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Article

The Analysis and AI Simulation of Passenger Flows in an Airport Terminal: A Decision-Making Tool

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Abstract: In this paper, a decision-making tool is proposed that can utilize different strategies to deal with passenger flows in airport terminals. A simulation model has been developed to investigate these strategies, which can be updated and modified based on the current requirements of an airport terminal. The proposed tool could help airport managers and relevant decision makers proactively mitigate potential risks and evaluate crowd management strategies. The aim is to eliminate risk factors due to overcrowding and minimize passenger waiting times within the terminal to provide a seamless, safe and satisfying travel experience. Overcrowding in certain areas of the terminal makes it difficult for passengers to move freely and increases the risk of accidents (especially in the event of an emergency), security problems and service interruptions. In addition, long queues can lead to frustration among passengers and increase potential conflicts or stress-related incidents. Based on the derived results, the optimized routing of passengers using modern technological solutions is the most promising crowd management strategy for a sample airport that can handle 800 passengers per hour.

Keywords: crowd management; risk assessment; simulation model

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1. Introduction

According to the International Air Transport Association (IATA) [1], airport terminals should meet passenger demand and provide an adequate level of service in terms of waiting times in queues, crowdedness level and delays, considering government restrictions due to terrorism [2], infectious disease outbreaks (such as COVID-19) [3] and extreme weather events [4]. Therefore, airports may have to deal with increased demand and should accommodate more passengers. This is not only costly but also poses a major challenge for airports, from a logistical perspective, to meet the needs of passengers and optimize their movements within the terminal.

Artificial Intelligence (AI) models could provide successful solutions for crowd management in the transport sector [5], offering a double benefit by not only optimizing their operational efficiency but also improving overall sustainability. More specifically, virtual queues for better passenger orientation when arriving at the airport [6], queue management with buffer zones for passenger waiting areas [7] and smart queue management tools [8] could help flight managers optimize resource allocation and airport operations. Crowd management in airport terminals is essential to ensure safety and a high level of service for passengers, while optimizing terminal processes and resource allocation could achieve operational resilience for a more organized response to unexpected events and a higher level of sustainability.

In this context, this paper aims to develop a sophisticated decision-making tool that uses different strategies to deal with passenger flows in airport terminals based on a simulation model. The proposed tool could help airport managers and relevant decision makers proactively assess and mitigate potential risks by providing a data-driven approach to real-time decision making. This tool will also identify and analyze potential risks, due to queues and crowded stores, that could lead to negative consequences. Once the risks are assessed and categorized, implementation strategies will be imposed to mitigate or control these risks at an operational level. This will result in reduced queues and operational vulnerabilities and prevent crowd disruption.

The remainder of this paper is organized as follows: Section 2 provides an overview of previous research studies in the field of risk assessment in airport terminals and includes a review of the existing literature to date. Section 3 provides a detailed analysis and presentation of the proposed decision-making tool. Section 4 then presents the results obtained from the practical implementation of the proposed tool. Finally, Section 5 draws conclusions based on the results and provides key findings as valuable guidance for future research in the dynamic field of airport terminal risk assessment and management.

2. Research Background

2.1. The Level of Service in Airport Terminals

Airport terminals are important hubs of the global transportation network, managing internal and external flights as well as connecting flights and their corresponding passenger flows. The continuous growth and development of the aviation industry, as well as geopolitical crises and extreme weather conditions, make airport terminals necessary in order to provide passengers with a safe, efficient and successful travel experience. To cope with the complex environment of airport terminals, various crowd management strategies have been developed to streamline processes and provide passenger-friendly design [9]. More recent studies focus on advanced technologies, information systems and smart applications developed to improve scheduling, optimize airport operations and increase the quality of service for passengers [10,11].

In this context, research reports conducted both before and after the COVID-19 pandemic summarize the future of airport terminals and aviation in general, focusing on how modern technology could improve security processes and increase the level of service to passengers [12,13]. In terms of operational efficiency, Thampan et al. [14] have presented and analyzed how analytical methods can be used to evaluate service quality, considering the spatial, operational and technological changes in airport terminals. More recently, Dong et al. [15] have used machine learning techniques to predict incidents leading to flight delays. This predictive capability could improve flight scheduling for more effective passenger service and mitigate security and economic risks in the airport environment.

In addition, several crowd management strategies have been proposed to improve airport terminal environments that use simulation approaches, covering areas such as optimization, passenger behavior, security, and building design. Kim and Wu [16] used an agent-based simulation approach to optimize passenger service levels in a cost-effective manner by considering the degree of crowding and passenger waiting times. Similarly, Mekić et al. [17] used an agent-based model for airport terminal operations to investigate how passenger behavior affects waiting time, expenses, missed flights and operational costs. In terms of security, Jassen et al. [18] proposed agent-based models and Monte Carlo simulations to comprehensively assess and manage security risks.

On the other hand, the research community has also investigated how new airport infrastructures and terminal expansions might affect the level of service for passengers [19,20]. Passenger characteristics have also been studied in conjunction with terminal layout, and airport retail revenue has been investigated using an agent-based simulation approach [21]. In addition, passenger preferences for shopping and catering activities within the terminal have been investigated [22], as well as how their arrival times should be considered when managing the commercial area of an airport at a strategic level [23]. Recent studies also investigated methods and strategies to improve social distancing due to COVID-19 and minimize the crowded areas within terminals [24,25].

The high level of complexity exhibited by airport terminals can be captured using agent-based models [26] that represent different groups of stakeholders and depict their interdependencies. In addition, sustainability indicators, covering economic, environmental and social aspects, could be used to evaluate the performance of airport terminals, using data analysis and simulation models as well as qualitative and quantitative information [27]. Assessment tools such as LCA (Life Cycle Analysis) are increasingly being used to help decision makers select strategies, operations and policy mechanisms [28]. It is also worth mentioning that the CSR (Corporate Social Responsibility) of airports [29] is a business model that could be used to measure the environmental, economic, energy and social impacts of applied strategies and operational activities to achieve commitment from decision makers [30].

2.2. Sustainability in Airport Terminals

Considering short-term initiatives for sustainability in airport terminals, optimizing resource allocation and improving operational efficiency may be among the most important goals of airport managers and relevant decision makers. Their focus on day-to-day measures includes energy-efficient strategies and renewable energy devices, as well as smart technologies for real-time monitoring and control [31]. Educational campaigns for passengers could also contribute to sustainability by raising passenger awareness and encouraging them to participate in environmentally friendly actions and programs. In addition, a sustainable connection of the airport terminal to public transportation could reduce the GHG (Greenhouse Gas) emissions associated with passenger and employee commuting [32].

On the other hand, long-term sustainability includes measures that pave the way for sustainable airports that will define their future operations, approaches and tools. Smart infrastructures represent an indicative long-term strategy that will enable the use of smart applications and technologies in daily operations [33]. The design of airport terminals (either for expansion or new construction) could be developed with a focus on sustainability, using energy-efficient materials, natural light and green terraces or roofs [34]. Finally, connecting airport managers and relevant decision makers with other stakeholders and interested actors, such as public authorities and industry representatives, and actively involving them can create economic opportunities and joint initiatives that benefit both the airport and its surroundings in the long run [35].

3. The Decision-Making Tool

The proposed decision-making tool is based on a simulation model that provides a visual representation of how passengers move within the airport terminal environment. This enables airport managers and relevant decision makers to identify flow patterns, potential congestion points and bottlenecks. The main goal is to reduce waiting times in the security control area and at the entry points of stores in order to provide a higher quality of service to passengers. The corresponding performance metrics set the basis upon which to evaluate different usage scenarios, and Figure 1 depicts the main concept of the proposed decision-making tool. The scenarios include the base case and the implementing of various crowd management strategies such as technology integration, trained security personnel, multiple entry points, access control, etc. These strategies are thoroughly designed to optimize passenger flows and improve the efficiency of airport terminal operations.

The base case simulates passengers' movement in a stochastic way to capture the flows before any crowd strategy implementation. Three main strategies are examined to simulate different technology applications and operational approaches. More specifically, the technology integration strategy could lead to improved navigation through the use of modern mobile applications, which consider several parameters and restrictions (i.e., passengers' preferences, the maximum capacity of stores, etc.). The trained security personnel strategy is also used by the proposed tool for optimizing service time in check-in and security control areas. Finally, the strategy of multiple entry points is also studied, exploring higher efficiency for both economy and business/gold class passengers.

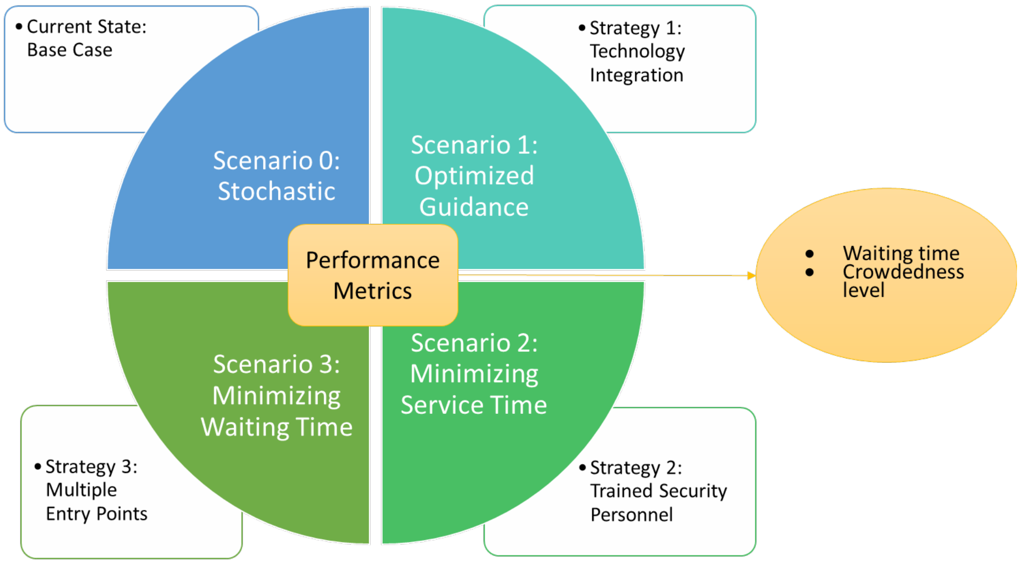


Figure 1. Concept of the proposed decision-making tool.

Moreover, the decision-making tool can also consider passengers' specific preferences for visiting different stores within the airport terminal area. It also accounts for the number of passengers waiting to visit each store and takes the maximum capacity of the stores and other relevant parameters into account. The proposed tool can also facilitate continuous improvements by updating and refining the model with current real-data and passengers' feedback in an attempt to avoid inefficiencies and prevent congestion-related issues. An iterative implementation process is proposed to ensure that the model remains adaptable, helping to proactively address inefficiencies and mitigate any potential challenges, fostering a more responsive and passenger-centric airport environment.

3.1. The Simulation Model

Due to overcrowding in the security control area and at the entry points of different stores, health hazards (especially during pandemics), accidents and safety threats have appeared in airport terminals. Therefore, efficient crowd management is needed to plan flows during operating times and guide passengers, reducing waiting times in queues and improving the level of service for passengers. More specifically, the input of the developed simulation model is the list of passengers (800 in total) that have arrived at the airport terminal and are waiting for their departing flight. Each passenger has specific characteristics that are considered in the simulation model (i.e., flight number, ticket category, check-in status, preferences for visiting stores in the airport terminal).

Figure 2 depicts the sequence of actions and flows within the studied sample airport terminal, as well as the decision points in the different processes that the simulation model considers. The first step is to examine if the passenger has checked in online or if s/he needs to visit the check-in desks. The simulation model checks whether the check-in is open (which means that the flight departs in less than 2.5 h) and the passenger proceeds to the desks. Otherwise, s/he needs to wait until the check-in opens. Then, the passenger should go to the security control area and their waiting time depends on the queue length and the efficiency of the security personnel. It should be mentioned that improved services (with reduced waiting time) are offered to the gold class members and passengers with business tickets, compared to those in economy, in the check-in and security control areas.

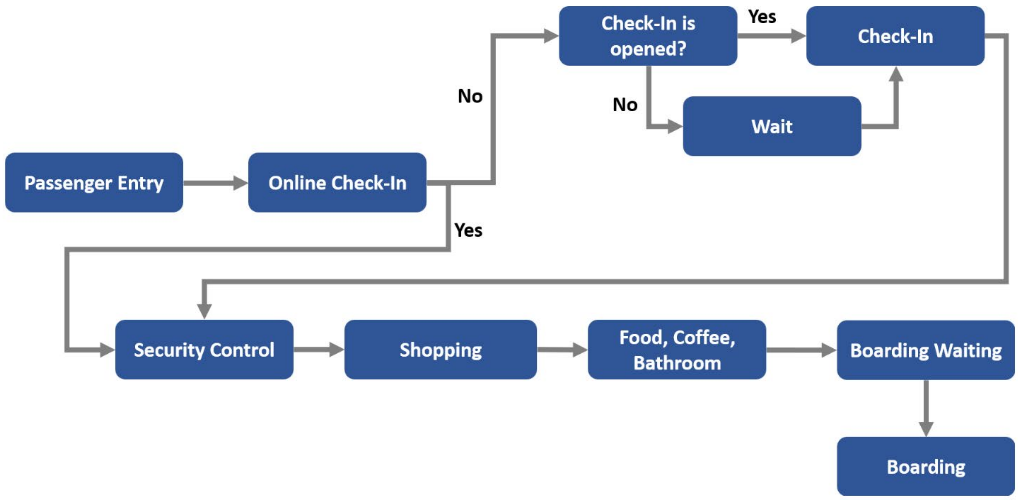


Figure 2. Flow diagram of passengers' movements in the simulated sample airport terminal.

The next processes involve shopping in the airport's duty-free stores (two in total), optical stores (two in total), clothing stores (two in total), jewelry stores (two in total) and perfume stores (two in total), as well as using catering and revitalization services (three restaurants in total, three coffee shops in total and two WCs in total) before the passenger's boarding. Passengers visit stores in the shopping area in a predefined order, based on their preferences, or avoid this step. In the latter case, they proceed to the catering services and extra waiting time is needed for them to be served. Last, they proceed to the gates and wait for boarding to start, or embark in case where the boarding of their flight has already started. Note that when boarding starts, the passengers should proceed to the gates. For this reason, the simulation model continuously checks if boarding has started.

3.2. Usage Scenarios

3.2.1. Scenario 0—Base Case Strategy

The first scenario follows a stochastic approach to simulate passengers' movements (800 passengers per hour) [36,37] as they visit their preferred stores in the shopping area within the airport terminal. Passengers visit the shopping area and the catering services in a non-deterministic manner, making their choices based on a random probabilistic functions. This scenario serves as the base case scenario, in which passengers are not guided to visit airport stores in a predefined sequence. Instead, they independently select stores based on their personal preferences in an ad hoc, non-directed fashion, contributing to a realistic representation of spontaneous passenger behaviors within the shopping and catering/revitalization areas of an airport terminal.

3.2.2. Scenario 1—Technology Integration Strategy

In this scenario, passengers are being guided via modern technology and, more specifically, an optimization algorithm, which considers passengers' preferences and the stores' restrictions. The aim is to guide passengers to the stores with the current lowest crowdedness levels, as described in Equation (1), via a mobile app. Therefore, the algorithm embedded in the app considers passengers' preferences, the maximum allowed capacity of each store, the number of passengers that are about to visit each store after using the mobile app, the number of passengers in each store at that time and the number of passengers that are waiting to be served as well as their service time.

$$F_i = \begin{cases} \left(F_{i,r} + F_{i,w} + \frac{F_{i,in}}{F_{i,max}}\right) * T_i & F_{i,max} = F_{i,in} \\ \left(F_{i,r} + \frac{F_{i,nn}}{F_{i,max}}\right) * T_i - c & F_{i,max} > F_{i,in} \end{cases} \quad (1)$$

where

- $F_{i,w}$ is the number of passengers waiting to enter store i;
- $F_{i,r}$ is the number of passengers going to store i;
- $F_{i,in}$ is the number of passengers inside store i;
- $F_{i,max}$ is the maximum capacity in passengers of store i;
- T_i is the service time of a passenger in store i;
- c is a negative constant to capture the crowd avoidance preference.

When a passenger passes the security check, the algorithm is used to calculate store i with the minimum crowdedness level F_i, which indicates the place with the maximum current capacity limit. After a passenger exits this store, the algorithm re-calculates the minimum crowdedness level F_i for the remaining stores and directs the passenger to the next one. This process continues until the passenger has visited all the stores they like. The same procedure is also followed for visiting the airport restaurants, coffee shops and bathrooms.

3.2.3. Scenario 2—Trained Security Personnel Strategy

Passenger service time is reduced in this scenario as highly skilled and proficient security personnel [38] can perform their tasks with higher efficiency. Their advanced skill set allows them to perform tasks more competently, making substantial contributions to expediting the passenger handling processes at key checkpoints, including the check-in and security control areas. These well-trained personnel possess an in-depth understanding of security protocols and are adept at streamlining and expediting the requisite procedures. Their competence enables them to conduct security checks and verification processes quickly, without compromising on the effectiveness of security measures. Their proficiency in operating metal detectors, x-ray machines and other screening equipment allow them to identify items that may pose a security risk. Therefore, a seamless and secure experience for passengers can be achieved within the airport terminal.

3.2.4. Scenario 3—The Multiple Entry Points Strategy

This scenario is focused on minimizing passenger waiting time in an airport terminal through the utilization of a multiple entry points strategy. This based on the ticket category, such that passengers with “business” tickets and gold class members can use dedicated entry points that are separate from passengers with “economy” tickets. This separation optimizes the flow of passengers with “business” tickets and gold class members by reducing congestion and waiting times at the check-in and security control areas. In addition, passengers with “economy” tickets also benefit from reduced waiting times because of the decreased congestion at their designated entry points. This grouping approach [39] to passengers, allowing them to use multiple entry points, is expected to result in an overall improvement in passengers’ flows and enhance their level of service and satisfaction.

4. Experiments and Results

4.1. Experimental Setup

We conducted 500 simulation runs for each scenario and the experimental results for efficient crowd management strategies in an airport terminal are ranked according to their average performance metrics, i.e., waiting time and level of crowdedness. The primary objective is to minimize the waiting times for the different processes (i.e., check-in, security check, shopping/catering/revitalization areas, boarding area, boarding queue) and the secondary objective is to keep a low crowdedness level for all areas of the airport terminal. However, these two objectives can be either conflicting or complementary, because the low crowdedness level may either reduce or increase the waiting time of the different processes. Thus, for the evaluation of the different proposed strategies, several experiments are performed for each of the established scenarios (Table 1).

Table 1. Examined strategies.

Strategy	Scenario
Base Case	Scenario 0: Stochastic
Technology Integration	Scenario 1: Optimized Guidance
Trained Security Personnel	Scenario 2: Minimizing Service Time
Multiple Entry Points	Scenario 3: Minimizing Waiting Time

4.1.1. Scenario 0—Base Case Strategy

In Scenario 0, we consider 800 passengers that arrive at the airport terminal; 15% of them either have purchased "business" tickets or are gold class members. A total of 60% of the passengers have already checked-in online and, thus, the service time in the check-in area is 4 min for each passenger. Additionally, the service time at security control is 3 min for each passenger.

4.1.2. Scenario 1—Technology Integration Strategy

In Scenario 1, we keep the same values for all the parameters, as we need to determine how a mobile app guides the passengers more efficiently within the airport terminal environment.

4.1.3. Scenario 2—Trained Security Personnel Strategy

In Scenario 2, we consider 800 passengers that arrive at the airport terminal; 15% of them either have purchased "business" tickets or are gold class members. In addition, 60% of them have already checked-in online. As we are examining the higher efficiency of trained security personnel, the service time in the check-in area is now 2 min for each passenger and the service time at security control is 1.5 min for each passenger.

4.1.4. Scenario 3—The Multiple Entry Points Strategy

Scenario 3 examines the effects of the utilization of a multiple entry points strategy, and of the 800 passengers that arrive at the airport terminal, we considered 40% of passengers to have either purchased "business" tickets or been gold class members. The service time is 4 min in the check-in area and 3 min at security control, while 60% of all passengers have already checked-in online (the same as the base case).

4.2. Computational Results

Figure 3 summarizes the results obtained in the different scenarios in terms of minimizing the waiting time during the different processes within the airport terminal. Based on the results reported, we realized that Scenario 3 presents the minimum waiting time overall, i.e., 47 min on average per passenger. However, each of the different scenarios manages to achieve a waiting time reduction within the terminal processes, i.e., the check-in area, security check area, shopping, catering and revitalization areas, boarding area and the boarding queue during embarkment. More specifically, Scenario 1 minimizes the total waiting time in the shopping, catering and revitalization areas, i.e., 1 min on average per passenger. Scenario 2 minimizes the total waiting times in the check-in and security areas, i.e., 1 min on average per passenger and 17 min on average per passenger, respectively. Correspondingly, Scenario 3 minimizes the total waiting time in the boarding area, i.e., 20 min on average per passenger, and in the boarding queue during embarkment, i.e., 3 min on average per passenger.

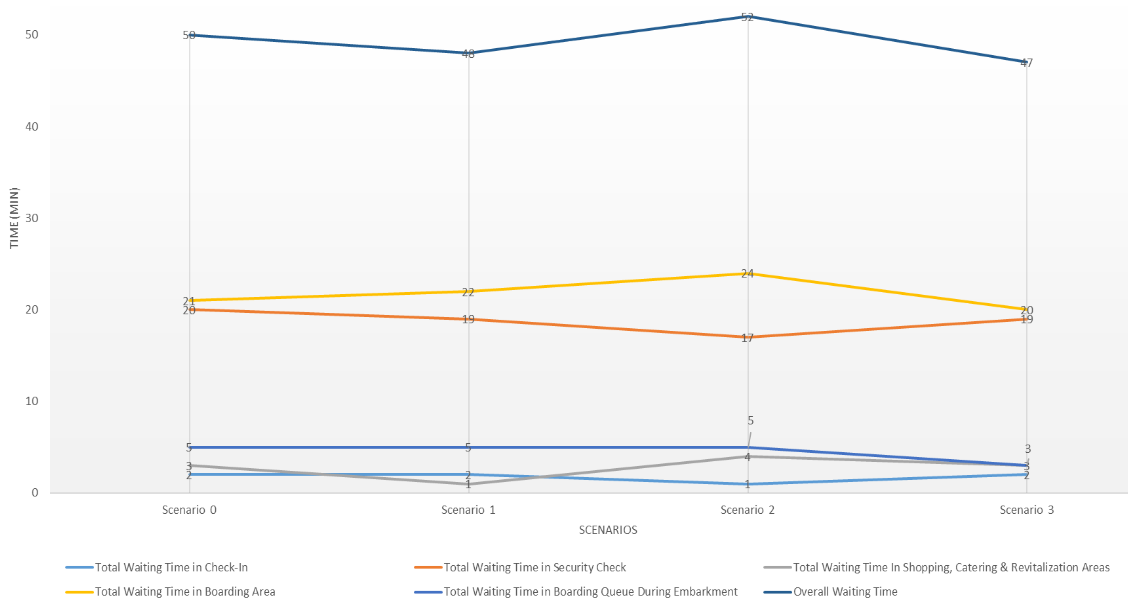
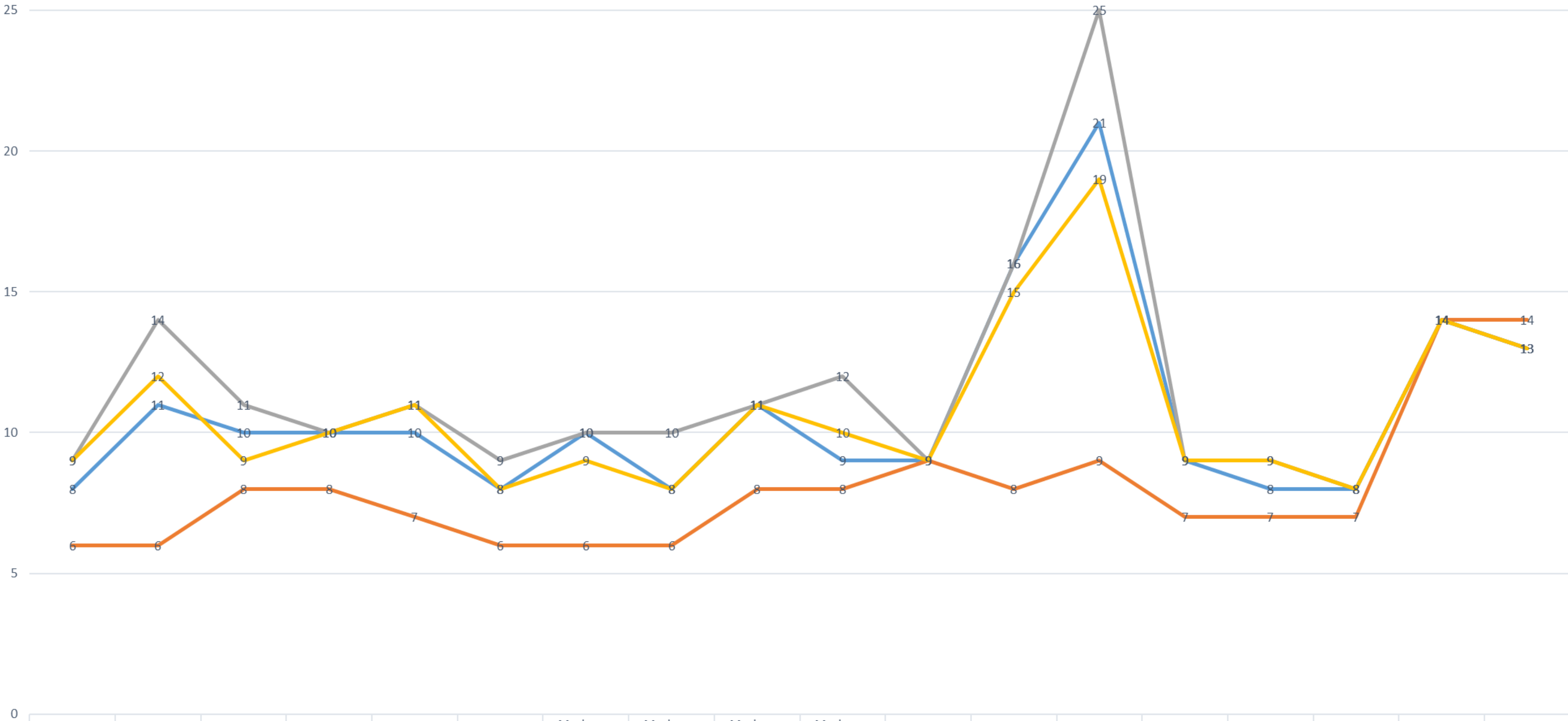


Figure 3. Waiting times within the airport terminal for each scenario.

Regarding the level of crowdedness, Figure 4 summarizes the results obtained for each part of the shopping, catering and revitalization areas. We can observe that the level of crowdedness is minimized by implementing Scenario 1 in all cases except for the maximum number of passengers waiting for WC2, which is 14 passengers in total. The minimum is 13 passengers (same as the base case) and this is also achieved by Scenarios 2 and 3. More specifically, Scenario 1 achieves a reduction of up to 25% in the total maximum number of passengers in different stores compared to the base case (Scenario 0). It is worth mentioning here that Scenario 2 results in an increased level of crowdedness for the shopping, catering and revitalization areas of 9%. This is reasonable, as Scenario 2 improves the efficiency of the check-in and security control areas, which belong to the first part of processes in an airport terminal. Hence, passengers gain some time to spend in the shopping, catering and revitalization areas before their embarkment.

In more detail, Figure 5 presents how each scenario affects the crowdedness level within the terminal. The highest reductions were achieved using Scenario 1. The maximum number of passengers is minimized in Restaurant 3 (a 57% reduction) compared to the base case scenario. It is worth mentioning that Scenario 2 increases the crowdedness level within the terminal, and the highest increase in the maximum number of passengers appeared in Duty-Free Shop 2. Reductions are also achieved using Scenario 3, and its highest decrease in the crowdedness level (13%) is achieved in Coffee Shop 3.

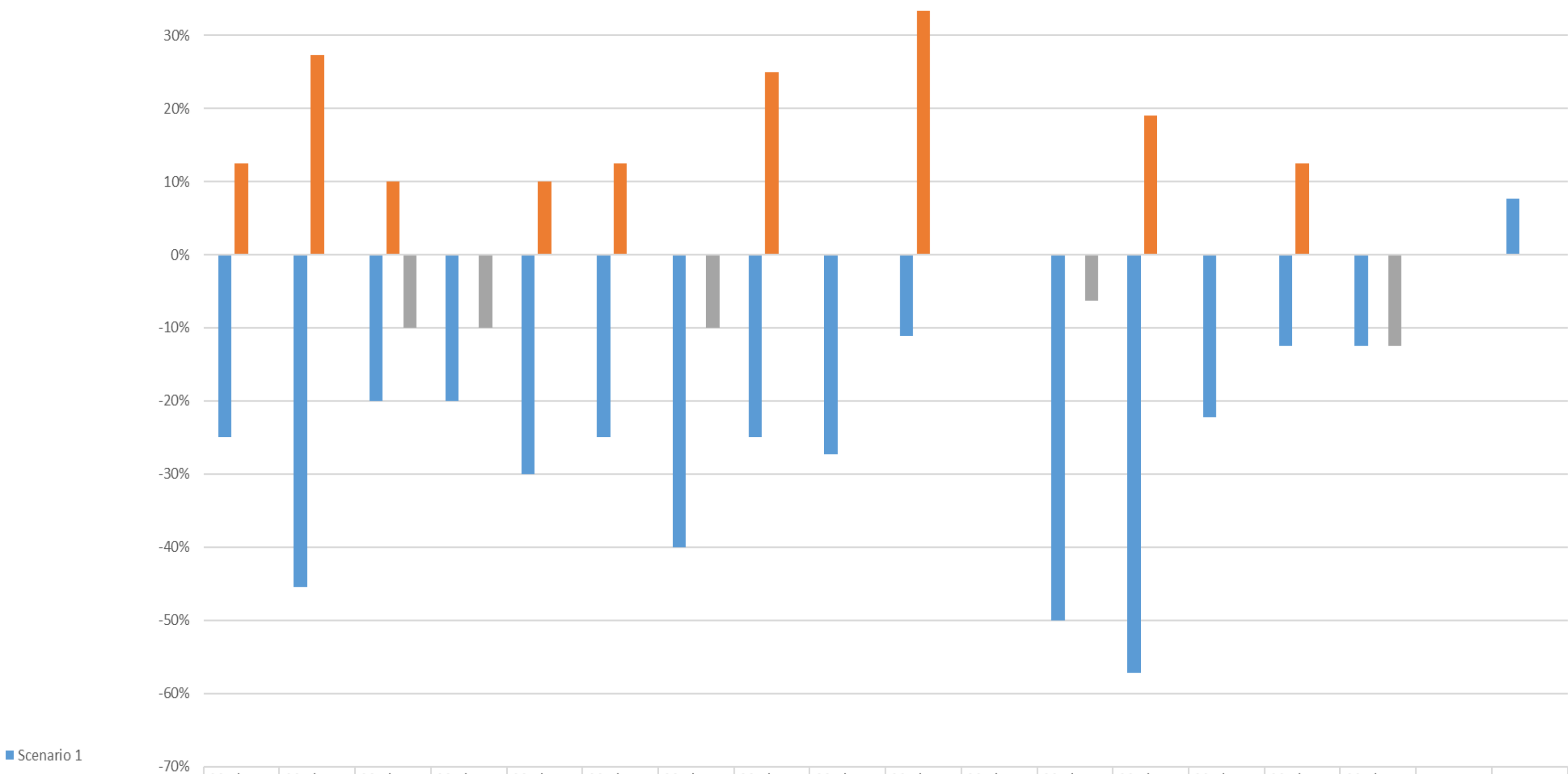
Overall, it is apparent that the optimal strategy is to enable technology integration in the processes, which will guide passengers more efficiently. This strategy keeps the crowdedness level low, with a maximum number of 14 passengers waiting for service at WC1 and WC2. Moreover, the crowdedness level is remarkably reduced (about 25% less) for all processes in the shopping, catering and revitalization areas (i.e., 144 passengers in total for all processes). Additionally, the cumulative total waiting time for all the processes in the airport terminal is 48 min on average per passenger, only 1 min more than the optimum waiting time achieved by Scenario 3. On the other hand, Scenario 3 results in a higher crowdedness level of up to 34% compared to Scenario 1 (i.e., 193 passengers in total for all processes in the shopping, catering and revitalization areas). This underscores that the efficacy of technology integration is not only minimizing waiting times but also optimizing overall passenger flow and, as such, enhancing passenger satisfaction within the airport terminal.



	Maximum Number of Passengers / Crowdedness Level (Duty Free Shop 1)	Maximum Number of Passengers / Crowdedness Level (Duty Free Shop 2)	Maximum Number of Passengers / Crowdedness Level (Optical Store 1)	Maximum Number of Passengers / Crowdedness Level (Optical Store 2)	Maximum Number of Passengers / Crowdedness Level (Jewelry Store 1)	Maximum Number of Passengers / Crowdedness Level (Jewelry Store 2)	Maximum Number of Passengers / Crowdedness Level (Clothing Store 1)	Maximum Number of Passengers / Crowdedness Level (Clothing Store 2)	Maximum Number of Passengers / Crowdedness Level (Perfume Store 1)	Maximum Number of Passengers / Crowdedness Level (Perfume Store 2)	Maximum Number of Passengers / Crowdedness Level (Restaurant 1)	Maximum Number of Passengers / Crowdedness Level (Restaurant 2)	Maximum Number of Passengers / Crowdedness Level (Restaurant 3)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 1)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 2)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 3)	Maximum Number of Passengers / Crowdedness Level (WC 1)	Maximum Number of Passengers / Crowdedness Level (WC 2)
Scenario 0	8	11	10	10	10	8	10	8	11	9	9	16	21	9	8	8	14	13
Scenario 1	6	6	8	8	7	6	6	6	8	8	9	8	9	7	7	7	14	14
Scenario 2	9	14	11	10	11	9	10	10	11	12	9	16	25	9	9	8	14	13
Scenario 3	9	12	9	10	11	8	9	8	11	10	9	15	19	9	9	8	14	13

Scenario 0 Scenario 1 Scenario 2 Scenario 3

Figure 4. Crowdedness level within the airport terminal for each scenario.



	Maximum Number of Passengers / Crowdedness Level (Duty Free Shop 1)	Maximum Number of Passengers / Crowdedness Level (Duty Free Shop 2)	Maximum Number of Passengers / Crowdedness Level (Optical Store 1)	Maximum Number of Passengers / Crowdedness Level (Optical Store 2)	Maximum Number of Passengers / Crowdedness Level (Jewelry Store 1)	Maximum Number of Passengers / Crowdedness Level (Jewelry Store 2)	Maximum Number of Passengers / Crowdedness Level (Clothing Store 1)	Maximum Number of Passengers / Crowdedness Level (Clothing Store 2)	Maximum Number of Passengers / Crowdedness Level (Perfume Store 1)	Maximum Number of Passengers / Crowdedness Level (Perfume Store 2)	Maximum Number of Passengers / Crowdedness Level (Restaurant 1)	Maximum Number of Passengers / Crowdedness Level (Restaurant 2)	Maximum Number of Passengers / Crowdedness Level (Restaurant 3)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 1)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 2)	Maximum Number of Passengers / Crowdedness Level (Coffee Shop 3)	Maximum Number of Passengers / Crowdedness Level (WC 1)	Maximum Number of Passengers / Crowdedness Level (WC 2)
Scenario 1	-25%	-45%	-20%	-20%	-30%	-25%	-40%	-25%	-27%	-11%	0%	-50%	-57%	-22%	-13%	-13%	0%	8%
Scenario 2	13%	27%	10%	0%	10%	13%	0%	25%	0%	33%	0%	0%	19%	0%	13%	0%	0%	0%
Scenario 3	0%	0%	-10%	-10%	0%	0%	-10%	0%	0%	0%	0%	-6%	0%	0%	0%	-13%	0%	0%

Figure 5. Percentage of reduction/increase in the crowdedness level within the airport terminal for each scenario compared to the base case (Scenario 0).

The experiments illustrate the relevance of the simulation model for the representation of passengers' flows in applying different management strategies and underlining the role of the proposed decision-making tool. Based on computational experience, Scenario 3 excels in total waiting time (i.e., 4 min less compared to the base case) and Scenario 1 excels in the crowdedness level (i.e., 49 passengers less compared to the base case). To that end, we observed that, in this case, the best overall improvement is achieved by Scenario 1 as it also reduces the waiting time by 4% compared to the base case. On the other hand, Scenario 3 manages to reduce the crowdedness level by only 3%. Clearly, a more efficient guidance of passengers using a mobile app could offer improved service quality to passengers and reduce risks due to a high level of crowdedness in the airport terminal. Therefore, Scenario 3 could offer enhanced service quality and mitigate the risks associated with high levels of crowdedness within an airport terminal.

To sum up, Scenario 1, the "Technology Integration" strategy, provides a more efficient and pleasant experience to passengers and reflects a commitment to adopting eco-friendly and innovative solutions aligned with modern sustainability practices. Satisfied passengers are more likely to be engaged in sustainable behaviors and foster support for subsequent initiatives within the airport terminal environment. The maintenance of a low crowdedness level allows for the more efficient identification and mitigation of potential risks, contributing to improved operational resilience. This is crucial for managing unexpected events, reducing disruptions, and maintaining a sustainable and consistent level of service for passengers.

5. Conclusions

This paper presents a simulation model developed for a decision-making tool in order to analyze different crowd management strategies in the context of the risks posed by passenger flows in airport terminals. Different usage scenarios were developed to investigate the different management strategies, to optimize passenger routing and minimize service and waiting times. The scenarios of the simulation model can be updated according to current requirements, which enriches the academic discourse on dynamic modeling in airport operations. This flexibility of the simulation model is also important for management, as it can be adapted to the specific needs of an airport terminal. Managers can tailor crowd management strategies to the unique characteristics and current challenges of their terminals, ensuring a customized and effective approach to managing passenger flows that promotes long-term sustainability.

One research direction worth pursuing is the integration of real-time data into the simulation model to improve its accuracy and responsiveness. Research into human-centered terminal design should investigate how physical layouts and design elements influence crowd dynamics and passenger satisfaction. As research moves towards more realistic and richer problems, the development of real-world models that capture the use of strategies that improve sustainability and resilience is of great interest, as they could mitigate the potential risks in airport terminals more efficiently.

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