needed. On the other hand, other projections imply a lower baggage injection rate for the same period, mainly due the rise of LCCs and their respective hold baggage additional costs. This analysis confirmed that certain resources had been overestimated during the design phase and could be excluded from the system, resulting in staff reductions while maintaining the same waiting times.

Furthermore, given that the work was developed in a more generalised approach, its takeaways can be applicable to airports with similar characteristics, including the size, features and equipment.

6.2 Future work

This work's contributions are focused on the baggage handling processing up to the carousel and do not include the baggage unloading of the system, as it does not significantly impact the queueing times experienced in the system. However, the baggage unloading process can produce queues if the airport experiences delays in the arrival of airplanes. In the event that a flight is set to depart and the respective airplane is not yet available, baggage can either be transported to a baggage storage or remain in the carousel until the plane is ready to loaded.

A possible expansion of this work would be to incorporate flight delays in the modelling of the system. Deterministic queueing dynamics can be used to predict flight delays. Notwithstanding, this approach yields overly optimistic predictions, whereas adopting a stochastic approach leads to accurate forecasts of expected congestion levels and delays [43].

In addition, baggage injection to the system could be modelled by using the airport flight schedule. For every flight, the policy for passenger arrival time is selected dependent on the airline and relevant distributions can be determined for each time interval before departure time. Lastly, the aggregate number of passengers arriving per time interval is obtained to estimate the volume of passengers arriving at the airport [44].

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A

Baggage injection rate

The baggage injection to the system was determined through auxiliary calculations, further detailed in this appendix.

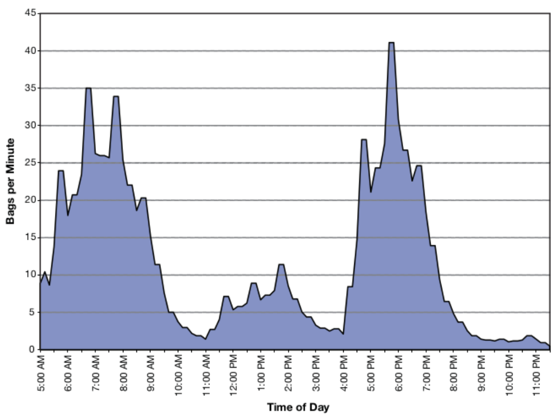


Figure A.1: Outbound bag volume [5].

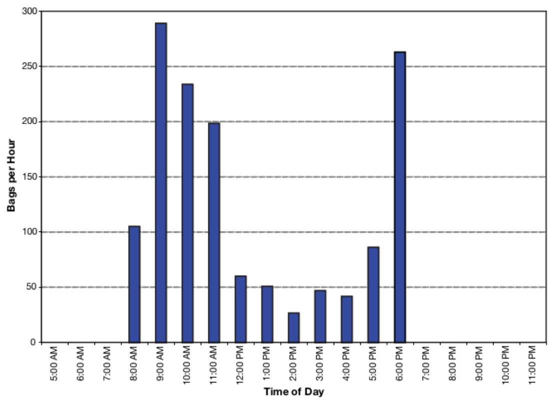


Figure A.2: Transfer bag volume [5].

Outbound baggage		Transfer baggage	
Bags/hour	3600	Bags/hour	454
Bags/min	60	Bags/min	7,56

Time	Bags/min	Bags/min fixed	Bags/hour	Bags/min	Bags/min fixed
05:00	9	46			
05:30	14	71			
06:00	18	91			
06:30	35	177			
07:00	26	131			
07:30	34	172			
08:00	26	131	105	1,75	6
08:30	20	101			
09:00	15	76	290	4,83	17
09:30	5	25			
10:00	3	15	235	3,92	14
10:30	2	10			
11:00	2	10	200	3,33	12
11:30	4	20			
12:00	7	35	60	1	4
12:30	8	40			
13:00	9	46	50	0,83	3
13:30	9	46			
14:00	11	56	25	0,42	1
14:30	6	30			
15:00	3	15	50	0,83	3
15:30	2	10			
16:00	1	5	45	0,75	3
16:30	15	76			
17:00	21	106	90	1,5	5
17:30	42	212			
18:00	30	152	260	4,33	15
18:30	24	121			
19:00	20	101			
19:30	10	51			
20:00	5	25			
20:30	3	15			
21:00	2	10			
21:30	2	10			
22:00	2	10			
22:30	3	15			
23:00	2	10			
23:30	1	5			
Average	11,87	59,95	128,18	2,14	7,56

Figure A.3: Auxiliary calculations: outbound and transfer baggage arrival rate in bags per minute.

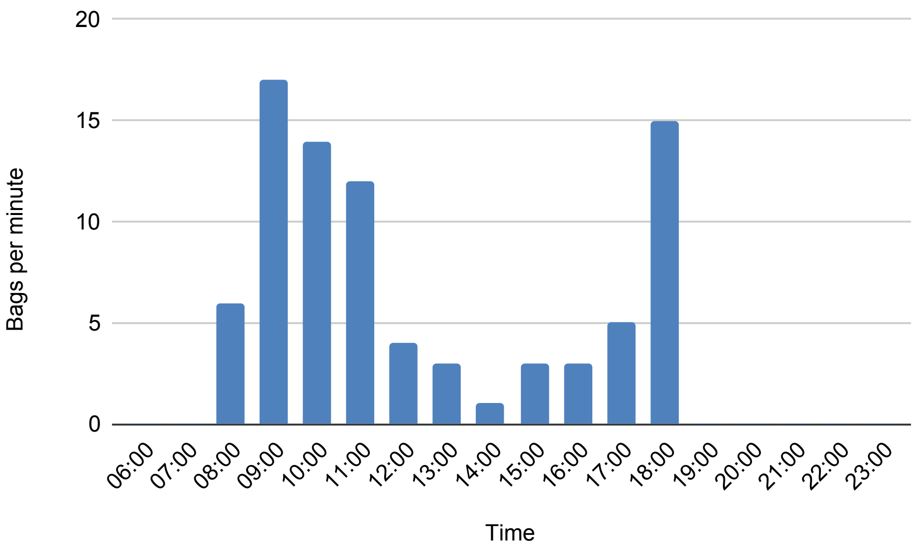


Figure A.4: Transfer bag volume in bags per minute.

In order to determine the future predictions for the year 2032, data was gathered from INE regarding the number of passengers departing from Lisbon airport as well as predicted annual growth rates from IATA and Eurocontrol.

Year	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	18 019	1 214	1 412	1 892	2 368	2 530	2 718	2 935	2 950	-	-	-	-
2021	12 160	420	124	199	358	565	859	1 244	1 698	1 632	1 851	1 721	1 492
2020	9 268	2 185	2 115	1 110	27	62	155	505	878	744	601	360	527
2019	31 185	1 980	1 894	2 382	2 685	2 762	2 912	3 107	3 131	2 958	2 804	2 281	2 289
2018	29 045	1 917	1 853	2 233	2 465	2 583	2 655	2 884	2 897	2757	2 642	2 086	2 073
2017	26 680	1 665	1 612	1 906	2 261	2 279	2 422	2 709	2 731	2 577	2 467	2 022	2 029
2016	22 463	1 369	1 344	1 564	1 734	1 919	2 002	2 313	2 367	2 229	2 145	1 723	1 754
2015	20 107	1 287	1 207	1 489	1 694	1 729	1 856	2 072	2 124	1 964	1 832	1 425	1 428
2014	18 154	1 117	1 023	1 282	1 536	1 593	1 646	1 890	1 969	1 823	1 669	1 274	1 332
2013	16 023	1 012	950	1 185	1 301	1 421	1 451	1 656	1 708	1 573	1 456	1 114	1 196
2012	15 314	989	937	1 111	1 293	1 301	1 380	1 607	1 648	1 528	1 387	1 054	1 079

Table A.1: Passenger's movement at Lisbon airport, in thousands [11].

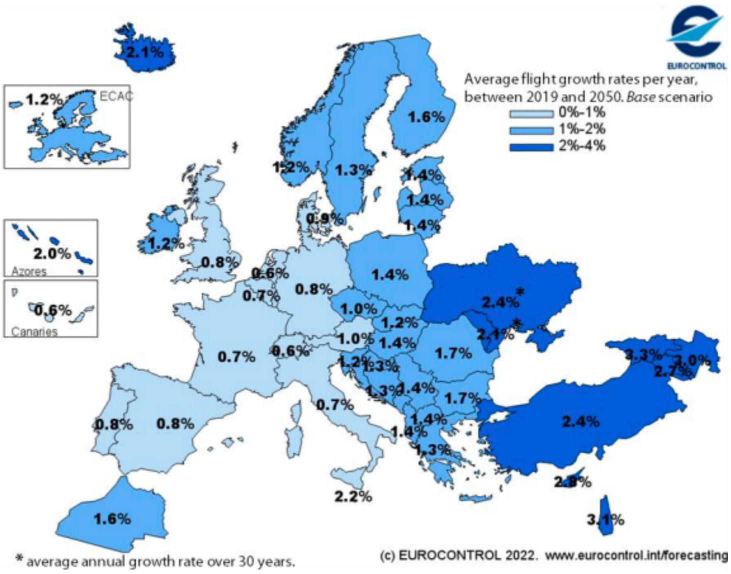
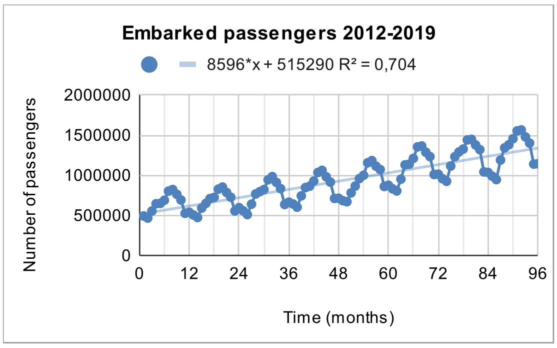


Figure A.5: Eurocontrol 30 year forecast [8].

INE



Feb 2032	Aug 2032
218	224
2389218	2440794

IATA	Eurocontrol
0,025	0,008

IATA		Eurocontrol	
Feb 2022	970675	Feb 2022	954576
Aug 2022	1604638	Aug 2022	1578024
Feb 2023	994942	Feb 2023	962213
Aug 2023	1644753	Aug 2023	1590648
Feb 2024	1019815	Feb 2024	969910
Aug 2024	1685872	Aug 2024	1603373
Feb 2025	1045311	Feb 2025	977670
Aug 2025	1728019	Aug 2025	1616200
Feb 2026	1071444	Feb 2026	985491
Aug 2026	1771220	Aug 2026	1629130
Feb 2027	1098230	Feb 2027	993375
Aug 2027	1815500	Aug 2027	1642163
Feb 2028	1125685	Feb 2028	1001322
Aug 2028	1860888	Aug 2028	1655300
Feb 2029	1153828	Feb 2029	1009332
Aug 2029	1907410	Aug 2029	1668543
Feb 2030	1182673	Feb 2030	1017407
Aug 2030	1955095	Aug 2030	1681891
Feb 2031	1212240	Feb 2031	1025546
Aug 2031	2003972	Aug 2031	1695346
Feb 2032	1242546	**Feb 2032**	1033751
Aug 2032	2054072	**Aug 2032**	1708909

Figure A.6: Auxiliary calculations: predictions for 2032.

Ratio 1	Ratio 2	INE				IATA				Eurocontrol			
		Ratio 1		Ratio 2		Ratio 1		Ratio 2		Ratio 1		Ratio 2	
0,97	0,69	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
		70,10	66,99	49,87	47,66	36,46	56,38	25,93	40,10	30,33	46,91	21,58	33,37

Time	Bags/min	INE (ratio 1)		INE (ratio 2)		IATA (ratio 1)		IATA (ratio 2)		Euro (ratio 1)		Euro (ratio 2)	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
05:00	9	53	51	38	36	28	43	20	30	23	36	16	25
05:30	14	83	79	59	56	43	67	31	47	36	55	25	39
06:00	18	106	102	76	72	55	86	39	61	46	71	33	51
06:30	35	207	198	147	141	108	166	76	118	89	138	64	98
07:00	26	154	147	109	104	80	124	57	88	66	103	47	73
07:30	34	201	192	143	137	104	162	74	115	87	134	62	96
08:00	26	154	147	109	104	80	124	57	88	66	103	47	73
08:30	20	118	113	84	80	61	95	44	68	51	79	36	56
09:00	15	89	85	63	60	46	71	33	51	38	59	27	42
09:30	5	30	28	21	20	15	24	11	17	13	20	9	14
10:00	3	18	17	13	12	9	14	7	10	8	12	5	8
10:30	2	12	11	8	8	6	10	4	7	5	8	4	6
11:00	2	12	11	8	8	6	10	4	7	5	8	4	6
11:30	4	24	23	17	16	12	19	9	14	10	16	7	11
12:00	7	41	40	29	28	22	33	15	24	18	28	13	20
12:30	8	47	45	34	32	25	38	17	27	20	32	15	22
13:00	9	53	51	38	36	28	43	20	30	23	36	16	25
13:30	9	53	51	38	36	28	43	20	30	23	36	16	25
14:00	11	65	62	46	44	34	52	24	37	28	43	20	31
14:30	6	35	34	25	24	18	29	13	20	15	24	11	17
15:00	3	18	17	13	12	9	14	7	10	8	12	5	8
15:30	2	12	11	8	8	6	10	4	7	5	8	4	6
16:00	1	6	6	4	4	3	5	2	3	3	4	2	3
16:30	15	89	85	63	60	46	71	33	51	38	59	27	42
17:00	21	124	119	88	84	65	100	46	71	54	83	38	59
17:30	42	248	237	176	169	129	200	92	142	107	166	76	118
18:00	30	177	169	126	120	92	143	66	101	77	119	55	84
18:30	24	142	135	101	96	74	114	52	81	61	95	44	67
19:00	20	118	113	84	80	61	95	44	68	51	79	36	56
19:30	10	59	56	42	40	31	48	22	34	26	40	18	28
20:00	5	30	28	21	20	15	24	11	17	13	20	9	14
20:30	3	18	17	13	12	9	14	7	10	8	12	5	8
21:00	2	12	11	8	8	6	10	4	7	5	8	4	6
21:30	2	12	11	8	8	6	10	4	7	5	8	4	6
22:00	2	12	11	8	8	6	10	4	7	5	8	4	6
22:30	3	18	17	13	12	9	14	7	10	8	12	5	8
23:00	2	12	11	8	8	6	10	4	7	5	8	4	6
23:30	1	6	6	4	4	3	5	2	3	3	4	2	3
Average	11,87	70,10	66,99	49,87	47,66	36,46	56,38	25,93	40,10	30,33	46,91	21,58	33,37

Figure A.7: Auxiliary calculations: outbound baggage rate.

Transfers	Bags/min	INE (ratio 1)		INE (ratio 2)		IATA (ratio 1)		IATA (ratio 2)		Euro (ratio 1)		Euro (ratio 2)	
		Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug	Feb	Aug
8	1,75	7	7	5	5	4	6	3	4	3	5	2	3
9	4,83	20	19	14	14	10	16	7	11	9	13	6	10
10	3,92	16	15	12	11	8	13	6	9	7	11	5	8
11	3,33	14	13	10	9	7	11	5	8	6	9	4	7
12	1	4	4	3	3	2	3	2	2	2	3	1	2
13	0,83	3	3	2	2	2	3	1	2	1	2	1	2
14	0,42	2	2	1	1	1	1	1	1	1	2	1	1
15	0,83	3	3	2	2	2	3	1	2	1	2	1	2
16	0,75	3	3	2	2	2	2	1	2	1	2	1	1
17	1,5	6	6	4	4	3	5	2	4	3	4	2	3
18	4,33	18	17	13	12	9	14	7	10	8	12	6	9
Average	2,14	8,8	8,44	6,28	6,00	4,59	7,10	3,27	5,05	3,82	5,91	2,72	4,20

Figure A.8: Auxiliary calculations: transfer baggage rate.

B

Future scenarios

The purpose of this appendix is to aggregate results from simulation runs, namely regarding the use of resources and queueing data.

Scenario 1

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	11.56	8.78	29.85	25.83	4261	3653
First stage	9.03	7.74	32.61	26.47	827	676
Second stage	17.13	17.84	51.87	53.34	1087	1124
ATR	11.07	8.91	34.26	30.55	3852	3400
MTR	0.77	0.48	6.38	3.98	25	13

Table B.1: Queueing data in scenario 1.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	12.28	11.51	3.68	3.45	21	22
Second stage	60.84	58.24	7.30	6.99	12	12
Third stage	4.22	4.00	0.34	0.32	4	5
Fourth stage	0.56	0.34	0.04	0.03	1	1
ATR	63.73	60.78	50.98	48.62	80	80
MTR	58.09	55.04	4.65	4.04	8	8

Table B.2: Resource use in scenario 1.

Scenario 2

KPI	Total	No screening	1	2	3	4
Completed jobs	58846	2402	34055	21929	454	6
Minimum CT	3.88	3.88	5.46	7.21	9.21	14.32
Average CT	14.27	6.78	11.18	19.74	20.96	24.07
Maximum CT	49.13	20.27	27.45	49.13	48.71	48.64
AWT	7.18	2.16	4.79	11.38	10.49	6.97
MWT	38.41	13.41	16.91	38.41	37.43	24.59

Table B.3: KPI results for scenario 2 (August).

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	0.57	0.31	5.75	4.35	833	623
First stage	2.25	1.17	9.95	9.04	258	227
Second stage	8.38	6.60	26.73	23.70	572	487
ATR	4.52	3.33	14.03	10.86	1564	1198
MTR	0.46	0.53	3.47	4.73	15	18

Table B.4: Queueing data in scenario 2.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	8.68	8.13	2.60	2.44	22	22
Second stage	43.74	41.44	5.25	4.97	12	12
Third stage	2.83	2.53	0.23	0.20	5	5
Fourth stage	0.22	0.32	0.02	0.03	1	1
ATR	45.30	43.08	36.24	34.46	80	80
MTR	40.89	39.08	3.27	3.13	8	8

Table B.5: Resource use in scenario 2.

Scenario 3

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	0.003	2.28	0.124	11.79	19	1690
First stage	0.014	4.94	0.72	17.49	20	467
Second stage	0.84	11.44	7.08	35.79	142	792
ATR	0.31	6.64	3.29	20.93	367	2351
MTR	0.15	0.41	2.27	4.07	10	13

Table B.6: Queueing data in scenario 3.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	6.32	9.84	1.89	2.95	16	22
Second stage	32.02	48.90	3.84	5.87	12	12
Third stage	2.11	3.15	0.17	0.25	4	5
Fourth stage	0.42	0.38	0.03	0.03	1	3
ATR	33.10	51.22	26.48	40.98	80	80
MTR	29.02	45.75	2.32	3.66	8	8

Table B.7: Resource use in scenario 3.

Scenario 4

KPI	Total	No screening	1	2	3	4
Completed jobs	49417	2061	28504	18401	444	7
Minimum CT	3.86	3.86	5.50	7.20	9.10	13.69
Average CT	8.41	5.11	7.05	10.78	13.00	18.52
Maximum CT	34.19	18.17	20.82	33.52	34.19	30.58
AWT	1.37	0.51	0.71	2.46	2.51	1.85
MWT	22.18	10.54	10.94	22.18	21.33	12.98

Table B.8: KPI results for scenario 4 (August).

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	0.001	0.006	0.05	0.19	7	27
First stage	0	0.18	0.15	3.22	4	83
Second stage	0.01	1.89	0.52	12.04	10	250
ATR	0	0.51	0.05	3.91	7	441
MTR	0.12	1.00	2.10	8.46	7	30

Table B.9: Queueing data in scenario 4.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	4.46	6.93	1.34	2.08	16	20
Second stage	22.51	34.69	2.70	4.16	12	12
Third stage	1.51	2.45	0.12	0.20	4	5
Fourth stage	0.10	0.36	0.008	0.028	1	2
ATR	23.35	36.10	18.68	28.88	80	80
MTR	21.68	33.38	1.74	2.67	8	8

Table B.10: Resource use in scenario 4.

Scenario 5

KPI	Total	No screening	1	2	3	4
Completed jobs	58623	2439	33666	22029	483	6
Minimum CT	3.85	3.85	5.49	7.17	9.25	14.60
Average CT	13.68	6.57	10.45	19.23	21.46	21.18
Maximum CT	46.34	19.63	26.18	46.34	44.09	33.08
AWT	6.59	1.97	4.06	10.86	10.99	4.41
MWT	35.31	12.34	17.07	35.31	33.81	15.28

Table B.11: KPI results for scenario 5 (August).

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	0.001	0.27	0.05	3.79	9	550
First stage	0.001	0.99	0.22	8.36	5	225
Second stage	0.24	7.92	3.26	23.23	64	495
ATR	0.004	2.77	0.31	9.86	32	1119
MTR	0.18	0.48	3.37	4.70	12	16

Table B.12: Queueing data in scenario 5.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	5.29	8.14	1.59	2.44	14	20
Second stage	26.64	41.8	3.20	5.02	12	12
Third stage	1.72	2.76	0.14	0.22	5	4
Fourth stage	0.37	0.29	0.03	0.02	1	1
ATR	27.46	42.81	21.97	34.25	80	80
MTR	24.83	38.79	1.99	3.10	8	8

Table B.13: Resource use in scenario 5.

Scenario 6

KPI	Total	No screening	1	2	3	4
Completed jobs	41518	1795	23897	15453	369	4
Minimum CT	3.86	3.86	5.50	7.20	9.14	15.47
Average CT	7.16	4.60	6.37	8.58	10.70	19.00
Maximum CT	21.78	9.94	11.75	16.03	16.96	21.78
AWT	0.16	0.02	0.05	0.32	0.37	0.79
MWT	4.91	1.16	2.34	4.91	4.32	2.75

Table B.14: KPI results for scenario 6 (August).

Queue	AWT		MWT		Maximum size	
	February	August	February	August	February	August
First conveyors	0	0.002	0.04	0.08	6	13
First stage	0	0.002	0	0.34	1	9
Second stage	0.01	0.35	0.91	4.28	15	99
ATR	0	0.04	0	0.84	1	93
MTR	0.02	0.12	0.97	2.34	4	10

Table B.15: Queueing data in scenario 6.

Resource	Utilization (%)		Average use		Maximum use	
	February	August	February	August	February	August
First stage	3.98	5.87	1.19	1.76	13	18
Second stage	20.11	28.69	2.41	3.44	12	12
Third stage	1.44	1.97	0.12	0.16	4	4
Fourth stage	0.20	0.23	0.02	0.02	1	1
ATR	20.86	30.22	16.68	24.17	71	80
MTR	18.77	27.24	1.50	2.18	8	8

Table B.16: Resource use in scenario 6.

Scenario 7

Queue	AWT		MWT		Maximum size	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First conveyors	0	11.38	0.04	28.17	6	4063
First stage	0	8.99	0	30.31	1	786
Second stage	0.01	18.91	0.80	52.47	11	1150
ATR	0	10.78	0	32.51	1	3658
MTR	0.05	0.73	1.26	5.28	4	21
Carousel	2.51	10.05	30.21	41.08	2153	4580

Table B.17: Queueing data in scenario 7.

Resource	Utilization (%)		Average use		Maximum use	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First stage	3.96	12.32	1.19	3.70	12	22
Second stage	19.68	60.83	2.36	7.3	12	12
Third stage	1.11	4.09	0.09	0.33	3	5
Fourth stage	0.12	0.34	0.01	0.03	1	1
ATR	20.6	63.52	16.48	50.81	73	80
MTR	18.20	57.41	1.46	4.60	8	8

Table B.18: Resource use in scenario 7.

Scenario 8

KPI	Total	No screening	1	2	3	4
Completed jobs	28393	1088	16294	10775	232	4
Minimum CT	3.85	3.85	5.49	7.21	9.23	13.60
Average CT	7.02	4.64	6.30	8.25	10.38	15.97
Maximum CT	18.01	9.12	11.62	13.21	13.53	18.01
AWT	0.005	0.003	0.004	0.007	0.004	0.005
MWT	0.99	0.25	0.98	0.99	0.12	0.016

Table B.19: KPI results for scenario 8 with 90% availability (Low rate).

KPI	Total	No screening	1	2	3	4
Completed jobs	86874	3547	50177	32421	720	9
Minimum CT	3.91	3.91	5.51	7.21	9.07	15.82
Average CT	42.09	20.74	39.62	48.05	50.14	67.03
Maximum CT	118.50	50.95	95.10	116.94	117.80	118.50
AWT	34.95	16.11	33.18	39.62	39.66	48.12
MWT	106.15	43.54	86.10	106.15	105.82	99.35

Table B.20: KPI results for scenario 8 with 90% availability (High rate).

Queue	AWT		MWT		Maximum size	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First conveyors	0	11.26	0.04	29.11	6	4197
First stage	0	8.70	0	31.04	1	789
Second stage	0.003	5.16	0.35	20.33	9	493
ATR	0	14.67	0	43.02	1	4788
MTR	0.03	0.45	0.99	3.96	5	15

Table B.21: Queueing data in scenario 8 with 90% availability.

Resource	Utilization (%)		Average use		Maximum use	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First stage	3.93	11.97	1.18	3.59	12	21
Second stage	17.32	51.61	2.42	7.23	14	14
Third stage	1.34	3.77	0.11	0.30	3	4
Fourth stage	0.17	0.61	0.01	0.05	1	1
ATR	20.77	63.61	16.62	50.89	76	80
MTR	19.44	56.76	1.56	4.54	8	8

Table B.22: Resource use in scenario 8 with 90% availability.

KPI	Total	No screening	1	2	3	4
Completed jobs	28137	1165	16176	10561	232	3
Minimum CT	3.80	3.80	5.47	7.18	9.18	13.71
Average CT	6.99	4.55	6.31	8.24	10.34	14.52
Maximum CT	15.84	9.19	11.20	13.29	14.69	15.84
AWT	0.004	0.003	0.004	0.005	0.002	0.004
MWT	1.42	0.21	1.22	1.42	0.025	0.012

Table B.23: KPI results for scenario 8 with 100% availability (Low rate).

KPI	Total	No screening	1	2	3	4
Completed jobs	87242	3527	50188	32750	770	7
Minimum CT	3.85	3.85	5.49	7.16	9.17	17.11
Average CT	42.44	23.20	42.04	44.99	47.50	74.85
Maximum CT	111.01	60.56	102.46	106.00	107.97	111.01
AWT	35.29	18.58	35.61	36.55	36.99	56.55
MWT	96.44	53.11	92.99	95.92	96.44	92.90

Table B.24: KPI results for scenario 8 with 100% availability (High rate).

Queue	AWT		MWT		Maximum size	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First conveyors	0	11.16	0.03	28.67	5	4073
First stage	0	8.97	0	29.12	1	683
Second stage	0.001	0.43	0.23	2.75	4	75
ATR	0	17.06	0	52.82	1	5931
MTR	0.04	0.40	1.42	3.88	6	16

Table B.25: Queueing data in scenario 8 with 100% availability.

Resource	Utilization (%)		Average use		Maximum use	
	Low rate	High rate	Low rate	High rate	Low rate	High rate
First stage	3.92	12.24	1.18	3.67	13	22
Second stage	14.46	45.39	2.31	7.26	15	16
Third stage	1.19	4.20	0.10	0.34	4	5
Fourth stage	0.09	0.43	0.007	0.04	1	1
ATR	20.60	63.76	16.48	51.01	74	80
MTR	18.39	56.47	1.47	4.52	8	8

Table B.26: Resource use in scenario 8 with 100% availability.