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Professional paper

THE USE OF SIMULATION IN OPTIMIZATION OF AIRPORT BAGGAGE SORTING SYSTEM

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Abstract
This paper aims to optimize baggage sorting through simulation modelling. Using Tecnomatix Plant Simulation software, manual sorting methods, which create bottlenecks, were analysed. The goal is to transport luggage swiftly, synchronize with passenger travel times, and minimize transport duration using simulation tools. Results reveal delays and capacity constraints inherent to manual sorting. The proposed automated system integrates RFID tracking, baggage diverters, and sensors for real-time monitoring, tested through simulations. This model demonstrated operational and economic benefits, enhancing sustainability. Findings emphasize the importance of simulations in improving accuracy, efficiency, and scalability of baggage handling. Practical recommendations are offered for transitioning to automated systems to streamline operations and boost airport competitiveness. By combining predictive analytics and simulations, airports can better anticipate peak periods, optimize processes, and achieve significant operational improvements.
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Key Words: Optimization, Simulation, Airport, Automated Baggage Sorting, Modelling

1. INTRODUCTION

Baggage handling is crucial for airport operations, impacting passenger satisfaction, efficiency, and competitiveness. Growing air traffic demands sophisticated management tools like simulation technology. Integrating these tools streamlines baggage flow, improving the passenger experience and airport appeal.

1.1 Operational challenges and the need for dynamic solutions

Increased global air traffic heavily burdens current baggage handling systems, requiring more sophisticated management due to fluctuating passenger demand, disruptions, and regulations [1, 2]. The Baggage Handling Systems (BHS) market is projected to grow from USD 9.4 billion in 2023 to USD 14.3 billion by 2030, at a 6.1 % compound annual growth rate (CAGR), reflecting industry investment in solutions [3, 4].

Higher air traffic volume disproportionately stresses BHS, as passenger increases don't always proportionally increase baggage volume [5]. Traditional planning based solely on passenger forecasts is inefficient because baggage peaks and passenger behaviour (e.g., more carry-on bags) impact BHS demand differently. Thus, adaptive, data-driven systems are needed to account for various factors beyond just passenger count [6, 7] necessitating dynamic simulation models for accurate resource allocation and congestion prevention.

1.2 The strategic role of simulation technologies

Simulation technologies are crucial for airport operations. Discrete Event Simulation (DES) models create digital system replicas, enabling predictive analysis, bottleneck identification, and risk-free testing without disrupting real operations [8]. This approach mitigates operational and financial risks. Optimizing processes via simulations significantly improves efficiency and cuts costs. For example, simulations can reduce delays and boost conveyor system throughput by up to 15 % [9]. They also optimize resource allocation, aligning staffing and equipment with demand to lower operating expenses and enhance customer satisfaction [10]. Beyond performance prediction and bottleneck identification, simulation is crucial for designing systems resilient to unforeseen disruptions. Research shows its critical role in addressing large-scale disruptions, such as analysing social distancing's impact during COVID-19 [11]. This highlights simulation's strategic value in future-proofing airport operations, enabling proactive design and testing of robust, adaptable systems to ensure continuity and minimize losses during crises.

To understand the complexity of this process, it is essential to comprehend its basic functions. The baggage handling system performs three critical functions: moving baggage from check-in to boarding, between gates for transit, and from arrival gates to baggage claim (see Fig. 1). Optimizing these complex functions requires advanced analytical tools, such as simulation models, which allow for predicting system performance, identifying bottlenecks, and testing improvements without disrupting real operations [12].

Figure 1: A three-part set of functions of a baggage handling system [13].

1.3 Enabling technologies and sustainability

The potential of simulations is fully realized when applied to modern, technologically advanced systems. Automated baggage handling systems are rapidly advancing, driven by integrated technologies. Radio Frequency Identification (RFID) has revolutionized baggage tracking, offering faster, more accurate identification than barcodes, reducing mis-sorting by over 20 % and scanning failures to nearly zero [14, 15]. Internet of Things (IoT) sensors provide real-time monitoring of baggage movement, minimizing congestion and aiding predictive maintenance [16, 17]. Intelligent Conveyor Systems, often integrated with RFID and sensors, significantly reduce sorting errors and improve timeliness by optimizing scheduling to reduce peak-time congestion [18]. Artificial Intelligence (AI) and Machine Learning (ML) are transforming airport operations from reactive to proactive. AI-enhanced predictive algorithms boost baggage sorting efficiency by anticipating peak periods and dynamically adjusting system capacity. These systems can also forecast passenger flow, optimize gate allocation, and intelligently schedule staff. [19]. AI, particularly neural networks like Convolutional Neural Networks (CNNs), are being applied in advanced security measures, such as Foreign Object Debris (FOD) detection on runways, improving accuracy and automating detection [20]. Automated baggage security checks using artificial neural networks can significantly reduce false alarms and increase security check speed. AI/ML also enhances aviation safety through predictive analysis and real-time monitoring to identify potential safety issues before they escalate [21]. While powerful, automated systems are energy-intensive, making optimization vital for cost and environmental sustainability. Simulations, like those at JFK, show potential for up to 8 % energy reduction during peak hours. New, more efficient systems can cut consumption by 10 %

and CO_2 emissions by 8 %. Airports like Frankfurt are integrating energy management into sustainability policies, using high-efficiency HVAC, LED lighting, and waste heat from baggage handling systems for heating [22]. Advanced AI/ML fosters a symbiotic relationship with operational efficiency and sustainability. Beyond optimizing operations and enabling predictive maintenance, AI and ML contribute to sustainability goals. For example, multi-objective simulation optimization [23] aims to simultaneously minimize waiting times and energy consumption.

1.4 Economic implications and implementation challenges

Beyond environmental sustainability, the economic and operational viability of automation is a key factor. First is cost reduction and return on investment (ROI). While initial investments in automated systems can be substantial, the economic benefits are significant. Research indicates that automated systems can lead to a 20 % reduction in labour costs within three years [24]. However, transitioning to automated solutions presents significant challenges, primarily high initial costs for infrastructure, technology, and integration. Merging new systems with existing, often incompatible, legacy infrastructure frequently results in "spaghetti integration" without a robust framework. This leads to fragmented information, slower decision-making, inconsistent data, and complex maintenance. Therefore, a structured, long-term IT architecture with integration middleware and an Airport Operational Database (AODB) is crucial for data quality and reliability. Without this, automation's long-term benefits could be undermined by inefficiencies and rising maintenance costs from poorly integrated systems [25].

1.5 Simulation tools and paper objective

Several powerful software tools are available on the market to implement these simulation-driven optimizations. Tecnomatix Plant Simulation is popular for optimizing material flow and resource use in manufacturing and logistics, including airport sorting and evaluating Level of Service (LoS) [8, 16, 26]. FlexSim, a 3D platform, enables experimentation and optimization of airport processes like security and baggage services, minimizing cost and risk [27]. AnyLogic supports simulation and multi-objective optimization for complex airport systems, including Early Bag Storage (EBS), with flexible modelling and database integration [28, 29]. Simio comprehensively models airport processes (check-in, security, baggage claim) to determine capacity, re-engineer processes, and achieve capital savings [30, 31]. Finally, Witness simulates airport check-in systems, analysing wait times and customer satisfaction [8].

The primary objective of this paper is to optimize airport baggage sorting by simulating the transition from a manual to an automated system. It first analyses current manual handling at a Slovak international airport using Tecnomatix Plant Simulation to identify bottlenecks. Based on this analysis, a new automated system with RFID tracking, diverters, and real-time sensors is proposed and then evaluated through simulation to demonstrate its significant operational and economic benefits, such as improved efficiency and reduced errors. The study also acknowledges challenges like high initial investment and integration complexities. The document further details the methods, results, and directions for future research.

2. MATERIALS AND METHODS

2.1 Slovak airport description

This paper addresses baggage sorting issues at a Slovak international airport, which handles scheduled and charter flights. With over 60,000 passengers in 2023 and a capacity for five concurrent flights, the airport currently relies on manual baggage check-in and sorting. This process is time-consuming and carries a risk of misallocation.

Fig. 2 illustrates the baggage flow from passenger handover to trolley loading. The handling system includes a main conveyor, a roller conveyor for sorting, an X-ray screening device, and sensors to monitor baggage flow and prevent overloading. The flow of baggage at the airport starts at the check-in counters, which is where passengers hand over their luggage to airline staff. Check-in counters are the point of interaction between passengers and airline staff. The airline staff takes the luggage from the passenger, and the check-in process follows. The check-in process consists of two steps:

- attaching an RFID tag to the luggage, which contains encrypted information and is used to identify it, monitor it in real time and route it to the designated aircraft;
- recording your baggage in the airline's system.

Labelled baggage with flight information is placed on a conveyor belt that moves the luggage to the X-ray screening equipment. This equipment is an important part of the airport's security systems and is located just behind the check-in area. Once the X-ray screening is completed, the baggage continues its journey on the conveyor belt and is directed to the sorting area. The entire baggage movement process is continuously monitored by a series of sensors and tracked by a supervisor on monitors.

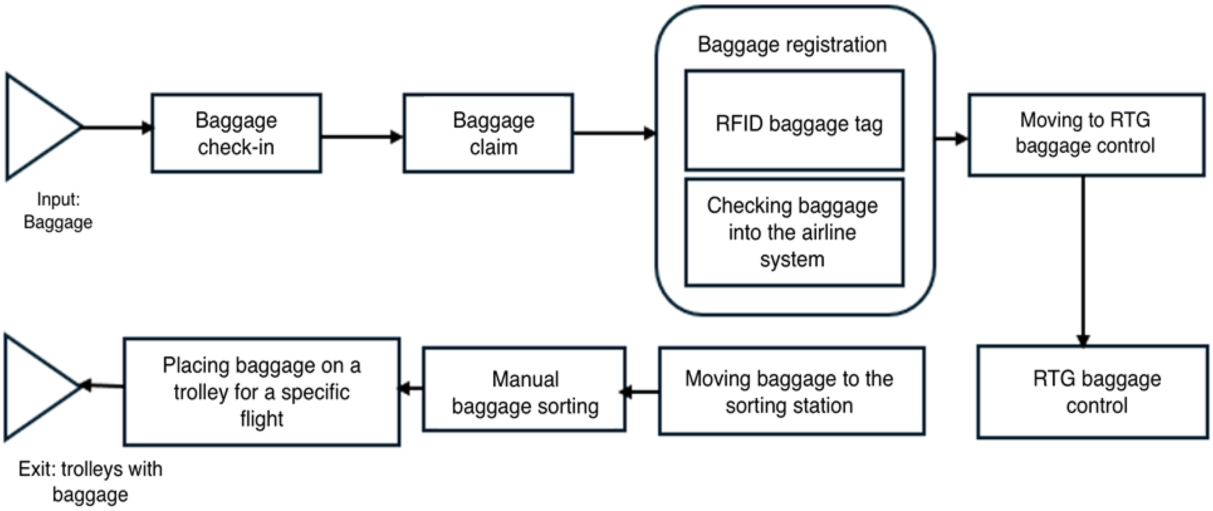

Figure 2: Baggage flow from handover to passengers to loading into trolleys for a specific flight.

In the sorting section, a roller conveyor follows the conveyor belt, Fig. 3 (left). The beginning of the roller conveyor is again equipped with a set of sensors. Their main function is to monitor the baggage picking process and initiate measures to prevent piling or overloading of the roller conveyor.

Figure 3: Sorting space (left) and 'Bingo card' (right).

When the luggage arrives at the sorting room, the staff member in charge will direct each piece of luggage to the designated flight. Staff are provided with a 'Bingo card' (paper document), Fig. 3 (right), on which the expected quantity of baggage for each flight is indicated. The numbers on this card correspond to the expected number of baggage allocated to specific flights. When the baggage arrives, the staff member detaches the adhesive part of the tag from the baggage and sticks it to the number on the paper 'Bingo card'. The 'Bingo card' is a dynamic visual tracking system of the baggage assigned to a particular flight. This process provides visual confirmation that each bag is processed and loaded into the trolley for the appropriate flight (all numbers on the 'Bingo card' are covered by sticky labels). During the sorting process, baggage is categorised based on criteria such as passenger class (e.g. business class) and whether it has a connecting flight. Once categorised, these special bags are allocated a designated loading area on the aircraft.

The current baggage sorting process relies heavily on human physical strength. Operators must accurately identify, sort and categorise baggage based on a variety of criteria including destination, priority and size. Human physical limitations, such as fatigue over time, especially in busy environments with large volumes of baggage, compromise the quality of the sorting process and increase the risk of sorting errors, thereby reducing the efficiency of the sorting process. Thus, the reliance on manual labour brings limitations in terms of physical capacity, efficiency and consistency of process execution.

2.2 Problem description and methodology of simulation processes

Manual baggage sorting is the bottleneck of the current baggage transfer system, from passenger collection to loading onto the aircraft, as it is now reaching its limits, with baggage piling up at the baggage sorting area becoming more and more frequent. Problems arising in baggage sorting can be solved by replacing manual sorting with automated sorting. The introduction of automation would increase the capacity, efficiency and throughput of baggage through the sorting office. A simulation was selected to assess the introduction of automation of the sorting process. Simulation model was created with the program Plant Simulation, Tecnomatix. This program is used to simulate, visualize and analyse various manufacturing systems and logistics processes in order to optimize material flow and resource utilization.

The following algorithm was created for the purpose of introducing automation into the airport's operational processes:

1. Based on a system analysis of the current state of the baggage sorting process, a simulation model was developed in a simulation program. Subsequently, a simulation of the current state was performed.
2. Design of the automated sorting system, design of parts of the new system (equipment, sensors, conveyors, etc.).
3. Creation of a simulation model of an automated sorting system and simulation.
4. Design assessment based on a capacity assessment of the baggage handling facility in the Tecnomatix simulation program.

A constraining design condition is that the new automated baggage sorting system must be able to be accommodated within the existing infrastructure. The integration of the new sorting system is necessary as there has been an increase in passengers in recent years and this increasing trend is expected to continue for the coming years.

3. RESEARCH RESULTS AND INTERPRETATION

3.1 Simulation of the current state of the airport for the baggage handling process

The simulation model captures the current state of baggage sorting. It is based on the fact that the maximum number of flights for which baggage is checked in at the same time is five.

Although this heavy traffic condition occurs only at the most exposed times of the day, otherwise the airport handles passengers for less than 5 flights simultaneously. Therefore, the baggage handling process will be reviewed for this heavy load, i.e., passenger handling for five flights simultaneously. The simulation model (Fig. 5) captures the above situation and is developed under the following assumptions and conditions (see the Table I).

Table I: Overview of airport baggage handling processes.

Process/Area	Description
Passenger entry	One passenger enters the airport premises every minute. Airports are most often served by aircraft with a capacity of 115 people, 80 % of whom have purchased tickets. Approximately half of the passengers have checked-in baggage (46 pieces per flight). Cabin baggage is not included.
Baggage check-in	Baggage is currently being checked in for five flights at the same time.
Check-in queue	On average, there are eight people standing at check-in.
Check-in time	Average 2 minutes per passenger to check documents and check baggage.
Conveyor belt	Total length 45 m: check-in area (27 m), security check area (9 m), sorting belt (9 m).
Security control zone	X-ray scanning for baggage screening takes 15 seconds.
Sorting room	At the entrance, the luggage temporarily stays in a tray with a capacity of 10 pieces. Baggage sorting by flight and loading onto trolleys takes 20-40 seconds per piece.
Carts	After sorting, the luggage is transported by trolleys, each of which can carry 40-50 pieces of luggage.

A model of the current state of the airport concourse is shown in Fig. 4.

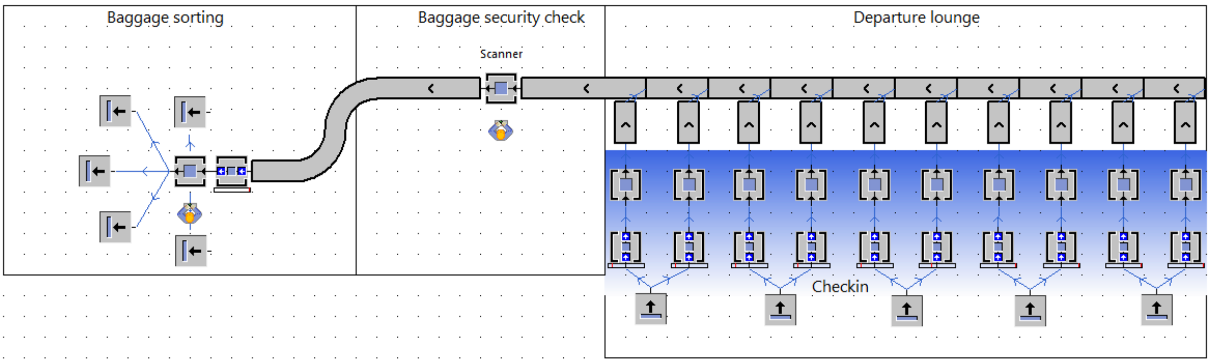

Figure 4: Model of the current state of the airport concourse.

The simulation is carried out for an average airport load situation with baggage handling of five flights. This implies an average aircraft occupancy and an average number of checked-in baggage of 46 pieces per flight. Already from the visualization of the process flow, it is evident that the sorting room is overloaded, and baggage is piled up in the bin and on the conveyor in front of the sorting room (Fig. 5).

The outputs of the simulation are shown in Figs. 6 and 7. The workload graph for the baggage screening workstation, Fig. 6 (left), reflects the workload of the baggage screening and sorting staff. As can be seen, the workstation of the sorting room is fully loaded, therefore baggage is accumulated in the tray and on the conveyors, Fig. 6 (right). This makes the security check workstation underutilized and idle for more than half of the simulation time.

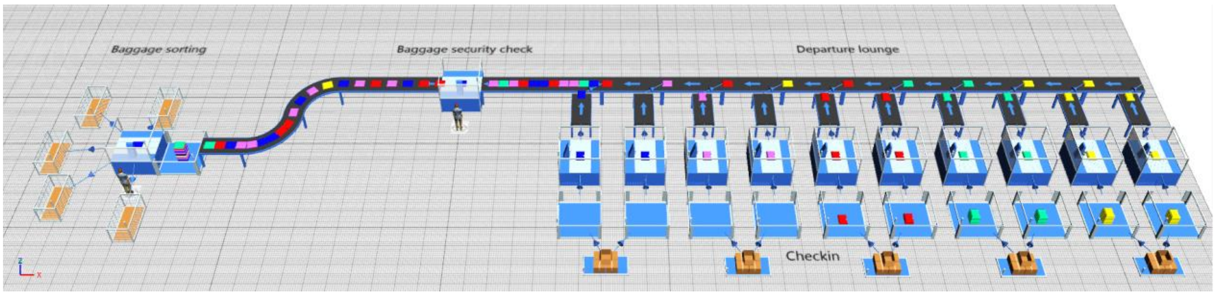

Figure 5: Current status during full load at the airport baggage claim.

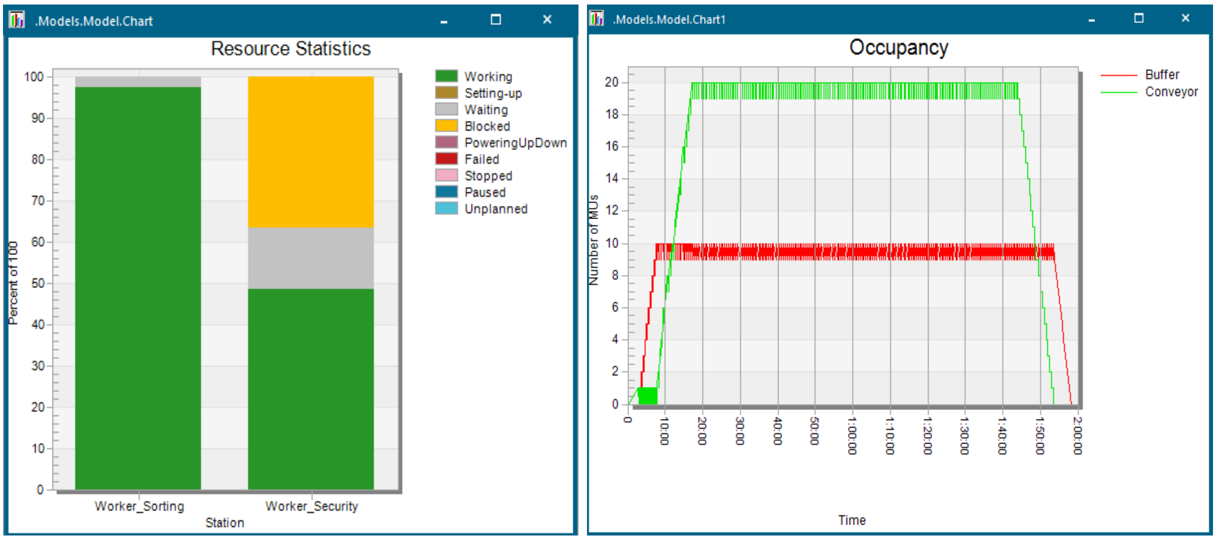

Figure 6: Scanning and baggage sorting workload for 5 flights (left) and bin and conveyor occupancy (right).

From the simulation output in Fig. 7, we see that the simulation time, i.e., the time to check-in baggage for five flights is 1:59 hours. On average, the baggage spends about 11 % of the simulation time in the scanning and sorting process (production), about 50 % of the simulation time in the transport process (transport), and about 39 % of the simulation time in the bin (storage). The value added process is represented only by the activities of check-in, security check and sorting. On average, these activities account for 8 % of the total simulation time. The last column graphically shows the time share of the activities production (green bar), transport (yellow bar) and storage (red bar).

Simulation time: 1:59:00.0000

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Cart1	Flight1	21:36.3783	46	23	13.70%	64.00%	22.30%	12.77%	
Cart2	Flight2	27:36.1487	46	23	11.99%	58.51%	29.50%	10.07%	
Cart4	Flight4	47:41.4200	46	23	11.12%	42.14%	46.74%	5.77%	
Cart3	Flight3	38:46.1919	46	23	10.90%	47.17%	41.94%	7.06%	
Cart5	Flight5	53:12.9678	46	23	10.85%	44.06%	45.09%	5.15%	

Production
Transport
Storage

Figure 7: Simulation output for the clearance of 5 flights.

3.2 Design of a new automated sorting system

As is clear from the previous analysis, the bottleneck at the airport is baggage sorting, which is currently done manually by staff. In addition to large time losses, this sorting system causes incorrect allocation of baggage to flights and other human errors. These shortcomings would be eliminated by the introduction of a fully automated baggage sorting system. The proposed automated sorting method requires the installation of new technical equipment:

- an intelligent RFID reader to track the passage of baggage, read RFID tags on baggage and provide additional data on the license plates for sorting (e.g. priority status baggage),
- a short conveyor that moves the luggage towards the luggage diverters,
- horizontal baggage diverters (Baggage Diverter) to divert baggage to individual routes (flights),
- gravity conveyors to move luggage from the diverters to the loading area,
- sensors to monitor baggage entering the sorting system, check the position of baggage diverters, monitor the fill level of the gravity bins and to check that baggage has been picked up and placed on the trolley,
- smart screens to replace the 'Bingo card'.

Automated sorting is followed by manual loading of luggage into trolleys by the operator. The new system will sort luggage in five different directions using two diverters. A detail of the model of the automated baggage sorting system is shown in Fig. 8.

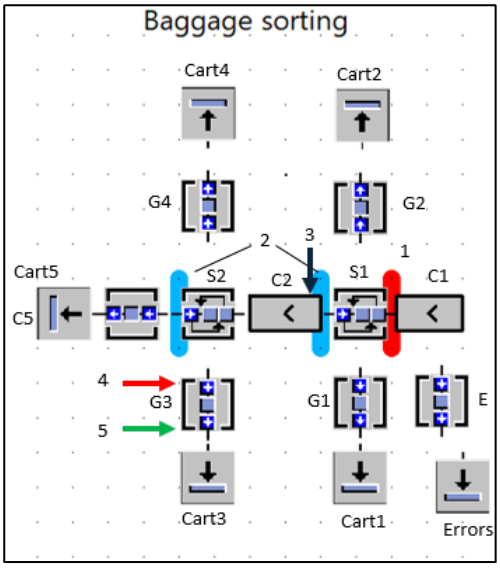

Figure 8: Detail of a model of an automated baggage sorting system.

The new automated system consists of the above equipment. The description of the parts of the proposed system (Fig. 8) in the simulation model is as follows:

- 1 (red marker) – scanning device that distinguishes the RFID tag.
- C1 – short pass conveyor that moves luggage to the S1 baggage diverter and unseparated luggage.
- E – gravity conveyor for undifferentiated luggage leading to the Errors tray.
- S1 – the first baggage diverter, which sorts baggage for flight 1 and 2.
- C2 – passport conveyor for transfer to the second baggage untie.
- S2 – a second baggage diverter that sorts baggage into three flights and moves it onto gravity conveyors.
- G1–G5, E – gravity conveyors.
- 2 (blue markers) – the diverter position sensor monitors the position of the diverter.
- 3 (black arrow) – luggage position sensor. As soon as the luggage moves onto conveyor C2, conveyor C1 will drop the next luggage into the sorting.
- 4 and 5 (red and green arrows) – on each of the 5 gravity conveyors (G1–G5) 2 sensors are mounted to monitor their filling status.
- Cart 1–5 – carts that end the sorting system.

- Next to each trolley, at the end of the gravity conveyor, a digital screen will be mounted to provide all the data on the loading status of the baggage for that flight.

3.3 Algorithm of the proposed automated baggage sorting system

Baggage will enter the automated sorting process from the conveyor as in the current state. Upon entering the sorting area, the RFID tag will be scanned by an infrared scanning device. Once scanned, the baggage will proceed along the conveyor belt to the first baggage diverter while the un-sorted baggage is removed to the side of the gravity conveyor. The first baggage diverter sorts the baggage into two directions (flights), diverts the baggage to one of the two gravity conveyors, or drops the baggage onto the next section of the conveyor belt heading to the second diverter.

Once the baggage is diverted or moved to conveyor C2, conveyor C1 will drop the next baggage into the sorting. The second baggage diverter sorts the baggage in three directions and diverts the baggage to one of the three gravity conveyors (G3–G5). The filling status of the gravity conveyors is monitored by sensors. This completes the automatic sorting process.

Operators manually remove the luggage and load it into the trolley. A digital screen will be placed at the end of each gravity conveyor to provide data to operators at the end of baggage sorting: a summary of checked-in baggage for the flight, information on priority baggage, transfer baggage, etc., as well as a confirmation that the baggage has been removed from the gravity conveyor.

With this design, it is possible to sort luggage for 5 different directions at the same time. If luggage is loaded only for 2 flights, additional sorting can be programmed: e.g. luggage for each flight is additionally divided into two categories – normal luggage and business class luggage, etc.

3.4 Simulation outputs of the proposed automated system

Simulation of the proposed automated system confirmed that the bottleneck related to baggage sorting has been removed. The sorting area and conveyors are no longer congested; the baggage handling process is smooth. (Fig. 9).

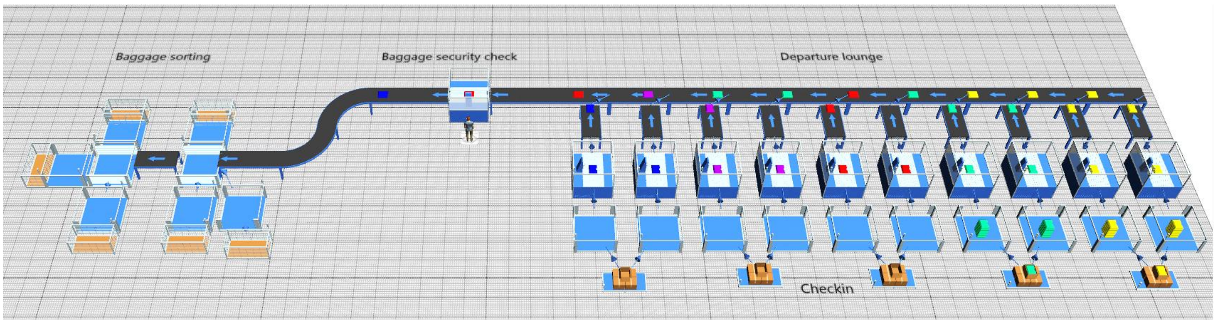

Figure 9: Simulation status of the proposed baggage sorting system.

Simulation time: 1:14:46.8243

Object	Name	Mean Life Time	Throughput	TPH	Production	Transport	Storage	Value added	Portion
Cart1	Flight1	3:07.4910	45	36	72.37%	27.63%	0.00%	72.00%	
Cart2	Flight2	3:58.5200	46	37	56.60%	43.40%	0.00%	56.60%	
Cart4	Flight4	12:50.7156	46	37	20.76%	39.18%	40.06%	17.52%	
Cart3	Flight3	5:06.4330	46	37	44.06%	55.94%	0.00%	44.06%	
Cart5	Flight5	24:05.1460	46	37	15.40%	25.77%	58.83%	9.34%	
Error	Flight1	3:14.8243	1	1	69.29%	30.71%	0.00%	69.29%	

Production
Transport
Storage

Figure 10: Simulation output for the handling of 5 flights by the proposed automated system.

The simulation outputs for the handling of 5 flights by the proposed system (Fig. 10) show a speeding up of the whole process from 1:59 h to 1:14 h, which represents a 38 % reduction in the check-in time for passengers with baggage. The proportion of time consumed by activities such as transport and storage has been significantly reduced, thus significantly increasing the proportion of value-added activities. The model also captures baggage diverted to the mislabelled baggage bin, which is set to 0.5 % in the model.

4. CONCLUSION

The study analyses current challenges within airport logistics, specifically focusing on baggage handling, and identifies key bottlenecks in manual sorting processes. Moreover, it underscores the critical role of simulation modelling in addressing these contemporary issues, particularly in enhancing baggage handling efficiency. By analysing and optimizing manual baggage sorting processes through simulation, significant improvements were achieved, including a 38 % performance enhancement, elimination of sorting workstation congestion, and reduced human error. These findings underscore the pivotal role of simulation, exemplified by the development of an automated baggage sorting system in a real airport setting. Such simulations, conducted using Tecnomatix software, not only demonstrate tangible economic benefits through cost reduction and increased efficiency but also pave the way for integrating advanced technologies like RFID, intelligent baggage drop-offs, and congestion sensors. Looking forward, the integration of artificial intelligence and predictive algorithms promises to further optimize operational scenarios, anticipate peak loads, and ensure the sustainability and flexibility of airport operations.

Future research could focus on several perspectives. The first is the implementation of machine learning and IoT sensors to improve fault prediction and maintain systems more efficiently. The second area is research on the energy consumption of automated systems and finding solutions that combine high efficiency with environmental sustainability. A third direction is the analysis of the impact of automation on the working environment, in particular on the transformation of the roles of airport employees. In addition, it is important to pay attention to security issues, where simulations can help in the design of security measures for baggage protection. In conclusion, the deployment of advanced simulation and automation tools represents a fundamental path to improving airport performance, and the integration of these systems must be accompanied by further research aimed at their optimisation and sustainability.

ACKNOWLEDGEMENT

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