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Improving Airport Baggage Handling System (BHS) Efficiency with Simulation-Based Design

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Abstract

Efficient baggage handling is essential for smooth airport operations, directly impacting passenger satisfaction, airline performance, and logistical efficiency. With rising air travel demand, especially in Japan where labor shortages and limited space are critical issues, conventional Baggage Handling Systems (BHS) face increasing strain. This research proposes a compact Early Baggage Storage (EBS) system to address these challenges by optimizing baggage flow and minimizing delays. Unlike fixed-constraint models that assume uniform baggage arrival, the proposed simulation-based approach accounts for real-world fluctuations, such as passenger arrival patterns, enabling dynamic system responses. The study comprises three stages: model construction, simulation using AnyLogic (2024), and performance evaluation. The model replicates baggage flow from check-in to final loading, including sorting, screening via Explosive Detection System (EDS), and make-up area processing. Two EBS algorithms are analyzed: a conventional model and a proposed dynamic model that adjusts storage duration and baggage release intervals. The evaluation highlights the limitations of the conventional EBS, where smaller storage capacities cause congestion, and only larger capacities maintain smooth operations, though this comes with increased infrastructure costs. In contrast, the proposed EBS dynamically regulates baggage, improving subsystem balance and enabling smaller storage sizes to achieve comparable performance. This approach reduces congestion and infrastructure needs, making it a more efficient and cost-effective solution. Future work includes validating the proposed system in real airport settings and addressing make-up area delays through adaptive scheduling or buffer strategies to ensure broader applicability and operational robustness.

Keywords
Baggage Handling Systems (BHS), Early Baggage Storage (EBS), Simulation, Sorter, Make-up area.

1. Introduction
1.1. Background
Airports are essential transportation hubs that facilitate the global movement of people and goods. At the core of airport operations is the Baggage Handling System (BHS), an automated network that efficiently transports and sorts baggage through various stages: check-in, security screening, sorting, and aircraft loading. A reliable and efficient BHS is vital not only for timely baggage delivery but also for enhancing passenger satisfaction, airline efficiency, and overall airport logistics.

A typical BHS consists of subsystems such as check-in counters, collectors, Explosive Detection System (EDS), sorters, Early Baggage Storage (EBS), and make-up areas, which work in sequence to process outbound baggage (Rekiek 2024). For departing flights, baggage begins its journey at the check-in counter, passes through collectors and EDS for security screening, and is then routed by the sorter either to the make-up area for immediate loading or to the EBS if it arrives ahead of schedule.

With rising passenger volumes and constraints on space and labor, especially in smaller airports, optimizing baggage handling processes has become increasingly important. The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT 2024) has emphasized the need for labor-saving automation and more efficient baggage management. Their recommendations include improvements in tracking, storage, and loading systems. A significant operational challenge involves managing Early Baggage (EB), which refers to items checked in well before departure. Traditional EBS systems are often basic, functioning only as temporary storage without optimizing flow. This results in congestion, inefficient use of storage space, and increased strain on sorters during peak periods (MLIT 2024).

1.2. Scope of this Research

This research focuses exclusively on the baggage handling process for departing flights. It covers the journey of baggage from the check-in counter to the make-up area, where it is staged for aircraft loading. Operations related to arriving flights, such as baggage claim, are not part of this study.

The flow begins at the check-in counter (Figure 1), where baggage enters the upper stream of the system via the collector. From there, it proceeds to the sorter, which directs it through the EDS for security screening. After screening, baggage is either sent directly to the make-up area or temporarily stored in the EBS if it arrives significantly before departure. Early baggage is later reintroduced to the sorter and continues to the make-up area.

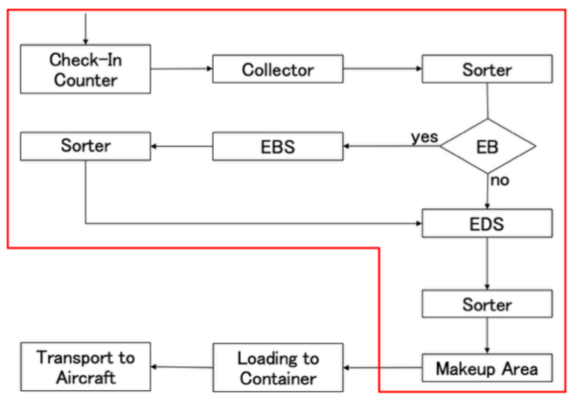

Figure 1. Flow of Baggage for Departing Flights

This analysis concludes at the make-up area, where baggage is prepared for loading onto the aircraft. Although later stages, such as container loading and aircraft transport, are part of the broader process, they fall outside the scope of this research. By concentrating on the red-marked section of the system diagram in Figure 1, the study allows for a focused evaluation of baggage flow, storage efficiency, and system optimization in airports with space and labor constraints.

1.3. Objective

This study aims to design a compact and efficient EBS system that integrates smoothly with existing BHS frameworks to improve operational performance in small-scale airports. The specific objective is to streamline the handling of early baggage from check-in to the make-up area, reducing congestion and improving the overall flow within the system.

To meet this goal, a simulation-based approach is used to reflect real-world variability, such as fluctuating baggage arrival times influenced by passenger behavior. In contrast to static, constraint-heavy models that require oversized infrastructure to handle peak volumes, simulation allows for dynamic analysis. This supports the development of more flexible and resource-efficient systems. The target is to achieve high performance while minimizing the storage footprint, thereby creating a more adaptable and dependable BHS in space-limited airport environments.

1.4. Contribution

This research contributes to the growing body of studies focused on operational optimization in airport environments, particularly for small-scale facilities facing spatial and labor constraints. Unlike existing studies that improve EBS performance through capacity expansion or theoretical optimization, this study introduces a dynamic flow-regulation mechanism that coordinates early baggage release with downstream availability. This strategy reduces dependency on large storage areas and enables efficient handling even under limited infrastructure.

Furthermore, the research demonstrates how a simulation-based model can identify bottlenecks and evaluate alternative configurations by capturing variability in baggage arrival and system load. The proposed system not only minimizes delay rates but also improves subsystem utilization and flow distribution. These findings offer practical insights for designing cost-effective, adaptable baggage handling solutions suitable for space-constrained airports.

2. Related Studies

Enhancing the efficiency of BHS has been a focal point in airport operations research, particularly as airports face increasing demands for throughput and reliability. Notable studies by Cavada et al. (2017), Hemeimat and Abdel Aal (2024), and Ageling and Alm (2022) have explored various methodologies to address BHS inefficiencies. Each of these works leverages simulation-based methods, acknowledging the limitations of traditional optimization or scheduling techniques when confronted with the stochastic nature of airport environments. These approaches align with the current study's use of simulation to investigate and refine Early Baggage Storage (EBS) performance under dynamic operational conditions.

While similar in methodology, the scope and focus of these prior works vary considerably. Cavada et al. (2017) model the BHS of an international airport broadly but exclude EBS, limiting relevance to scenarios requiring early baggage coordination. Hemeimat and Abdel Aal (2024) focus on optimizing outbound baggage flow using Arena simulation, yet do not incorporate EBS or propose new architectural designs. Ageling and Alm (2022) come closest in theme by analyzing EBS operations through scheduling adjustments to the make-up area. However, their study overlooks physical design constraints, making it less applicable to airports with limited infrastructure or space.

Table 1. Comparison of Related Studies on BHS

Study	Focus Area	EBS Consideration	Simulation Tool	Strengths	Limitations
Cavada et al. (2017)	General BHS simulation	No	Quadstone Paramics for microscopic modeling	Detailed modeling of baggage flow	No EBS integration, lacks space efficiency focus
Hemeimat and Abdel Aal (2024)	Outbound baggage flow	No	Rockwell Arena simulation software	Real-case application at Queen Alia Airport	Does not model EBS or structural redesign
Ageling and Alm (2022)	EBS operation timing	Yes	MATLAB-based analysis of EBS release timing	Focuses on timing control to reduce delays	Ignores space limitations and compact design
Current study	Compact EBS design for small airports	Yes	AnyLogic (2024) for dynamic, multi-method simulation	Space-efficient, adaptable, layout-validated	Limited to a simplified model for demonstration

Table 1 summarizes the key differences among the reviewed studies, offering a comparative overview of their scope, simulation approach, and limitations. While previous research contributes valuable insights into BHS efficiency, most either focus broadly on system modeling without addressing EBS, or they consider EBS only from a scheduling perspective without accounting for spatial constraints. In contrast, this study uniquely tackles both the operational and physical challenges of implementing EBS in space-limited airport environments. By leveraging AnyLogic's (2024) multi-method simulation capabilities, the proposed approach enables dynamic modeling of subsystem interactions and real-world variability, such as baggage arrival times. This allows for flexible and robust system evaluation, making it better suited for small airports with fluctuating baggage volumes and limited infrastructure.

A critical reason for adopting a simulation-based approach lies in the inherent unpredictability of passenger behavior and baggage arrival times. At the design stage, these variables are not only unknown but also vary widely between airports, making it impractical to construct universal mathematical models. Traditional theory-based or optimization algorithms often require fixed parameters or worst-case scenarios, which can lead to overdesign and inefficient use of resources. Simulation allows for the modeling of diverse and realistic conditions, enabling flexible design decisions that are robust to changes in passenger flow and operational constraints. This makes simulation especially suitable for small and medium-sized airports that must balance performance with limited infrastructure.

3. Methodology

This research methodology consists of three major phases: model construction, simulation, and evaluation. Each phase is designed to contribute toward developing a compact and efficient EBS system suitable for small airports.

3.1. Model Construction

The model construction phase involves designing a detailed and simulation-ready representation of the Baggage Handling System (BHS), capturing the essential components and operational logic of a small airport environment. The design includes six primary subsystems: the check-in area, collector, sorter, EDS, EBS, and make-up area. These components are arranged in a process flow that reflects typical baggage operations for departing flights.

The EBS is implemented as a floor-based storage area measuring 14 by 8 square meters. It is initially configured to store 150 bags, with the flexibility to expand up to 450 bags if necessary. However, the focus of this study is on minimizing the storage footprint while maintaining efficient baggage flow. The location of the EBS is fixed across all experiments to ensure consistent evaluation.

To define the simulation conditions, several assumptions are made. Two flights, designated as Flight A and Flight B, are modeled, each carrying 300 passengers. Every passenger check in two bags. Flight A is scheduled to depart at 03:00 and Flight B at 04:00. All baggage is assumed to be uniform in size and passes through the EDS without requiring additional screening. These parameters simplify the analysis and center attention on system behavior and storage performance.

AnyLogic (2024) is selected as the simulation platform due to its robust multi-method modeling capabilities. It enables discrete-event modeling for baggage movement, agent-based modeling for handling passenger behavior, and system dynamics for analyzing resource trends over time. These features allow for a comprehensive depiction of the BHS, including both physical layout and decision logic. The physical layout and decision logic of the BHS model are visualized in Figures 2 and 3. These illustrations provide a clearer understanding of the system components and the logical structure that governs baggage movement.

Figure 2 shows the spatial arrangement of the BHS components. The process begins at the check-in area, where baggage is introduced into the system. Bags are collected and routed through the collector, which feeds into the central sorter loop. This sorter acts as a dynamic hub, distributing baggage based on destination and operational requirements. Security screening is conducted through the EDS, while early baggage is diverted into the EBS and re-entered into the sorter at the appropriate time. The final step in this simulation ends at the make-up area, where bags are prepared for aircraft loading.

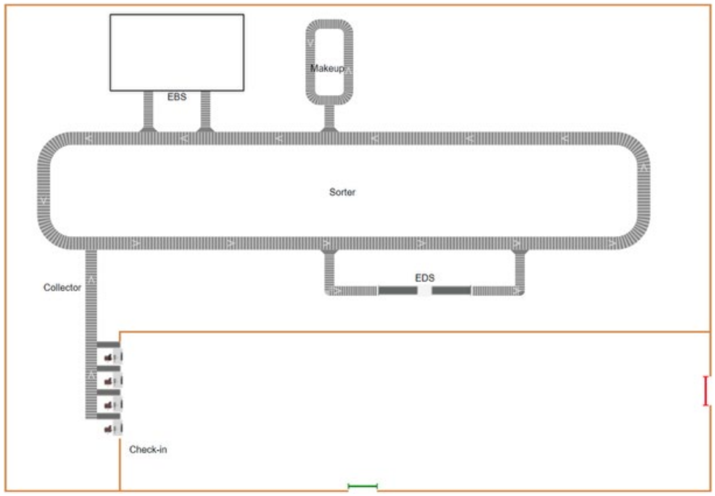

Figure 2. 2D View of BHS

Figure 3 presents the logic flow structure implemented in the simulation. The flow begins with baggage from Flights A and B entering the system. The process includes several conditional checks, such as verifying arrival times and determining whether the baggage qualifies as early. Non-early baggage proceeds through the EDS and continues to the make-up area, while early baggage is stored in the EBS until its designated release time. Decision points, holding conditions, and routing paths are visually organized, enabling the model to simulate varied operational scenarios. By integrating spatial modeling with logic-based routing, the constructed BHS model in AnyLogic (2024) effectively captures the timing, flow, and interaction of baggage through the system. This structure allows for a thorough analysis of performance under varying conditions, particularly regarding the optimization of EBS capacity and placement within a constrained airport layout.

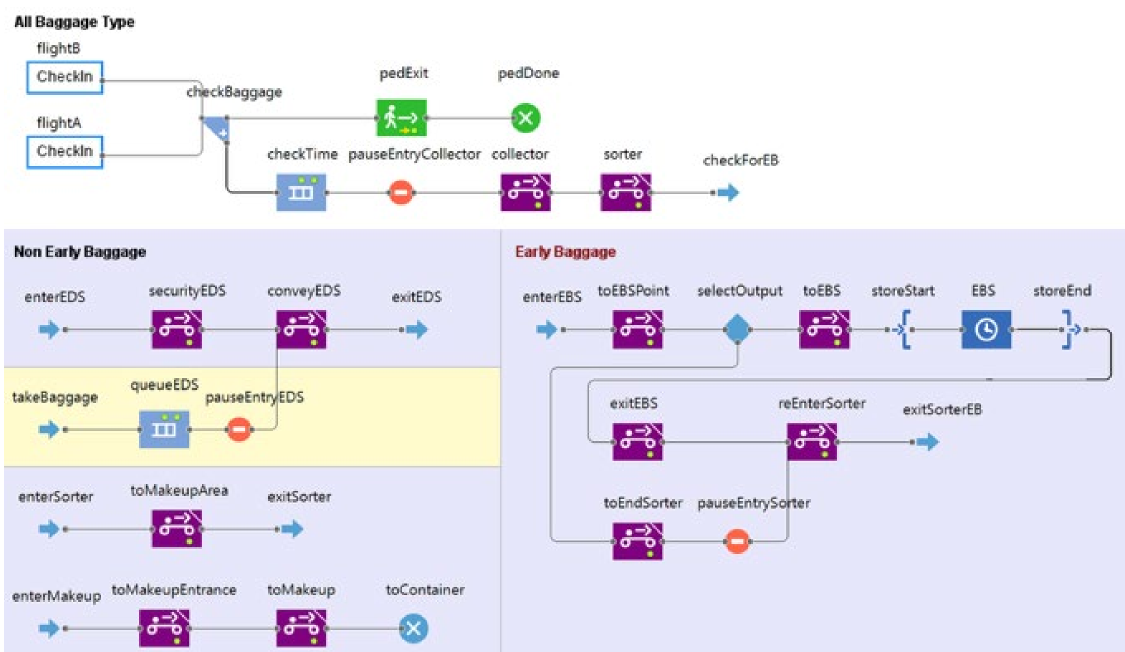

Figure 3. Logic Flow of BHS

3.2. Simulation

The simulation phase evaluates the performance and efficiency of the proposed BHS, with particular emphasis on the EBS component under conditions typical of a small airport. Implemented in AnyLogic (2024), the simulation spans a four-hour window, covering the scheduled departures of Flight A at 03:00 and Flight B at 04:00. The EBS is initially configured with a storage capacity of 150 bags, approximately one-quarter of the baggage load for a 300-passenger flight. This setup allows for the assessment of system behavior under constrained capacity while also providing a foundation for analyzing potential scalability.

To support performance evaluation, the simulation environment collects two types of experimental data throughout each run. The first type is baggage trace logs, which records each bag's flight designation (A or B) and timestamps corresponding to its arrival at key subsystems, including the collector, sorter, EDS, EBS, and make-up area. The second type is subsystem load logs, which captures the number of bags present in each subsystem at fixed time intervals. These datasets serve as the input for the analysis phase and form the basis for performance comparison between different EBS configurations.

The simulation also incorporates modeled passenger check-in patterns generated using Python. A fixed random seed ensures that passenger arrival behavior remains consistent across different simulation runs. All passengers are assumed to arrive on time each checking in two bags. Flight A passengers predominantly arrive 80 to 90 minutes prior to departure, aligning with observed trends from previous studies. On the other hand, Flight B passengers begin arriving approximately 170 minutes before departure. This intentional overlap around 01:30 creates a peak load condition that stresses the BHS, particularly in terms of early baggage accumulation. Figure 4 illustrates this by showing the number of passenger arrivals to airport every 10 minutes, clearly highlighting the 01:30 peak. This period stresses the BHS and demonstrates the necessity of an effective early baggage handling system. The EBS serves a critical role during this time by temporarily storing early arriving baggage from Flight B until downstream systems are ready to process it, thereby helping manage congestion and maintain operational efficiency.

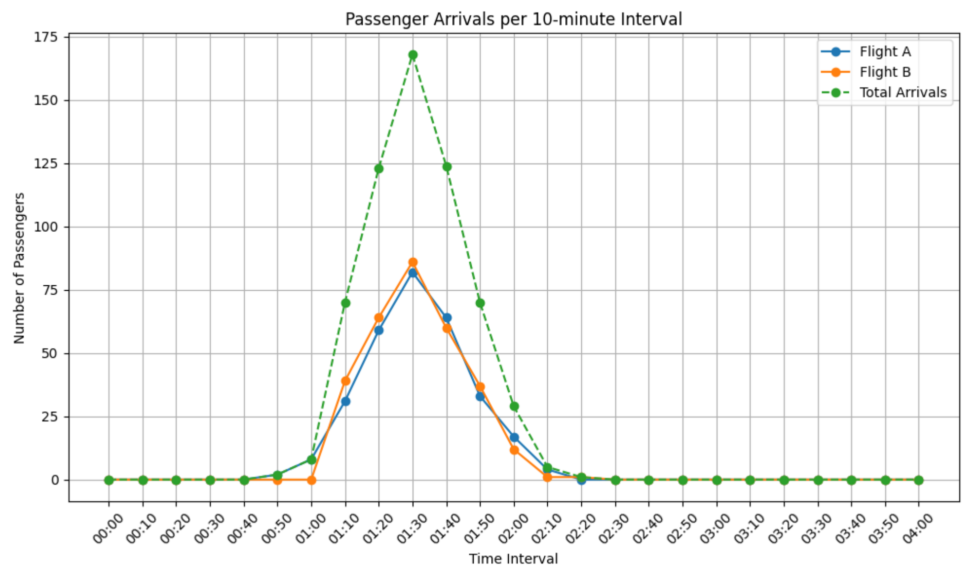

Figure 4. Passenger Arrival Rates to Airport

The identification of early baggage is based on a defined time threshold set at two hours prior to each flight's departure. Baggage is classified as early if it arrives at the collector before this threshold. To determine this, the model calculates a storage time for each bag using the following formula.

$$StorageTime = FlightDepartureTime - 7200 - T_s \quad [seconds]$$

where T_s is the timestamp at which the baggage arrives at the end of collector, and 7200 seconds represents the two-hour cutoff. If the computed storage time is greater than zero, the baggage is categorized as early and routed to the EBS for temporary holding. If the result is zero or negative, the baggage is considered non-early and proceeds directly to the EDS. This logic is embedded in the simulation model to separate and manage baggage types based on arrival time, ensuring that early baggage does not overload downstream components during peak demand periods.

Two strategies for managing EBS are simulated: a conventional approach and a proposed dynamic method. In the conventional setup, baggage is routed to the EBS strictly based on pre-calculated storage time, without considering real-time system status. If the EBS reaches capacity, excess baggage is held in the sorter loop, potentially causing congestion. The proposed dynamic method, by contrast, recalculates the need for storage upon each bag's arrival at the EBS. It also includes a periodic release mechanism that forwards baggage to the make-up area in intervals, based on real-time system load and availability. This adaptive flow control is designed to minimize congestion and improve resource utilization, particularly in high-demand periods.

To support analysis and enhance model transparency, visual feedback is integrated into the simulation environment. Bags are labeled and color-coded to represent both flight assignment and baggage type. As shown in Figure 5, baggage for Flight A is labeled "A" and for Flight B "B." Early baggage is additionally colored red, allowing it to be easily identified as it moves through the system. Non-early baggage is displayed in black. This visual layer provides an intuitive representation of baggage flow and supports the evaluation of storage and routing behavior under varying operational conditions. By observing these interactions, the simulation offers valuable insights into system behavior. It enables assessment of EBS performance under peak-load conditions and helps validate the efficiency of the dynamic storage strategy in maintaining smooth and uninterrupted baggage flow.

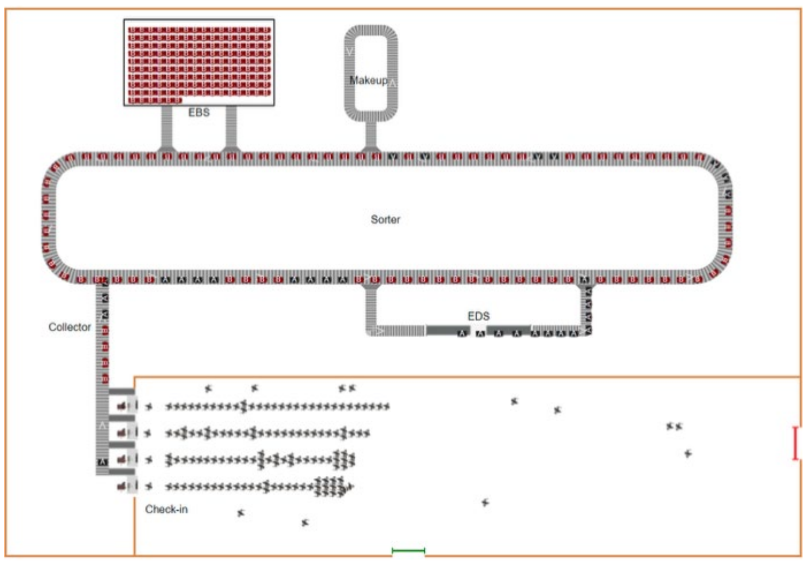

Figure 5. Overview of Simulation

3.3. Evaluation

The evaluation phase assesses whether the proposed BHS, incorporating EBS, achieves its operational objectives of timely baggage delivery and efficient performance under the constraints typical of small airports. Two key criteria are examined: on-time baggage delivery to the make-up area and the identification of system bottlenecks. To support this analysis, the simulation output is processed using Python's data science libraries, NumPy for numerical operations, Pandas for data manipulation, and Matplotlib for data visualization. These tools enable detailed examination of two primary datasets: baggage trace logs, which include flight designation and timestamps at each subsystem, and subsystem load logs, which track baggage accumulation over time. By analyzing this data, the evaluation identifies both deadline violations and patterns of congestion, providing insight into the performance of the proposed EBS design under different operating conditions.

The first aspect of the evaluation focuses on verifying that all baggage reaches the make-up area by the defined operational deadline. In this study, that deadline is set to 30 minutes before the scheduled departure of each flight, providing a buffer for aircraft loading. A baggage item is considered on time if its arrival time at the make-up area, denoted as T_f, satisfies the following condition.

$$T_f \leq FlightDepatureTime - 1800 \quad [seconds]$$

Here, 1800 seconds represents the 30-minute buffer. Any baggage item failing to meet this condition is classified as late-delivered. This criterion allows the simulation to detect delays and evaluate the system's reliability across different passenger arrival patterns and storage configurations. Ensuring consistent on-time delivery is especially important in smaller airports, where resources and flexibility are limited.

The second evaluation component focuses on identifying bottlenecks within the BHS. This is done by monitoring capacity utilization across key subsystems, including the collector, sorter, EDS, EBS, and make-up area. During the simulation, the system tracks whether these components reach or exceed their operating limits. While a single subsystem reaching full capacity does not necessarily indicate a system failure, simultaneous saturation of multiple components signals congestion that can hinder baggage flow. These insights reveal the system's stability and highlight specific modules that may restrict throughput during peak demand.

To refine the EBS configuration, an iterative adjustment process is employed. If bottlenecks or late deliveries occur, the EBS capacity is gradually increased until performance stabilizes. Conversely, if the system performs efficiently without fully utilizing the EBS, the storage size is reduced incrementally to determine the minimum required capacity. This process ensures that the EBS is neither over-dimensioned nor underutilized, supporting the design goal of a compact, scalable solution appropriate for airports with space and labor constraints. Collectively, these evaluation steps validate whether the proposed system delivers reliable, efficient performance and can adapt to varying passenger arrival behaviors without causing delays or operational bottlenecks.

4. Results

This section presents the simulation outcomes comparing the conventional EBS system with the proposed dynamic EBS under different storage capacities. The key evaluation metrics include the rate of late-delivered baggage and the maximum utilization levels of critical BHS subsystems.

4.1. Verification of Late-Delivered Baggage

Table 2 displays the delay rate and final baggage delivery times across each configuration. In the conventional EBS, with a capacity of 150 bags, the system failed to meet the delivery deadline, resulting in a 17.83% delay rate and a final delivery time of 2:50. Increasing capacity to 300 reduced delays to 8.5% with a 2:40 completion time, while a 450-bag configuration eliminated delays completely with baggage delivered by 2:30.

In contrast, the proposed EBS achieved 0% delay even with a storage size of only 150 bags. The final baggage delivery occurred at 2:20, ahead of all conventional setups. This result confirms the system's ability to maintain on-time performance without the need for increased capacity.

Table 2. Comparison of Late-delivered Baggage

	EBS Capacity (bags)	Final Delivery Time	Delay Rate (%)
Conventional EBS	150	2:50	17.83
	300	2:40	8.5
	450	2:30	0
Proposed EBS	150	2:20	0

4.2. Analysis of Bottleneck in BHS

As shown in Table 3, the conventional EBS reached 100% utilization in both the EBS and sorter when using 150 or 300 bags capacities. These scenarios triggered bottlenecks, especially between 01:35 and 02:00 for the 150-bag configuration. The makeup area remained underused at just 5% in both cases. Only with a 450-bags capacity did the system avoid congestion, though at the cost of substantial spatial requirements.

The proposed EBS, even with the same 150-bags capacity, demonstrated improved load balancing. The sorter peaked at only 30%, while makeup area utilization increased to 60%, reflecting more effective distribution of baggage flow. An additional test using a 50-bag EBS showed similar success, with the sorter and makeup area reaching 45% and 70% utilization respectively, and no bottlenecks observed.

Table 3. Maximum Utilization of EBS, Sorter, and Make-up Area

	EBS Capacity (bags)	Max EBS Utilization (%)	Max Sorter Utilization (%)	Max Make-up Area Utilization (%)	Bottleneck Period
Conventional EBS	150	100	100	5	01:35-02:00
	300	100	100	5	01:50-02:00
	450	100	50	30	None
Proposed EBS	150	100	30	60	None
(Additional Test)	50	100	45	70	None

5. Discussion

The simulation results clearly highlight the operational limitations of the conventional EBS system. Its reliance on increasing storage capacity to meet demand leads to inefficient resource use and challenges in environments where physical space is constrained. The bottlenecks observed in lower-capacity scenarios illustrate poor coordination between subsystems, as early baggage accumulates and overwhelms the sorter, causing delays upstream and leaving downstream areas like the makeup zone underutilized.

In contrast, the proposed EBS system presents a more effective and scalable alternative. By regulating baggage flow through timed release intervals, the system avoids sudden surges and ensures smoother transitions across components. This proactive strategy minimizes subsystem congestion and supports consistent delivery performance, even at significantly lower storage capacities. Furthermore, the success of the additional test using only 50 bags confirms that the proposed system remains functional under extreme capacity constraints. This illustrates its adaptability and robustness, reinforcing its potential for deployment in space-limited environments. By maintaining performance through strategic scheduling, the proposed EBS serves as both a compact storage system and an effective flow management tool.

Overall, the proposed EBS enables compact and intelligent baggage handling that aligns with the operational needs of constrained environments. Its ability to eliminate delays, avoid bottlenecks, and optimize resource use offers a robust solution for modernizing BHS without extensive physical expansion.

6. Conclusion

This study proposed a compact Early Baggage Storage (EBS) system to improve the operational efficiency of Baggage Handling Systems (BHS) in small airports. The objective was to design an EBS that functions within limited space while ensuring all baggage for departing flights is processed and transferred to the make-up area on time. A simulation-based approach was adopted, comprising model construction, simulation execution, and evaluation of performance indicators.

Two EBS strategies were examined. The conventional system treats EBS as a passive storage unit without regulating flow, whereas the proposed approach actively monitors downstream availability and releases baggage in scheduled intervals. Performance evaluation focused on two key aspects: verifying the timely delivery of baggage and identifying congestion within the system. Results demonstrated that the proposed EBS outperformed the conventional model by reducing dependency on large storage capacity and improving overall system flow. While the conventional EBS required a capacity of at least 450 bags to avoid congestion and delays, the proposed system maintained efficient performance even with smaller storage volumes. This was achieved by regulating baggage release to 10 to 20 bags every 90 to 120 seconds, which minimized sorter congestion and improved make-up area utilization. Furthermore, the proposed EBS served as a scheduling mechanism that prioritized baggage for earlier departing flights, reducing the likelihood of routing errors when multiple flights shared the same make-up zone.

Despite these positive outcomes, the study was based on a simplified BHS model intended to isolate key system behaviors. The simulation did not fully account for the complexity of real-world airport operations, such as variable flight schedules, inconsistent baggage arrival patterns, or infrastructure limitations. Future research should apply the proposed EBS design to actual airport settings to assess its practical effectiveness and adaptability across different operational environments. Moreover, this study assumed an ideal make-up area with no delays. In reality, delays at this stage can impact baggage readiness and flight departure times. Therefore, optimizing make-up area performance should be a key focus moving forward. One potential solution under consideration for improving BHS efficiency and reducing operator workload is the deployment of automated loading robots. Future studies should explore how such robotic systems can be effectively integrated into the make-up area, and what design considerations are necessary to support their implementation within the broader baggage handling workflow.

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