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SIMULATION AND MCDA-BASED FRAMEWORK FOR BORDER CROSSING PROCESS DESIGN WITH STATIC AND DYNAMIC CONTROL OF PASSENGER FLOW

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Abstract:
This paper presents an approach combining simulation and multi-criteria decision analysis (MCDA) to model and evaluate options for passenger service organisation at a terminal. The methodology is motivated by changes planned by the EU concerning the introduction of the Entry/Exit System (EES) for advanced border control of passengers crossing the Schengen border having an impact on a passenger flow at the Border Crossing Point (BCP). The primary outcome is the selection of a recommended process configuration, including the types and number of servers required to ensure an efficient passenger flow within the BCP, and satisfactory service levels from the passenger's perspective. The authors propose a methodology that relies on a multi-stage and multi-level graph structure of the BCP. It enables the implementation of alternative technological solutions supporting border control, i.e., Manual Border Control (MBC), and automated solutions such as e-Gates (e-Gs) and Self-Service Kiosks (SSKs) to create a complex BCP structure. Unlike traditional approach, in this research both static and dynamic phenomena of traffic flow modeling, allowing for comprehensive control of passenger movement at the BCPs, is proposed. The research integrates traffic control, the composition of technical resources, staffing considerations, and spatial analysis into a single evaluative framework, providing a methodology to find the compromise solution for the process design. It consists of six stages: 1) analysis of the current state, 2) design of process variants and formalisation of evaluation criteria, 3) simulation models development for variants, 4) simulation of the current state and process variants, and analysis of results, 5) selection and application of the decision aiding method to find the compromise variant, and 6) result analysis. The proposed methodology has been applied to redesign the border control process at an airport terminal in the context of new border control procedures. Assuming that 39% of passengers require 10–120% more processing time due to new procedures, the recommended process includes new equipment configuration, increasing the total number of units by two. At the same time, the number of border guards remains unchanged, and the space required for passengers waiting in the queues is reduced by 30%.

Keywords: *border crossing point, passenger terminal, multi-stage and multi-level process structure, dynamic simulation, TOPSIS ranking method*

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1. Introduction

Every facility referred to as a stop, port, or terminal is, in general, one of the key components of transport infrastructure associated with passenger transport systems. To maintain generality, such a facility can be described as a Passenger Service Facility – PSF. From the passenger's perspective, the PSF ensures the smooth initiation of the transportation process, facilitates a seamless transfer during the journey, or marks its completion. Thus, attributes of a PSF such as location, size, equipment, and other functional characteristics directly influence the efficiency of passenger flow within a specific time window at the PSF. Consequently, the design of PSF, whether from scratch or through the redesign of specific functional areas of an existing facility, should be closely linked to the target passenger service processes occurring within and in the immediate vicinity of the facility.

Global changes in a passenger transport, driven by security concerns such as the 9/11 attacks in 2001 or the SARS-CoV-2 pandemic in 2020, have compelled many PSF management entities to implement significant modifications to passenger traffic organisation. One example is an airport terminal, where security considerations necessitated organisational changes (e.g., passenger flow management, queue organisation for ticket and baggage check-ins), and in some cases, a complete redesign of the facilities. Currently, a major driver of change is the implementation of the Entry/Exit System (EES), an ICT-based solution for registering and controlling passengers crossing the Schengen border. The development of EES began in 2017 with EU Directive 2017/2226 (EP&CEU, 2017) and continues to this day. A key change enforced by the directive is the requirement for third-country nationals, i.e., non-Schengen citizens, to register biometric data, including fingerprints, retina and facial images. This process is supported by a new IT system. In practice, this significantly increases passenger processing times, potentially leading to disruptions or, in extreme cases, an inability of the entire PSF to function effectively. This underscores the need to assess the efficiency of passenger service processes in the existing PSFs or to conduct such analyses for newly designed facilities. This need is particularly pressing in areas such as passenger communication zones leading to border control points, queue formation and management, service provision in line with new procedures, and further communication after completing border control. Such a dedicated area within the PSF is referred to as a Border Crossing Point (BCP).

Passenger flow management within the BCP relies on an adopted functional structure of servers, representing a distinct subsystem of the transport infrastructure. The functional structure of BCP can take various forms, as illustrated in Figure 1. Each of them includes a passenger flow source (G), a waiting area where queues may form (Q), homogeneous servers (A–B), and an exit point (E) of the subsystem. The complexity of processes executed within such a subsystem depends on its structural design.

Depending on the number of homogeneous groups of servers, systems can be classified as either single-level (Figure 1a) or multi-level (Figures 1b–c). Regarding the complexity of actions, systems may be classified as single-stage (Figures 1a–b) or multi-stage systems (Figure 1c). According to Frontex (2017)

a) b) c)

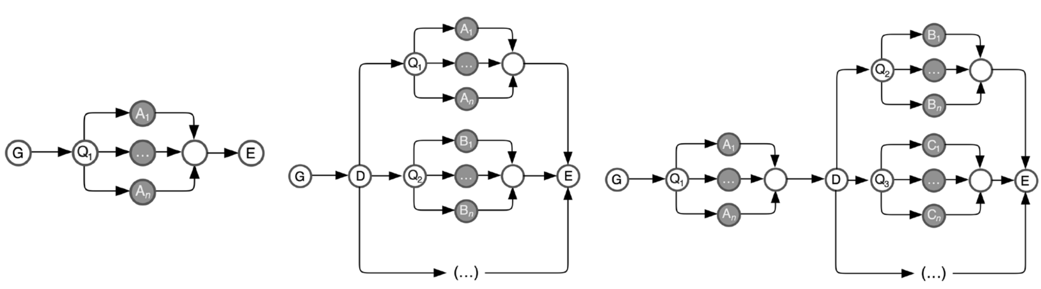

Fig. 1. The generic structure of BCP, a) single-stage, single-level system, b) single-stage, multiple-level system, c) multi-stage, multi-level system (authors' own work)

recommendations, border control for certain passenger groups may involve multiple stages, including pre-enrolment followed by enrolment. As a result, the functional structure should reflect its multi-stage nature. Furthermore, passengers crossing Schengen borders can be divided into at least four groups with distinct control procedures: citizens of member states (EU nationals), third-country nationals (TCNs) with visas (TCNs-VH), visa-exempt TCNs (TCNs-VE), and TCN residents permit holders (TCNs-RPH). EU nationals and TCNs-RPH passengers may be served either manually or through automated systems. This necessitates a multi-level functional structure comprising alternative service servers.

This paper focuses on developing a holistic methodology for designing passenger service processes within BCPs as a tool to aid in the planning and redevelopment of selected PSF areas. The proposed methodology aims to address whether the adopted planning assumptions regarding the functional characteristics of the BCP can be achieved from the perspective of the processes being implemented. Based on a review of the literature, presented in the subsequent sections, the authors identify a research area to be filled in, i.e., a methodology that simultaneously accounts for the selection and configuration of technical systems supporting border control processes, the stochastic and dynamic nature of passenger flow management, and a multi-criteria evaluation framework that supports a compromise solution. Therefore, the primary objective of this paper is to develop such a methodology and apply it in the context of an airport passenger terminal, taking into consideration its specific characteristics.

The first perspective of the holistic methodology involves selecting and determining the number of technical devices supporting passenger border control procedures. EU Directive 2017/2226 allows for the application of various technical solutions, such as manual border control (MBC) points, automated e-Gates, and self-service kiosks (SSKs). The selection of these solutions and the establishment of correlations between them is based on a generic multi-stage, multi-level functional structure of the BCP. The second perspective concerns the stochastic and dynamic nature of passenger flow control within the processes. Stochasticity relates to key characteristics of the process, primarily the time required to conduct passenger control and the timing of passenger arrivals at the BCP. Meanwhile, dynamic flow control procedures address queue formation and respond to real-time conditions, such as differing queue lengths at alternative groups of servers. Both phenomena are represented through mathematical modelling and simulation of BCP processes. The third perspective involves ensuring a compromise in terms of the applied evaluation criteria. Considering diverse process performance measures – whether organisational, technical, or economic – it is essential to identify a solution that best meets expectations across all the considered criteria. It is usually based on a trade-off that is achieved through the construction of a mathematical model (accounting for the specifics of each criterion), the development of a simulation model to estimate criteria values, and the selection of a decision aiding method to carry out computational experiments and to identify the best solution, i.e., the compromise one.

The remainder of the paper is structured as follows: Chapter 2 provides a literature review and identifies a research gap. Chapter 3 details the proposed methodology, including its general framework and key stages. Chapter 4 demonstrates the application of the methodology in designing passenger border control processes for a medium-sized BCP. Chapter 5 compares the proposed solution with alternative configurations and the current state. The final chapter summarises the results, discusses methodological and practical implications, and outlines directions for future work.

2. Literature review

As part of this research, the authors conducted a literature review focusing on the methods and procedures used in designing mass passenger service processes in airport terminals, covering a broader scope than border control alone. The most frequently identified passenger service areas in airport PSFs include three key zones: security control, check-in, and border control. Although these zones generally feature similar functional structures, they differ in purpose, procedures, and applied technical equipment. Consequently, the following sections outline the characteristics of studies related to the design of specialised passenger service zones in PSFs, with separate discussions for security control, check-in, and border control areas at the BCPs.

In studies focusing on security control zones in PSFs, the literature primarily addresses the use of simulation models and experiments to determine the key functional characteristics of these zones, considering various evaluation criteria (Leone, 2002; Kierzkowski and Kisiel, 2017, 2020; Li et al., 2024; Wang et al., 2023) and the application of fuzzy logic (Skorupski and Uchroński, 2015, 2018, Kierzkowski et al., 2024). Leone (2002) is among the first researchers to use simulation to assess the efficiency of a security control system for passenger baggage, identifying the minimum required number of devices based on the assumed detection frequency of suspicious items. The analysed system's structure reflects a typical single-stage, multi-level configuration, and the author also selects the scanning device type based on operational parameters to determine the optimal solution. Kierzkowski and Kisiel (2017) investigate the efficiency of security control zones, using a multi-stage (baggage unloading, baggage inspection, baggage collection with optional detailed inspection) and single-level process structure. A simulation model is built in FlexSim to reflect the system's operations, accompanied by an optimisation algorithm for scheduling human resources. The goal is to minimise process costs by ensuring the minimum required number of staff, aligned with current load levels in the security zone. In subsequent studies, the same authors explore security control efficiency under conditions of social distancing and queue formation in the baggage unloading zone (Kierzkowski and Kisiel, 2020). Li at al. (2024) delve into microscopic simulation of passengers' movement in the security checks area. Authors apply Cellular Automata (CA) model to reflect the probability of checkpoint selection by passengers analysing their behaviour, including the factors of spatial distance, number of queueing people and potential queueing passengers. The findings show aspects influencing waiting times, like checkpoint strategy, spatial layout, and arrival interval and verification time. Wang et al. (2023) use queue models and Monte Carlo simulation to calculate the costs of security control processes in a single-stage, multi-level configuration. Their study seeks an optimal solution that minimises the cost of servicing all passengers in a single day while keeping passenger waiting times below a specified threshold. The number of open control servers serves as the decision variable. Additionally, Wang et al. model various passenger queueing behaviours, allowing for autonomous decision-making by passengers in this regard. Skorupski and Uchroński (2015, 2018), in turn, focus on designing rules to support the identification of potential threats using fuzzy logic. Simulation experiments conducted by the authors demonstrate the relationship between threat detection in baggage control processes and the overall efficiency of the security control system for both baggage and passengers. Kierzkowski et al. (2024) combine simulation with fuzzy logic to assess various configuration of airport security control systems in the sustainable development context. The authors focus on such aspects of evaluation as energy savings, efficiency, passenger safety and reliability of human resources involved in operations carried out in the analysed area. The simulation model is constructed in FlexSim and it serves as a tool for calculating energy consumption and system's efficiency. It represents the procedures of passenger and baggage control. The output data of simulation feed the next model built in Matlab. Its application results in the overall assessment of the system taking into consideration the appropriate level of all aspects being analysed.

Regarding the design and evaluation of check-in zones, the literature reveals a significant focus on optimisation techniques, including binary programming (Yan et al., 2004), integer programming (Hsu et al., 2012), as well as heuristic algorithm (Yang et al., 2023), simulation (Kalbarczyk et al., 2023), fuzzy logic (Kiyildi and Karasahin, 2008), and mixed approaches combining optimisation and simulation (Mota, 2015; Adacher and Flamini, 2021). Yan et al. (2004) optimise the allocation of shared check-in counters at an airport, aiming to maximise counter utilisation and minimise passenger travel distances. They build a binary model and solve it using an exact branch-and-bound algorithm, applying a single-stage, multi-level functional structure by default. Hsu et al. (2012) and Mota (2015) focus on allocating check-in counters to passengers. Hsu et al. optimise the dynamic assignment of check-in counters and passenger allocation to minimise waiting times and maximise counter utilisation. They develop an integer programming model based on the Sequential Stochastic Assignment Problem (SSAP), considering stochastic passenger arrivals and varied service needs. Experiments demonstrate that applying SSAP and clustering services significantly reduces passenger waiting times and improves counter utilisation. Similarly, Mota (2015) uses an approach combining optimisation and simulation. Passenger-counter assignments are determined using an evolutionary algorithm considering operational constraints, e.g., the number of counters per flight and balanced workload distribution. Optimal assignments are then verified through a simulation model to account for the process's dynamic and stochastic nature. This approach, like Hsu et al., aims to minimise passenger waiting times and maximise counter utilisation. The improvement of check-in counter efficiency is also considered by Yang et al. (2023). This approach is based on the assumption that the utilization rate of check-in counters under the condition of unchanged resource allocation should be improved. The study is focused on counter-sharing method and the essence of a solution procedure is an evolutionary algorithm. The main assessment parameters are passenger's total walking distance and waiting time in the queues in front of the check-in stands. To maximize the counter-sharing rate the internal departure sequence of flights is adjusted, and the idle counters sharing between airlines in adjacent check-in is analysed. Kalbarczyk et al. (2023) use simulation in SIMIO, to model and evaluate three scenarios of passenger process at check-in stands. The main difference between these scenarios is the type of the equipment employed, including the traditional check-in desk and new technologies like Self-Service Kiosk (SSK) and on-line check-in. The most important parameters to be applied within the simulation model are: 1) service time represented by a minimum, average and maximum value, and 2) the frequency of passengers' departure wave. The result of simulations is the number and type of the check-in equipment, as well as information on waiting time of passengers to be checked-in. Kiyildi and Karasahin (2008) focus on capacity analysis in the check-in area with a high intensity of passenger flow. The random number of passengers and the random number of luggage are considered as an input data. Authors apply two different fuzzy logic methods to obtain total capacity of check-in unit per hour. The result can serve as management strategy to prevent queues of passengers in this area of the airport. In another study, Adacher and Flamini (2021) address the optimisation of airport check-in systems using a bi-criteria model for operational costs and queue waiting times. They assume a single-stage, multi-level functional structure and solve the problem using heuristic methods, some coupled with simulation techniques. The results include reduced waiting times and rationalised operational costs of check-in counters.

In publications dedicated to the design of border control zones, also called Border Crossing Points – BCPs, simulation approaches are evident on both macro (Ruiz et al., 2014) and micro scales, often based on risk assessment (Wang et al., 2021; Jain et al., 2020, 2023; Nie et al., 2012). Ruiz et al. (2014) assess border crossing processes for migrants using a multi-agent simulation (MAS) model to reflect interactions between migrants and border guards. The model evaluates how border policies influence migrants' route and crossing point choices, helping predict migration trends and assess regulatory impacts. On a micro scale, Wang et al. (2021) employ a two-stage, multi-level queuing model with limited capacity, distinguishing control server groups based on epidemic risk assessment. The first stage classifies passengers by epidemic risk, while the second stage directs them to appropriate control levels with varying server numbers, durations, and intensity of control procedures. The authors develop an analytical performance model for the entire system, considering average waiting times, rejected passenger counts, and security levels. The goal is to balance control efficiency and security by determining the necessary number of servers at each level. Jain et al. (2020, 2023) also apply risk-based passenger control, relying on profiling derived from biometric and behavioural data. Their model features a multi-stage, multi-level process, including preliminary classification, passenger identification, and single- or double-stage interviews with border guards for selected passengers. Using Monte Carlo simulation, the authors dynamically allocate resources by classifying passengers by risk level, minimising waiting times for low-risk passengers while focusing resources on high-risk individuals. Nie et al. (2012) take a similar approach, emphasising risk assessment but introducing Selectee Lanes for detailed control of high-risk passengers. Risk assessment forms a separate step in the process, supported by a combination of simulation, mathematical modelling, and rule-based systems to allocate passengers to the appropriate lanes. Their work aims to maximise threat detection efficiency.

The presented literature review yields the following key conclusions:

– The design of systems and processes for border control and the analysis of other passenger service zones within PSFs, including check-in and

security control, are methodologically aligned. The primary focus is on identifying sufficient resources to ensure smooth passenger service, with the main objectives being minimising waiting times and/or maximising resource utilisation.
- The publications are mostly focused on security control and check-in operations, while the number of research devoted to border control activities is very limited.
- Systematic analyses are based on single- or multi-level structures, primarily reflecting single-stage procedures, while the application of multi-stage procedures is rare due to the nature of the processes being controlled or serviced.
- In studies concerning the design of border control processes, existing approaches primarily evaluate the relationship between applied technology and risk assessment algorithms with the operation of border crossings in airport terminals. There is a lack of studies analysing control procedures and dynamic passenger flow management based on time-varying assessments of BCP conditions.
- Developed quantitative models for evaluating PSF areas, particularly BCP zones, are typically single-criterion, focusing on passenger waiting times, operational costs, or other aspects. Few studies seek compromise solutions across multiple criteria.

Based on this synthesis of the current state of knowledge, the authors identify a research gap addressed in this paper, i.e., there are few studies focused on border crossing point design in comparison to the research on check-in and security control operations. These studies do not concentrate on dynamic character of the passenger flow at the BCP, as well as control procedures and multi-criteria character of their assessment. Therefore, to closely reflect the reality of BCP operations, the methodology for its design or redesign should focus on several key aspects:
- The configuration of technical devices, i.e., addressing the composition problem by determining the types and quantity of equipment required for deployment at the BCP.
- Human resource planning for border control, i.e., determining the number of border guards and auxiliary staff needed to ensure the smooth flow of passenger traffic at the BCP.
- Accounting for the stochastic and dynamic nature of passenger flow, i.e., managing both the randomness of applied parameters and queue-based traffic control strategies.
- A comprehensive evaluation of BCP processes, i.e., ensuring that the recommended solution is assessed within a multi-criteria framework.

All three systems considered in the literature review, i.e., check-in, security check, and border control, are examples of queuing systems. However, each of them incorporates organisational solutions that prevent them from being regarded as universal models. A typical check-in system follows a single-stage and single-level structure (see Figure 1a), where baggage check-in and picking-up ticket occur within a single operation. Passengers wait in a single queue, which leads to multiple alternative servers. A typical security check system also generally follows a single-stage and single-level structure, but at each server, a sequence of operations is carried out in a continuous flow: placing personal belongings in trays, baggage screening, automatic and manual passenger screening, and retrieval of personal items. Although a single queue is formally present before the server, secondary queues may emerge due to the necessity of repeated passenger screenings. Additionally, the flow of screened personal items and passengers may become mixed-up. For the border control system, all three structures presented in Figure 1a–c are applicable. Certain distinct operations, such as pre-enrolment and registration, may take place either at sequence of servers, each with separated queues, or at a single server with one queue. Furthermore, these systems may facilitate the processing of different passenger groups at dedicated service stations, while some passengers may be excluded from using specific devices. All these factors make the structure of the BCP unique, requiring dedicated solutions tailored to its specific operational needs for border control procedures.

Thus, the goal is to develop a holistic methodology dedicated for designing border control processes in airport passenger terminals, enabling the determination of technical equipment configurations (selection of types and quantities for each type), the application of static and dynamic passenger flow control to maximise resource utilisation while minimising passenger waiting times, and the inclusion of multiple evaluation criteria to achieve compromise solutions.

3. Proposed methodology for border control process design in PSFs

3.1. Assumptions and key stages of the proposed methodology

The developed methodology is based on the following assumptions:

- It focuses on an existing PSF for which a new BCP is to be designed or the efficiency of an existing border control processes at the BCP is assessed. The assessment aims to determine whether changes are necessary and, if so, the scope of such changes.
- The PSF under analysis operates with a fixed schedule of transport arrivals and departures, and the analysis is conducted for the busiest day of the year, including consideration of the highest passenger flow during that day.
- The analysed BCP considers stationary servers, excluding mobile devices.
- All available border control devices at the BCP operate continuously at maximum capacity – operational scheduling of resources is not assumed. Combined with the reference day of the highest passenger flow, this approach identifies the maximum capacity of the designed solution.
- The analysis focuses on standard border control procedures, excluding deviations from typical process flows, i.e., only first-line control is modelled, excluding second-line control for problematic or questionable passenger cases.

The holistic methodology for designing passenger service processes at the BCP involves six key stages (S1–S6), illustrated in Figure 2. The first stage (S1) involves the performance analysis of the existing BCP. This stage requires identifying the reasons for conducting the analysis (1) and establishing an initial set of evaluation criteria (2) to comprehensively assess the current solution. The outcome of this stage is an evaluation of the BCP's efficiency (3) based on the assumed criteria. The second stage (S2) is implemented regardless of whether the approach concerns a newly designed facility or the redesign of an existing one. In this stage, based on the evaluation of the current state (3) and design assumptions for process variants (4), potential border control process variants are created, and evaluation criteria are refined considering the initial set of criteria (2). The outcomes of this stage are a formalised set of border control process variants (5) and refined evaluation criteria (6). In the third stage (S3), for each variant (5), a simulation model is developed using a selected simulation tool (7).

This model reflects the simulated process states and enables functional testing. The final outcomes of S3 are verified and validated simulation models of the variants (8), which serve as the basis for the subsequent stage. The fourth stage (S4) is based on simulations of the variants (8) and an evaluation of the obtained results using the set of evaluation criteria (6). This stage is continued until evaluations of all analysed variants are obtained.

The result of S4 is a performance matrix of the BCP's organisation variants (9). Based on the variants' evaluations and using an algorithm for selecting the most suitable decision aiding method (10),

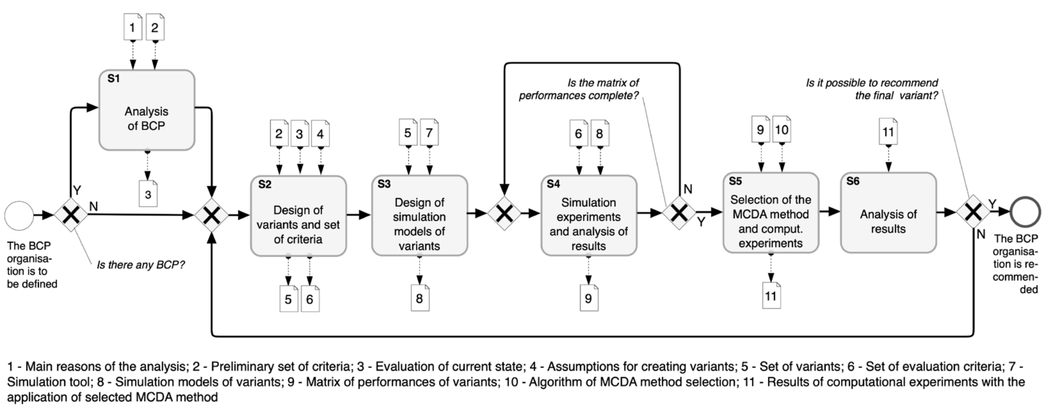

Fig. 2. Holistic methodology for designing passenger service processes at the BCPs

an appropriate MCDA method is chosen (S5). Its application results in the identification of the most favourable variant (11). In the final stage (S6) of the proposed methodology, the result obtained in stage 5 (S5) is analysed. If it is not possible to recommend the BCP organisation, the analysis should be repeated starting with stage 2 (S2) of the proposed methodology. The procedure is considered complete when the solution obtained in stage 6 (S6) enables the final configuration of the border control process in the designed BCP.
All stages of the proposed holistic methodology for designing passenger service processes in the BCPs are presented in detail in the next chapter, followed by the methodology application at an airport BCP.

3.2. Stage 1 – Analysis of BCP functioning

The analysis of the actions carried out at the BCPs in stage 1 (S1) applies to cases where the methodology is used to evaluate existing PSFs with an operational BCP. It is crucial to identify the reasons for conducting the analysis (1), such as pinpointing weaknesses in the organisation of the BCP. This analysis involves observations and an assessment of the efficiency of the existing solution, considering the set of criteria (refer to (2) in Figure 2). This evaluation forms the basis for identifying functional problems in the existing solution, such as queue lengths, the intensity of their formation, their frequency, waiting times or existing reserves, such as unused technical and/or human resources. The result of this analysis, that is the evaluation of the current state (3), provides an input for the subsequent stage, where observations, problem areas, weaknesses, and threats help appropriately design new solutions. This result can also be used later in the validation of the simulation model (S3).

3.3. Stage 2 – Designing variants and set of evaluation criteria

Based on inputs, see (2)-(4) in Figure 2, variants of border control process within the BCP are designed in stage 2 (S2). Factors resulting from local constraints, applicable norms and guidelines from managing and regulatory border traffic institutions are considered. These factors include:

- Spatial constraints, resulting from the division of PSF space into functional zones;
- Resource limitations, including financial resources for investments and ongoing infrastructure maintenance;
- Capabilities to control different categories of travellers using available technical resources.

These factors directly define optional border control possibilities, differing in elements such as:

- The types of technical equipment used for passenger control;
- The division of control activities into stages and the use of varied devices to execute them;
- The application of static or dynamic passenger flow management within the BCP depending on the current situation.

The multitude of possibilities necessitates creating several process variants for passenger control, which should then undergo detailed verification. In S2, conceptual models of process variants (5) are developed, which will serve in S3 to create simulation models that reflect these variants and form the basis for simulation analyses. In this stage, mathematical formalisation is carried out, i.e., a functional structure for the BCP is assumed – for a given variant, a set of criteria describing the passenger control process (6) is built alongside a set of constraints.
The BCP structure can be represented as a graph $G = (V, E)$, composed of a set of nodes V, $v, v{+}g, v{+}h, \dots, \mathcal{V} \in V$, and edges $E \subseteq V \times V$. By classifying the nodes v, four categories can be distinguished:

- Source nodes $v: v = s \in V^s$ and target nodes $v: v = m \in V^m$, representing the flow of passengers through the BCP;
- Nodes representing various control devices within the BCP $v: v = n, n{+}g, n{+}h, \dots N \in V^c$, referred to as homogeneous border control group of servers;
- Decision nodes $v: v = k, k{+}g, k{+}h, \dots, K \in V^d$, where redirection or modification of the initially established passenger path may occur.

Thus, it can be stated:

$$s, k, n, m \in V \;\Rightarrow\; V^s, V^d, V^c, V^m \in V \tag{1}$$

Edges reflect possible passenger movement paths, i.e., $s, k, (k, k{+}1), \dots, (K, n),\ (n, n{+}1), \dots, (N, m) \in E$. Consequently, the graph representing the BCP structure takes the form:

$$G = (V^s, V^d, V^c, V^m, E) \tag{2}$$

The structure of the analysed graph is shown in Figure 3, which marks the individual nodes. As this is a

directed graph, the possible directions of flow between vertices are also indicated. This graph represents all feasible connections between the v-nodes.
For the problem structure defined above and in line with the research objective, the authors propose the adoption of a set of five evaluation criteria. Using the set of notations, see the list at the end of the paper, the set of criteria is expressed through formulas (3)-(18), while constraints are represented by formulas (19)-(20).
Criterion C_1 evaluates the share of passengers served during border control within a time not exceeding the assumed threshold value to all passengers being border checked. Service here refers to the total time spent by a passenger p in the BCP area, including both the time spent waiting in queues in front of the server, or servers, as a natural feature of multi-stage process, and the time required for control at the server, or servers. This service can be defined as the service level $T^{\max}$, which measures the efficiency of the adopted technical solution, i.e., passenger handling devices, and the organisational setup, i.e., passenger flow control and management at the BCP area. Criterion C_1 takes into account all control servers handling a single passenger, and their mutual connections and interactions.
The default path of the p-passenger of r-type at the BCP at a time $t, t \in [0, T]$, along the edge $(v, v+g)$, $v, v+g \in V$, is defined by the binary control variable $f_{(v,v+g),p,r,t}$. A value of 1 indicates that the edge $(v, v+g)$ belongs to the default path, while a value of 0 means otherwise. The default path for the p-passenger of r-type is initially parameterised as a feasible solution. The value of the control variable $f_{(v,v+g),p,r,t}$ can be modified using a binary function $\varrho_{(v,v+g),p,r,t}$.
In practice, if $\varrho_{(v,v+g),p,r,t} = 1$, the p-passenger of r-type remains on the edge $(v, v+g)$ of the default path at t -time, meaning $f_{(v,v+g),p,r,t} = 1$. Conversely, if $\varrho_{(v,v+g),p,r,t} = 0$, the passenger is redirected to an alternative edge $(v, v+h)$, where $g \neq h$, indicating $f_{(v,v+g),p,r,t} = 0 \wedge f_{(v,v+h),p,r,t} = 1$. This criterion is expressed by (3)-(5) as follows:

$$max\, C_1 = \frac{1}{P} \sum_{p \in P} \sum_{r \in R} c_{(v,v+g),p,r,t}\, ;\, (\%) \tag{3}$$

where $c_{(v,v+g),p,r,t}$ denotes whether p-passenger is served within the specified time frame or not.

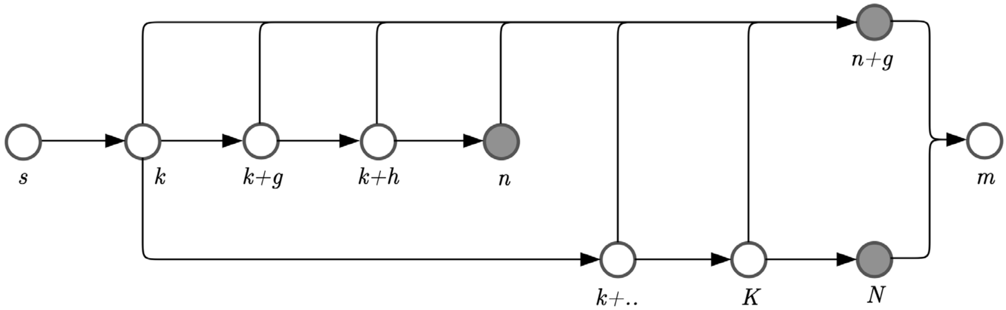

Fig. 3. The BCP area represented as a directed graph structure (authors' own work)

$c_{(v,v+g),p,r,t}$ can be described by the following equation:

$$c_{(v,v+g),p,r,t} = \begin{cases} 1, & \text{if} \sum_{v \in V} \sum_{v+g \in V^{\mathrm{c}}} \sum_{t \in [0,T]} \left(\tau^{\mathrm{c}}_{v+g,p} - \tau^{\mathrm{q}}_{v+g,p} + t_{(v,v+g),p,r} \right) \cdot f_{(v,v+g),p,r,t} \leq T^{\mathrm{acc}} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$
$$\forall p \in P, r \in R,$$

while:

$$f_{(v,v+g),p,r,t} = \begin{cases} 1, & \text{if } p\text{-passenger of } r\text{-type by default is moving from node } v \; to \; v+g \text{ at } t\text{-time} \\ 0, & \text{otherwise} \end{cases}. \tag{5}$$

The control of the p-passenger's path, $p \in P$, of r-type, $r \in R$, through modifications to its default trajectory can be implemented in two ways: static control or dynamic control. Static control assumes that, for $t \in [0, T]$ a part of p-passengers, no less than $\xi^s_{(v,v+g),p,r,t}$, regardless of the current situation at the BCP, remain on the default path containing the edge $(v, v+g)$. The remaining part, i.e., $1 - \xi^s_{(v,v+g),p,r,t}$, is redirected to an alternative path containing the edge $(v, v+h)$, where $g \neq h$. The redirection process is controlled by $\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{s}})$, according to formulas (6)-(7). In practice, static control relates to situations where legal or organisational regulations within the BCP restrict certain groups of passengers from accessing specific types of devices, for instance, due to passengers' height, level of disability, or age.

$$\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{s}}) = \begin{cases} 1, & \text{if} \sum_{\substack{p\in P \\ r\in R}} \sum_{v+g\in V} f_{(v,v+g),p,r,t} \Big/ \sum_{\substack{p\in P \\ r\in R}} \sum_{\substack{v+g, \\ v+h\in V}} \left(f_{(v,v+g),p,r,t} + f_{(v,v+h),p,r,t}\right) \le \xi^s_{(v,v+g),p,r,t} \\ 0, & \text{otherwise} \end{cases}; \tag{6}$$

$$\forall v \in V^{\mathrm{d}},\ \xi^s_{(v,v+g),p,r,t} \in [0,1],\ \xi^s_{(v,v+g),p,r,t} = \text{const.};\ \forall t \in [0, T]$$

then:

$$\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{s}}) = \begin{cases} 1, & \Rightarrow f_{(v,v+g),p,r,t} = 1 \ \wedge \ f_{(v,v+h),p,r,t} = 0 \\ 0, & \Rightarrow f_{(v,v+g),p,r,t} = 0 \ \wedge \ f_{(v,v+h),p,r,t} = 1 \end{cases} \tag{7}$$

Dynamic control assumes that, for $t \in [0, T]$, the redirection of the p-passenger from the default path containing the edge $(v, v+g)$ to the alternative path containing the edge $(v, v+h)$ depends on the current assessment of the queue lengths at the control servers located at nodes $v+g$ and $v+h$, where $v \in V^{\mathrm{d}}$; $v+g, v+h \in V^c$. If the queue length in front of the servers in node $v+h$ is $\xi^{\mathrm{d}}_{v+g,v+h,t}$ times longer of the queue length in front of the node $v+g$, the passenger remains on the default path $(v, v+g)$ and joins the queue in front of the server in the node $v+g$. Otherwise, the passenger is redirected to the alternative path $(v, v+h)$ and joins the queue in front of the node $v+h$. The principles of dynamic control are expressed by formulas (8)-(11):

$$\varrho_{(v,v+g),p,r,t}(\xi^d) = \begin{cases} 1, & \text{if } q_{v+g,t} \le \xi^{\mathrm{d}}_{v+g,v+h,t} \cdot q_{v+h,t} \\ 0, & \text{otherwise} \end{cases};\ \xi^{\mathrm{d}}_{v+g,v+g,t} \ge 0 \tag{8}$$

where:

$$q_{v+h,t} = q_{v+h,t-1} + \sum_{v\in V} \sum_{p\in P} \sum_{r\in R} f_{(v,v+h),p,r,t} - d^{\mathrm{c}}_{v+h,t};\ \ \forall t \in [0, T] \wedge t \in \mathbb{N},\ \forall v+h \in V^{\mathrm{c}} \tag{9}$$

$$q_{v+g,t} = q_{v+g,t-1} + \sum_{v\in V} \sum_{p\in P} \sum_{r\in R} f_{(v,v+g),p,r,t} - d^{\mathrm{c}}_{v+g,t};\ \ \forall t \in [0, T] \wedge t \in \mathbb{N},\ \forall v+g \in V^{\mathrm{c}} \tag{10}$$

then:

$$\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{d}}) = \begin{cases} 1, & \Rightarrow f_{(v,v+g),p,r,t} = 1 \ \wedge \ f_{(v,v+h),p,r,t} = 0 \\ 0, & \Rightarrow f_{(v,v+g),p,r,t} = 0 \ \wedge \ f_{(v,v+h),p,r,t} = 1 \end{cases} \tag{11}$$

Criterion C_2 evaluates the number of active d-devices, i.e., servers of the particular type, in v-nodes at t-time, participating in the passenger border control process at the BCP. The variable in this case is the number of $d_{v,t}$-devices. This criterion is minimised and expressed in items, as shown as (12)-(13):

$$min\,C_2 = \sum_{v\in V^{\mathrm{c}}}\sum_{t\in[0,T]} d_{v,t}\,;\ \text{(items)} \tag{12}$$

and

$$d_{v,t} = d^{\mathrm{b}}_{v,t} + d^{\mathrm{c}}_{v,t} + d^{i}_{v,t};\ \ \text{(items)} \tag{13}$$

Criterion C_3 evaluates the number of border guards involved in the control process at the BCP. Their involvement varies depending on the type of devices at the analysed BCP. For traditional manual border control (MBC) servers, one border guard is required per server. For automated devices, such as SSKs or e-Gates, the operation of several servers involves two border guards – one assisting passengers and the other supervising ICT systems. The number of border guards $b_{v,t}$ is a function of the number of $d_{v,t}$ devices. This criterion is minimised and expressed in persons, as shown in (14)-(15):

$$min\,C_3 = \sum_{v\in V^{\mathrm{c}}}\sum_{t\in[0,T]} b_{v,t};\ \text{(pers.)} \tag{14}$$

where:

$$b_{v,t} = \begin{cases} 0, & \text{if } d_{v,t} = 0 \\ b_{v,t,j} & \text{if } D^{\min}_{v,w} \le d_{v,t} < D^{\max}_{v,w} \\ \dots & \dots \\ b_{v,t,J} & \text{if } D^{\min}_{v,W} \le d_{v,t} < D^{\max}_{v,W} \end{cases}; \qquad \forall\, v \in V^{\mathrm{c}} \tag{15}$$

Criterion C_4 evaluates the number of auxiliary staff members engaged to assist in passenger handling within the BCP. The role of auxiliary staff is to manage and control movement within the BCP, specifically directing passengers towards optional v-nodes, i.e., groups of servers, if such redirection is necessary. Auxiliary staff are positioned at decision nodes $v \in V^{\mathrm{d}}$ within the BCP structure, where passengers may potentially be redirected from default paths to alternative ones. Their involvement depends on the number of implemented control procedures and their placement within the BCP structure. Passenger redirection from the default path defined by $f_{(v,v+g),p,r,t}$ is modulated by the binary function $\varrho_{(v,v+g),p,r,t}$, through either static control, as expressed by formulas (6)-(7), or dynamic control, see (8)-(11). This enables the p-passenger of r-type to either remain on the default path from node v to v+g or be redirected to an alternative path from node v to v+h, where $v, v{+}g, v{+}h \in V$. This criterion is minimised and expressed in persons, with the defined formulas (16)-(17).

$$min\,C_4 = \sum_{k\in V^{\mathrm{d}}} w_{v,p,r,t}\,;\ \text{(pers.)} \tag{16}$$

where $w_{v,p,r,t}$ identifies the occurrence of redirection procedures for p-passengers of r-type at t-time in decision node v, and is defined by equation (17).
Criterion C_5 evaluates the space required for passengers within the BCP. This directly impacts the design of the area necessary for conducting border control. In particular, it refers to the space needed to facilitate smooth movement and waiting in queues during passenger accumulation, i.e., peak hours. Consequently, this criterion identifies the maximum queue lengths observed during simulations at all v-nodes of control servers, $v{:=}\,n$. This criterion is

$$w_{v,p,r,t} = \\ = \begin{cases} 0, & \text{if } \left(\sum_{v\in V}\sum_{\substack{p\in P\\ r\in R}}\sum_{t\in[0,T]} \left(f_{(v,v+g),p,r,t}\right) \Big/ \sum_{\substack{v+g,\\ v+h\in V}}\sum_{\substack{p\in P\\ r\in R}}\sum_{t\in[0,T]} \left(f_{(v,v+g),p,r,t} + f_{(v,v+h),p,r,t}\right) \right) = \{0,1\}; \\ 1, & \text{otherwise} \end{cases} \qquad \forall v \in V^{\mathrm{d}}. \tag{17}$$

minimised, expressed in [m²], and formulated as (18):

$$min\, C_5 = u_v \cdot \left(\max_{t\in[0,T]} \sum_{v\in V^c} q_{v,t} \right);\ (\mathrm{m}^2) \tag{18}$$

To ensure the feasibility of the passenger service system, a set of constraints has been introduced, expressed in formulas (19)-(20). The first constraint (19) ensures the continuity of passenger flow through the BCP, from the source $v: v = s \in V^{\mathrm{s}}$ to the destination $v: v = m \in V^m$, passing through intermediate nodes $v: v = k \in V^{\mathrm{d}} \wedge v: v = n \in V^{\mathrm{c}}$. The second constraint (20) ensures that the maximum time spent by the passenger at the BCP area does not exceed the maximum total time for border control indicated by the threshold $T^{\max}$. These constraints are expressed as follows:

$$\sum_{v,v+g\in V} \sum_{t\in[0,T]} f_{(v,v+g),p,r,t} - \sum_{v+g,v+h\in V} \sum_{t\in[0,T]} f_{(v+g,v+h),p,r,t} = \begin{cases} P, & \text{if } v+g: s \in V^{\mathrm{s}} \\ -P, & \text{if } v+g: m \in V^{\mathrm{m}} \\ 0, & \text{if } v+g \in (V^c, V^d) \end{cases}; \quad \forall p \in P, r \in R; \tag{19}$$

$$\sum_{v\in V} \sum_{v+g\in V^{\mathrm{c}}} \sum_{t\in[0,T]} \left(\left(\tau^{\mathrm{c}}_{v+g,p} - \tau^{\mathrm{q}}_{v+g,p} + t_{(v,v+g),p,r} \right) \cdot f_{(v,v+g),p,r,t} \right) \le T^{\max}; \quad \forall p \in P, r \in R; \tag{20}$$

3.4. Stage 3 – Development of simulation models for process variants

According to the methodological assumptions (see Figure 2), stage 3 (S3) involves building a simulation model for the current state and its organisational variants. These models aim to reflect both the passenger border control process and the dynamics of occurring phenomena (including the formation and continuous changes in queues, as well as passenger redirection management based on queue lengths in front of the control servers). Moreover, they must comply with the defined set of criteria (S2), serving as the base for determining their values.

The foundation for constructing the simulation model in terms of its structure is the BCP model represented as a graph (see Figure 3). Based on this, the authors propose creating a simulation model of the current state and its variants whose functionality corresponds to the algorithmic logic presented as a pseudocode.

The concept of simulation model is illustrated in Figure 4. This process consists of 13 steps. In step 1, arrivals of p-passengers at the BCP are generated at the v=1 node. To this end, parameters of arrival time t^{a}_p and walking time between arrival at the terminal and BCP t^{w}_p are utilized. Next, p-passengers of r-types are distributed at time t (see step 2) for $t<T$ to one of three possible nodes: v=3 (p-passengers of type $r \in R_1$), v=6 (p-passengers of type $r \in R_3$), and v=8 (p-passengers of type $r \in R_2$), respectively. In step 3, at node v=3, for each p-passenger of type $r \in R_1$, a decision is made on whether the passenger should remain on the default path from v=3 to v=6 (ultimately to SSK) or be redirected from v=3 to v=8 (ultimately to MBC). The decision is based on a binary parameter $\xi^s_{(3,8),p,r,t}$, which, over the simulation time T, represents the fixed percentage of p-passengers to be redirected (to node v=8) from the default path. If p-passengers of type $r \in R_1$ remain on the default path, at node v=4 in step 4, a decision is made regarding whether the passenger should continue on the default path to node v=5, i.e., to SSK, and join to the corresponding queue, or be redirected to node v=8 (to MBC) and join another queue. This decision is based on the dynamic parameter $\xi^d_{(4,8),t}$, which represents the difference between reference queue lengths at time t, i.e., $q_{5,t}$, and $q_{8,t}$. All passengers remaining on the default path (to node v=5) are then queued (see step 5) until a server at node v=5 becomes idle, i.e., $d^i_{5,t} > 0$. Once available, each passenger is processed at node v=5 (see step 6) with a processing time $t_{(4,5),p,r}$. Then, p-passengers of type $r \in R_1$ are by default directed to node v=8 (to MBC), and, if required, queued in front of the server (see step 9). This queue also includes all p-passengers:

– redirected from node v=3 to v=8, after step 3,

- redirected from node v=4 to v=8, after step 4,
- of type $r \in R_2$ initially distributed from node v=2 to v=8, after step 2,
- of type $r \in R_3$ redirected from node v=6 to v=8, after step 7,
- of type $r \in R_3$ redirected from node v=7 to v=8, after step 8.

All queued passengers remain there until a server at node v=8 becomes idle, i.e. $d^i_{8,t} > 0$. When a server is available, each p-passenger is processed one by one (see step 10) with a processing time dependent on the origin node, i.e., $t_{(2,8),p,r}$, $t_{(3,8),p,r}$, …, $t_{(7,8),p,r}$.

All p-passengers of type $r \in R_3$ are directed by default from node v=2 to v=9, ultimately reaching e-Gate. In between, at node v=6, a decision is made based on the static parameter $\xi^s_{(6,8),p,r,t}$ to determine whether p-passenger should be redirected to the alternative path (to node v=8) or remain on the default path (see step 7). If the default path is selected, then at node v=7, another decision is made regarding whether the p-passengers of type $r \in R_3$ should remain on default path (to node v=9, i.e., to e-Gate) or to be redirected to node v=8 (MBC). This decision is determined based on the dynamic parameter $\xi^d_{(7,8),t}$, which represents the difference between reference queue lengths at time t, i.e., $q_{8,t}$ and $q_{9,t}$. All passengers remaining on the default path (to node v=9) are then queued (see step 11) until a server at node v=9 becomes idle, i.e., $d^i_{9,t} > 0$. Once available, each passenger is processed at node v=9 (see step 12) with processing time $t_{(7,9),p,r}$. All p-passengers redirected from the default path, i.e., statically at node v=6 (step 7) or dynamically at node v=7 (step 8), are added to the queue prior to node v=8 (step 9) and processed at v=8 (step 10), if available at t.

Finally, when the simulation time ends, i.e., t=T, and all planned passengers have been processed, i.e., p=P, all required criteria C_1- C_5 are calculated in step 13. Once this is completed, the simulation ends. If the number of passengers $p \leq$ P at the simulation time T, the simulation time T should be extended, and the process should be repeated.

A detailed description of the simulation procedure, in the form of pseudocode, is provided in Appendix B at the end of the paper. Its implementation can be carried out in any simulation tool with an open architecture. Stage 3 ensures that the simulation models accurately capture the processes and conditions of the BCP system while being adaptable for evaluation and optimisation using various simulation platforms.

In accordance with the assumptions outlined in Section 3.1, the constructed models should undergo verification (evaluation of their functional correctness) and validation (evaluation of the generated results). This process should utilise information obtained during the evaluation of the existing solution, see stage 1 (S1), and result (2), see Figure 2.

3.5. Stage 4 – Simulations and evaluation of the results

The simulation models of process variants developed and validated in stage 3, see (8) in Figure 2, form the basis for conducting dynamic simulations. These simulations aim to quantitatively verify how the border control process is implemented under specified conditions. On the one hand, they rely on input parameters; on the other, they involve control variables, whose optimal configuration must be determined during the simulation process. From this perspective, it is assumed that simulations will be conducted to test various configurations forming variants, in the following areas:

- Technical devices used. Different types of equipment primarily influence the unit time required for border control for the p-passenger of r-type at the control servers in v-nodes, dependent on their direction from node v to v+g, i.e., $t_{(v,v+g),p,r}$ for $v \in V^{\mathrm{d}}, v+g \in V^{\mathrm{c}}$;
- Process configurations. Different setups of servers in v-nodes and the configuration of default paths directing p-passengers of r-type represented by $f_{(v,v+g),p,r,t}$ for $v \in V, v+g \in V^{\mathrm{c}}$, with a possibility to be redirected by $f_{(v,v+h),p,r,t}$ for $v \in V, v+h \in V^{\mathrm{c}}$;
- Organisational rule modulation. The rules for redirecting p-passengers of r-type to alternative paths, redirected by $\varrho_{(v,v+g),p,r,t}$ for $v \in V^{\mathrm{d}}, v+g \in V$, using both static and dynamic control, i.e. $\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{s}})$, and $\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{d}})$;
- Quantity of technical devices. The number of d-devices in v-nodes, i.e., $d_{v,t}$ for $v \in V^{\mathrm{c}}$;
- Combinations of the above variables.

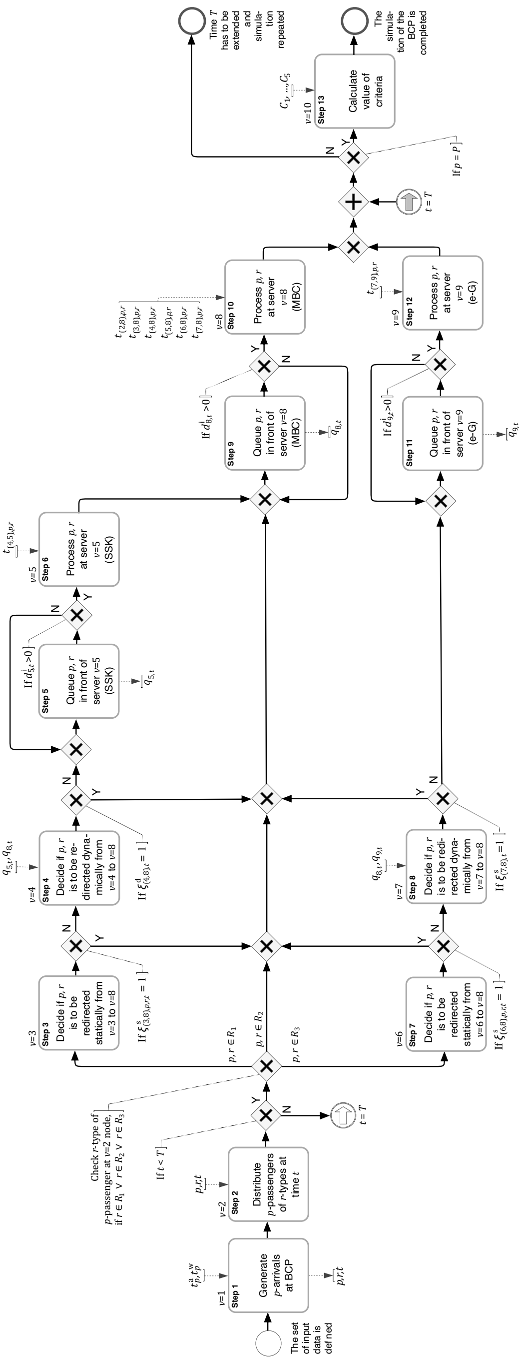

Fig. 4. Concept of the simulation model of the passenger process at the BCP (authors' own work)

Based on these variables and parameters, different variants are generated, which are then subjected to simulation verification and evaluation in stage 4 (S4). Following the proposed methodological framework, simulations are repeated from the first to the last variant to produce a performance matrix, i.e., a set of criteria values, see (6) in Figure 2, for each variant considered. The selection of the most advantageous variant, understood as a compromise solution, from the simulation-generated set of variants is addressed in stage 5 (S5).

3.6. Stage 5 – Selection and application of the MCDA method

Since the previously developed mathematical model assumes the existence of multiple evaluation criteria, a comprehensive assessment of the obtained solutions is necessary. For this reason, S5 involves selecting and applying a multi-criteria decision aiding (MCDA) method. According to Sawicki and Sawicka (2021), the choice of an appropriate MCDA method must be carefully conducted, primarily by considering the alignment between the method's characteristics and the decision-making problem, including the decision-maker's preferences. The selection process should not be arbitrary or based on the method's popularity within a particular research field or user preference. Guitouni and Martel (1998) suggest that despite the development of numerous MCDA methods, none can be deemed suitable for all decision-making situations. Over time, a rich collection of methods has been developed, comprehensively reviewed in various studies. The literature distinguishes between general-purpose methods, as by works such as Greco et al. (2016), and Sahoo and Goswami (2023), and specialised methods, including those tailored for transport applications, e.g., Yannis et al. (2020).

The challenge of selecting an appropriate MCDA method for a decision-making problem is widely discussed in the literature, e.g., Roy & Słowiński (2013), Sawicka (2012), and Sawicka (2020). Following the approach presented in Sawicka (2020), the authors adopted a four-step procedure comprising:

- Step 1: Comparative analysis of MCDA methods, including method classification, axiomatic analysis, and practical utility analysis;
- Step 2: Identification of the decision-making problem, including its structure, availability of information, nature and type of information, and the decision's time horizon;
- Step 3: Recognition of decision-maker preferences, encompassing the strategic level of decisions, precision of preference information, preference structure and its expression, timing of preference articulation, and the relationship between variants in the final outcome;
- Step 4: Comparison of results and selection of the most suitable MCDA method.

The result of these steps is the selection of MCDA method that best matches the decision-making problem and the decision-maker's preferences. Following Sawicki and Sawicka (2021), it is worth emphasising that while this phase aims to identify the most suitable MCDA method for the analysed problem, it may not necessarily be a universal method for addressing similar decision-making problems. This variability arises from the availability and type of information, as well as the subjective nature of the decision-maker's preferences, including how they are articulated and the expected outcome, i.e., the relationship between variants.

Based on the chosen decision aiding method, computational experiments are conducted. Depending on the research objective, these experiments may result in an appropriate ranking of BCP organisation variants, selection of the best variant, or classification of variants to predefined classes.

3.7. Stage 6 – Analysis of results

The final stage of the proposed methodology, i.e., stage 6 (S6), primarily focuses on analysing the results obtained through the application of the selected MCDA method. Formally, this represents a compromise solution aligned with the predefined objectives, i.e., the adopted evaluation criteria. While this stage might appear straightforward, it holds significant importance as the solution derived in stage 5 might not be definitive. Firstly, depending on the nature of the problem (e.g., ranking, selection or classification), there might be several equivalent compromise solutions. Secondly, the solutions may be characterised by incomparability. Each of these situations requires identifying a recommended solution; if this is not feasible, the analyses conducted in this stage may necessitate returning to stage 2 (S2) of the methodology. This involves reformulating the set of variants, as indicated in Figure 2, and the evaluation criteria. As a result, the sequence of stages S2–S6 must be repeated as many times as a recommended solution can be identified.

4. Application of the passenger control process design methodology at an airport BCP

4.1. Preliminary assumptions

The methodology presented in Section 3 was applied to evaluate the current and design the target functional area of the BCP as part of the redesign of a medium-sized passenger terminal, organized to handle over 6,000 pax daily. The motivation for undertaking these actions was the need to verify and, if necessary, adapt the terminal's capacity to new conditions related to preparing for the implementation of the Entry/Exit System (EES) and ensuring comfortable conditions for passengers using the terminal. Passenger comfort in this context is understood to encompass two key aspects: first, providing sufficient space for free movement and presence within the BCP, and second, ensuring efficient processing, measured by maximum total time $T^{\max}$ for border control of each passenger including waiting time in front of the server, set at 20 minutes.
The experimental section of the paper is focused on the BCP within an airport terminal located in western part of Europe. It was assumed that the structure and schedule of arrivals and departures would remain unchanged before and after the terminal's redesign. The primary motivation for organisational changes is the expected significant increase in border control times for TCN-VE and TCN-VH passengers following the implementation of the EES. The EES requires the identification and registration of key biometric parameters, such as iris recognition, facial shape, and fingerprints, which significantly extend the time needed to perform control activities during border crossing. This study specifically focuses on arrivals, using as a reference the arrival schedule from an anonymised flight timetable, which, on the day of peak traffic, includes 6,356 pax across 34 flights.

4.2. Stage 1 – Analysis of the airport BCP operations

The analysis of the current state of the border control process before the implementation of the EES begins with gathering information on the type and number of available equipment, the structure of passengers on arrivals, processing time (including waiting time before reaching the servers), the number of border guards involved in the BCP operations, and the space required for passengers in front of the servers. As a result, a preliminary set of five evaluation criteria, denoted as C_1-C_5, has been used: C_1 – the percentage of passengers processed in less than 10 minutes, C_2 – the number of servers engaged in the border control process, C_3 – the number of border guards assigned to border control operations, C_4 – the number of auxiliary staff assisting with passenger operations at the BCP, and C_5 – the total area allocated for passengers waiting in queues for border control.
The status quo of border control process is defined for four main passenger groups, including: EU nationals (59%), TCNs-VE (29%), TCNs-VH citizens (10%), and TCNs-RPH (2%). This process follows a single-stage approach, meaning that all passengers undergo comprehensive checks at the MBC servers (see Figure 1a). Processing times vary significantly by passenger type: for EU nationals it ranges between 19–23 seconds for TCNs-RPH 25–29 seconds, for TCNs-VE approximately 40–44 seconds, which is about twice as long as for EU nationals, and for TCNs-VH processing takes over four times longer, averaging 96–100 s. Based on measurements and observations, it was determined that passenger service time of all 6,356 passengers does not exceed 20 min, with 97% of passengers processed in under 10 minutes. A total of eight manual border control lanes (8 MBLs), staffed by eight border guards, are utilised for this purpose. No auxiliary staff are required to manage passenger flows within the BCP, as passenger movement relies solely on standard informational signage. A single queue is organised in front of all eight servers, accommodating a maximum of 160 passengers during peak periods. Consequently, an area of 239 m² is required to accommodate passengers waiting in the queue.
Considering the collected data and the anticipated changes to BCP operations, the decision problem has been defined as the redesign of the BCP organisational layout to ensure that, following EES implementation, passenger service time, including queueing time, does not exceed 20 minutes, while simultaneously maximising the number of passengers processed in less than 10 minutes.

4.3. Stage 2 – Variant design and formalisation of evaluation criteria

As part of stage 2 (S2), 140 variants of BCP organisation have been designed, all sharing the use of the same types of servers: Manual Border Control (MBC), Self-Service Kiosks (SSKs), and e-Gates (e-Gs). The variants differ in the number of devices, the number of border guards, the number of auxiliary staff, and options for redirecting passenger flows to various types of servers. After EES implementation there are distinguished six types of passengers, that are as follows:

- EU nationals, denoted as $r = 1$;
- TCNs-VE – first entry (f-e), denoted by $r = 2$;
- TCNs-VE – non-first entry (n-f-e), denoted by $r = 3$;
- TCNs-VH – first entry (f-e), denoted by $r = 4$;
- TCNs-VH – non-first entry (n-f-e), denoted by $r = 5$;
- TCNs-RPH, denoted by $r = 6$.

This classification results from different processing time using the above-mentioned types of the servers. To reflect the structure of the BCP where the target border control processes are to be implemented, a generic graph has been constructed. The functional structure of the BCP includes numbered nodes $v = 1,2,\dots,10$ with their roles identified in Figure 5:

- Source node (v=1) and a destination node (v=10), representing passenger entry to and exit from the BCP.
- Passenger control nodes using different types of devices: SSKs (v=5), MBC (v=8), and e-Gs (v=9);
- Decision nodes for managing passenger flow, such as: static allocation of passengers between SSKs and MBC (v=3) and between e-Gs and MBC (v=6), and dynamic allocation based on queue length comparison between SSKs and MBC (v=4), and between e-Gs and MBC (v=7).

Additionally, default passenger flow directions without redirections have been established, marked in Figure 5 with solid lines, i.e.:

- For EU nationals primarily using e-Gates: (1)−(2)−(6)−(7)−(9)−(10);
- For f-e TCNs-VE , n-f-e TCNs-VE , f-e TCNs-VH, and n-f-e TCNs-VH, primarily using the SSKs-MBC sequence: (1)−(2)−(3)−(4)−(5)−(8)−(10);
- For TCNs-RPH, primarily using MBC: (1)−(2)−(8)−(10).

The default flow of the p-passenger of r-type has been expressed in the form of matrices presented in Table 1. For instance, in the matrix on the left-hand side EU nationals identified as r=1, are directed from node 1 (row 1) to node 2 (column 2). In this case, the flow is assigned the value $f_{(v,v+g),p,r,t} = 1$. Next, EU nationals proceed from node 2 (row 2) to node 6 (column 6); hence, the intersection of row 2 and column 6 is also assigned a value of 1. Subsequently, EU national passengers proceed from node 6 (row 6) to node 7 (column 7), from node 7 (row 7) to node 9 (column 9), and finally from node 9 (row 9) to node 10 (column 10). These matrices serve as the foundation for the simulation of the border control process in the analysed BCP. Its variants include adjustments in passenger flows, such as changes based on the static and dynamic flow control, and the number of each type of the server (MBC, SSK, and e-G). To evaluate the BCP structure and the variants of the target border control process, the set of criteria and constraints presented in Section 3.3, equations (2)-(20), have been applied.

4.4. Stage 3 – Construction of variants' simulation models

To reflect current state of the BCP and its variants in the simulation model, the general scheme presented in Figure 4 in Section 3.4, along with corresponding pseudocode, has been utilised. Its implementation has been carried out using the ExtendSim v.10 software. The verification and validation of the developed model have been conducted for the current state, and following parameters have been applied for this purpose:

- the structure of BCP follows a typical single-stage process (see Figure 1a),
- the total number of passengers is 6,356 per day, following a detailed schedule (see Appendix A),
- 8 MBLs and 8 border guards are employed,
- the simulation time is T=1,440 minutes,
- processing times and their experimental distribution for four typical passenger groups have been adopted from Section 4.2.

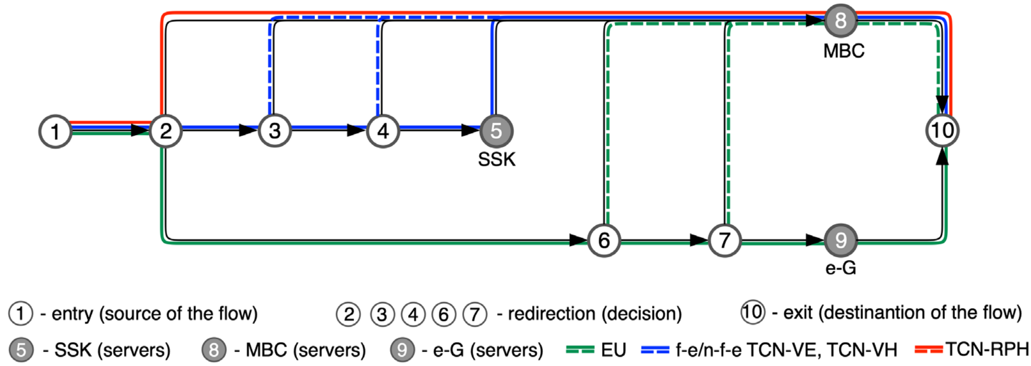

Fig. 5. An initially parametrised structure of the BCP as a graph (authors' own work)

Table 1. Function f matrices for p-passenger of r-type - default flow

$f_{(v,v+g),p,r,t};\ \forall r = 1$

v \ $v+g$	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	0	0	0	0
2	-	-	0	0	0	1	0	0	0	0
3	-	-	-	0	0	0	0	0	0	0
4	-	-	-	-	0	0	0	0	0	0
5	-	-	-	-	-	0	0	0	0	0
6	-	-	-	-	-	-	1	0	0	0
7	-	-	-	-	-	-	-	0	1	0
8	-	-	-	-	-	-	-	-	0	0
9	-	-	-	-	-	-	-	-	-	1
10	-	-	-	-	-	-	-	-	-	-

$f_{(v,v+g),p,r,t};\ \forall r = 2,3,4,5$

v \ $v+g$	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	0	0	0	0
2	-	-	1	0	0	0	0	0	0	0
3	-	-	-	1	0	0	0	0	0	0
4	-	-	-	-	1	0	0	0	0	0
5	-	-	-	-	-	0	0	1	0	0
6	-	-	-	-	-	-	0	0	0	0
7	-	-	-	-	-	-	-	0	0	0
8	-	-	-	-	-	-	-	-	0	1
9	-	-	-	-	-	-	-	-	-	0
10	-	-	-	-	-	-	-	-	-	-

$f_{(v,v+g),p,r,t};\ \forall r = 6$

v \ $v+g$	1	2	3	4	5	6	7	8	9	10
1	-	1	0	0	0	0	0	0	0	0
2	-	-	0	0	0	0	0	1	0	0
3	-	-	-	0	0	0	0	0	0	0
4	-	-	-	-	0	0	0	0	0	0
5	-	-	-	-	-	0	0	0	0	0
6	-	-	-	-	-	-	0	0	0	0
7	-	-	-	-	-	-	-	0	0	0
8	-	-	-	-	-	-	-	-	0	1
9	-	-	-	-	-	-	-	-	-	0
10	-	-	-	-	-	-	-	-	-	-

The verification of the simulation model was conducted during the development of the simulation model and after its final construction. This process involved checking the correctness of the object sequence in the constructed model, the parameters entered into individual objects, and the correctness of the flow of passengers and information within the model. The applied simulation tool being used has model verification functions, that significantly assist the analyst at this process. One of the significant measurable indicators of the correct operation of the simulation model was the total number of 6,356 passengers processed within assumed simulation time (24 hours), meaning that the number of passengers entering the model was matched in 100% by the number exiting after completing the border control procedure. The results obtained from this approach suggest that the simulation model was constructed correctly.

The validation process involves checking whether the constructed model accurately reflects the modelled system. If the system is real, as in the analysed case, validation is based on comparing data from the simulation experiments with real-world data. The study employed the confidence-interval approach to assess the differences in mean values obtained from the system and simulation experiments (Law & Kelton, 2000) for a 90% confidence interval. This method is justified for large data sets. An example is the difference between simulated average queue lengths and observed values during peak hours on a reference day, which did not exceed 5%. This was considered a satisfactory result. Furthermore, after applying the necessary modifications, the model has also been used to simulate variants of the BCP organisation.

4.5. Stage 4 – Running simulation experiments and evaluation of results

To simulate the border control process and its variants, the set of parameters presented in Table 2 and Table 3 has been utilised. A detailed schedule of arrivals has been included as an Appendix A to the paper. Most of the time-related parameters in Table 2 are assumed values. Specifically, T represents the expected 24-hour operational profile of the BCP, T^{acc} is derived from IATA recommendations, and $T^{\max}$ is based on an assessment of the current operational state. The parameter t_p^w is an empirical value obtained from observations of as is passenger behaviour. The parameter P is an assumed total passenger flow value, derived from the empirical arrival distribution presented in Table 7 (see Appendix B).

The values r and v are designations introduced to adapt the generalised structure shown in Figure 5 to the specific case under analysis. The dynamic control parameter ξ^{s} represents an acceptable variability range for passenger flow control, as defined for the purpose of this study, while the dynamic control parameter ξ^{d} for node v=2 is a fixed value, derived from the empirical passenger structure for the as is arrival schedule. The parameter $b_{v,t}$ is based on the equipment provider's guide–lines for devices used at border crossings.

Table 2. Key input parameters for the BCP – Target values on arrivals

Parameters	Values	E/A[1]	Parameters	Values	E/A
T	1,440 (min)	A	$\xi^{\mathrm{d}}_{v+g,v+h,t}$	$\xi^{\mathrm{d}} \in [0,10]$	A
$T^{\max}$	20 (min)	A	$\xi^{s}_{(v,v+g),p,r,t}$	$\forall v = 2, t \in [0,T]$ r=1 ∧ v+g=6 ⇒ ξ^{s} = .59	E
T^{acc}	10 (min)	A			
t_p^{w}	5-20 (min)	E		r=2 ∧ v+g=3 ⇒ ξ^{s} = .02 r=3 ∧ v+g=3 ⇒ ξ^{s} = .08	
P	6,356 (pax/24h)	E		r=4 ∧ v+g=3 ⇒ ξ^{s} = .06 r=5 ∧ v+g=3 ⇒ ξ^{s} = .23	
r	r=1 ⇒ EU natls. r=2 ⇒ f-e TCN-VE r=3 ⇒ n-f-e TCN-VE r=4 ⇒ f-e TCN-VH r=5 ⇒ n-f-e TCN-VH r=6 ⇒ TCN-RPH	A	$b_{v,t}$ $\forall t \in [0,T]$	r=6 ∧ v+g=8 ⇒ ξ^{s} = .02 $b_{5,t} = \begin{cases} 2 & 1 \le d_{5,t} < 8 \\ 3 & 9 \le d_{5,t} < 16 \\ 5 & 17 \le d_{5,t} < 24 \end{cases}$	A
$v = n$	n=5 ⇒ SSK n+g=8 ⇒ MBC n+h=9 ⇒ e-G	A		$b_{8,t} = d_{8,t}$ $b_{9,t} = \begin{cases} 2 & 1 \le d_{9,t} < 8 \\ 3 & 9 \le d_{9,t} < 16 \\ 5 & 17 \le d_{9,t} < 24 \end{cases}$	

[1] E – empirical value, A – assumed value

Table 3. Unit border control time per passenger $t_{(v,v+g),p,r}$ – Target values on arrivals

Passenger of r-type	Processing time $t_{(v,v+g),p,r}$ for r, depending on $(v, v+g)$, in (s)				
	v+g=5 (4, 5)	v+g=8 (2, 8) ∨ (3,8) ∨ ∨ (4,8)	v+g=8 (5, 8)	v+g=8 (6, 8) ∨ (7,8)	v+g=9 (7, 9)
r=1 ⇒ EU natls.	n/a A[1]	19-23 E	n/a A	20-24 E	25-29 E
r=2 ⇒ f-e TCN-VE	129-133 EP	91-95 EP	36-40 EP	n/a A	n/a A
r=3 ⇒ n-f-e TCN-VE	109-113 EP	71-75 EP	27-31 EP	n/a A	n/a A
r=4 ⇒ f-e TCN-VH	124-128 EP	135-139 EP	53-57 EP	n/a A	n/a A
r=5 ⇒ n-f-e TCN-VH	104-108 EP	115-119 EP	45-49 EP	n/a A	n/a A
r=6 ⇒ TCN-RPH	n/a A	25-29 E	n/a A	n/a A	n/a A

[1] E – empirical value, A – assumed value; EP – empirical value based on pilot

The time-related parameters presented in Table 3 are mostly empirical values, with a distinction made between two cases. The basic case (E) applies primarily to two passenger groups, i.e., EU and TCN-RPH, and is based on observations of regular as is processing. The pilot-based case (EP) refers to experimental data obtained during tests of SSK technology in combination with MBC, covering all TCN-VE and VH, for both first-entry and non-first-entry type passengers. Other cases, marked as n/a, indicate an assumed lack of processing capability for certain passenger groups using specific types of devices. The empirical distribution has been assumed for all empirical values in Tables 2 and 3, except for the total number of passengers, P, to be border-checked over 24 hours, which is a fixed value.

For the simulation of variants, the following control variables for the mathematical model described in Section 3.3 have been adopted:

– The utilisation of three key types of technical devices, i.e., different types of servers and applied technologies, that affect the processing time required for border control of p-passengers of r-type at respective v-nodes of BCP, depending on their direction from node v to node v+g, i.e., $t_{(v,v+g),p,r}$ for $v \in V^{\mathrm{d}}, v\text{+}g \in V^{\mathrm{c}}$;
– The process flow with various configurations of servers in v-nodes and structuring of default paths for p-passengers of r-type, directed by $f_{(v,v+h),p,r,t}$ for $v \in V, v\text{+}g \in V^{\mathrm{c}}$;
– The redirection of p-passengers of r-type to alternative paths, controlled by the value $\varrho_{(v,v+g),p,r,t}$ for $v \in V^{\mathrm{d}}, v\text{+}g \in V$, using both static and dynamic control, i.e. $\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{s}})$, and $\varrho_{(v,v+g),p,r,t}(\xi^{\mathrm{d}})$;
– The number of technical devices, i.e., servers in v-nodes of control points, $d_{v,t}$ for $v \in V^{\mathrm{c}}$.

After running a series of simulations, all solutions have been verified against the constraint set (19)-(20). Specifically, variants with values of maximum total time for border control of each passenger at the BCP including waiting time in front of the server higher than 20 minutes, i.e., $T^{\max} > 20$ min have been discarded. Ultimately, 140 solutions have been obtained constituting the set of variants. The simulations have been run 10 times per each variant, and the average criteria values have been calculated with the following ranges of variations: $C_1 = (94.9, 99.7)$ %, $C_2 = (9, 20)$ items, $C_3 = (7, 14)$ pers., $C_4 = (0, 8)$ pers., and $C_5 = (101, 270)$ m^2. Selected solutions are presented in Table 4. According to the next stage of the proposed passenger process design methodology, these variants have been subjected to multi-criteria analysis to identify a compromise solution.

4.6. Stages 5 and 6 – Selection of MCDA method, its application, and analysis of results

Based on the procedure for selecting an MCDA method presented in Section 3.6, the TOPSIS method (Hwang, Yoon, 1981) has been chosen as the most appropriate and consistent with the nature of the problem under consideration. The decision has been primarily influenced by the following factors:

– The objective is to rank solutions; thus, the analysis is focused on ranking methods;
– The set of variants is large; thus, some methods would be inefficient, e.g., methods based on pairwise comparisons of criteria and variants;
– The aim is to identify the variant closest to the ideal solution;
– Criteria values are deterministic; thus, only deterministic MCDA methods ware considered.

The principle of TOPSIS method is to select the variant that is the closest to the ideal solution and at the same time the farthest from the nadir solution. The ideal solution is created based on the best values of the set of evaluation criteria, i.e., maximum value among each benefit criterion and minimum value among each cost criterion, while the nadir solution is opposite. All criteria values in the performance matrix are normalized for a comparable range. Next, the Euclidean distance from each variant to ideal and nadir solutions is calculated. Finally, the relative closeness to the ideal solution is computed and the ranking of variants can be created with the best solution on the top, i.e., the variant with the highest value of the relative closeness to ideal solution.

The TOPSIS algorithm has been implemented in Excel, and the calculation results are presented in Table 5. This indicates that the top two positions, i.e., variant 24 and variant 23, achieved similar results. However, the former is better than variant 23 on 2 criteria, i.e. C_1 and C_2, the same on 2 other criteria, i.e., C_3 and C_4, and slightly worse on criterion C_5. Based on variant 24 and variant 23 proximity to the ideal solution a^* that equals 0.754 and 0.732, respectively, their superiority over other variants is evident. Therefore, variant 24 can be recommended for implementation.

5. Discussion of Results

The solution recommended for implementation in Section 4 is characterized by rational values for individual criteria. It guarantees service for 99.4% of passengers within a time of less than 10 (min), see criterion C_1, utilizing 10 servers, see criterion C_2, for passenger processing, i.e., 4 MBLs, 2 SSKs, and 4 e-Gates, see Tables 4 and 5.

Table 4. Summary of results – Values of decision variables and criteria (authors' own work)

Variants	Decision variables							Values of criteria				
				ξ^s for $(v, v+g)$		ξ^d dla $(v, v+g)$						
	d_5 (item)	d_8 (item)	d_9 (item)	(3,4) (-)	(6,7) (-)	(4,5) (-)	(7,9) (-)	C_1 (%)	C_2 (item)	C_3 (pers.)	C_4 (pers.)	C_5 (m^2)
1	10	5	2	1	1	0	1	97.0	17	10	2	189
2	9	5	2	1	1	0.5	1	96.2	16	10	4	221
3	9	5	3	1	1	1	1	95.9	17	10	4	266
4	9	5	3	1	1	2	1	97.9	17	10	4	221
5	7	6	3	1	1	5	1	97.5	16	10	4	226
6	5	7	3	1	1	10	1	97.3	15	11	4	227
7	11	5	4	1	1	0	0	99.1	20	10	0	192
8	8	4	4	1	1	0.5	0	96.1	16	8	2	230
9	8	5	4	1	1	1	0	98.3	17	9	2	219
10	6	6	4	1	1	2	0	98.3	16	10	2	201
..												…
21	9	3	4	.8	1	0	0	96.1	16	7	2	238
22	9	3	4	.6	1	0	0	97.1	16	7	2	232
23	4	4	4	.4	1	0	0	99.1	12	8	2	166
24	2	4	4	.2	1	0	0	99.4	10	8	2	167
25	9	4	4	.8	1	0	1	98.7	17	9	4	153
26	6	4	4	.6	1	0	1	98.3	14	8	4	152
27	4	4	4	.4	1	0	1	98.9	12	8	4	152
28	3	4	4	.2	1	0	1	99.7	11	8	4	155
29	9	4	3	.8	1	0.5	1	98.2	16	9	6	222
30	6	4	3	.6	1	0.5	1	97.5	13	8	6	219
…												…
73	10	5	2	1	.8	0.5	1	96.3	17	10	6	224
74	10	4	2	1	.6	0.5	1	94.9	16	9	6	270
75	9	5	2	1	.4	0.5	1	97.7	16	10	6	174
76	9	6	2	1	.2	0.5	1	97.0	17	11	6	184
77	9	5	2	1	.8	1	1	95.0	16	10	6	266
78	9	5	2	1	.6	1	1	95.7	16	10	6	251
79	8	6	2	1	.4	1	1	96.7	16	10	6	189
80	7	7	2	1	.2	1	1	97.9	16	11	6	161
81	8	6	2	1	.8	2	1	98.1	16	10	6	198
82	7	7	2	1	.6	2	1	98.3	16	11	6	204
…												…
134	6	6	1	.6	.2	2	1	98.4	13	10	8	203
135	5	4	3	.4	.8	2	1	97.5	12	8	8	221
136	4	5	2	.4	.6	2	1	97.8	11	9	8	222
137	4	6	1	.4	.2	2	1	98.9	11	10	8	198
138	3	5	2	.2	.8	2	1	98.0	10	9	8	238
139	3	5	2	.2	.6	2	1	98.5	10	9	8	201
140	2	6	2	.2	.4	2	1	99.4	10	10	8	152

Table 5. Matrix of performances and measures of relative closeness a^* to the ideal solution according to the TOPSIS method for selected variants; ranked by position in the ranking (authors' own work)

Variants	Values of criteria					Ranking	
	C_1 (%)	C_2 (item)	C_3 (pers.)	C_4 (pers.)	C_5 (m^2)	a^*	Position
24	99.4	10	8	2	167	0.754	1
23	99.1	12	8	2	166	0.732	2
28	99.7	11	8	4	155	0.629	3
27	98.9	12	8	4	152	0.619	4
64	98.7	10	8	4	183	0.611	5
7	99.1	20	10	0	192	0.604	6
68	99.1	10	8	4	191	0.603	7
59	99.4	12	8	4	172	0.600	8
63	99.3	12	9	4	156	0.599	9
56	99.5	12	8	4	174	0.598	10
…							…
135	97.5	12	8	8	221	0.374	95
138	98.0	10	9	8	238	0.374	96
79	96.7	16	10	6	189	0.368	97
120	97.4	11	9	8	221	0.368	98
136	97.8	11	9	8	222	0.367	99
128	98.0	10	10	8	219	0.366	100
…							…
113	98.2	16	10	8	182	0.305	131
90	97.9	16	11	6	226	0.303	132
77	94.9	16	10	6	266	0.302	133
89	97.2	16	11	6	230	0.299	134
129	97.3	15	9	8	236	0.296	135
109	97.6	16	9	8	220	0.294	136
85	97.2	16	11	6	236	0.293	137
87	96.6	16	12	6	222	0.283	138
115	97.3	15	11	8	202	0.272	139
131	97.6	15	10	8	232	0.270	140

The passenger flow requires the involvement of 10 personnel, including 8 border guards, see criterion C_3), and 2 auxiliary staff, see criterion C_4, tasked with overseeing and managing passenger flows. This solution assumes a traffic management model that directs 20% of TCNs-VE and TCNs-VH passengers to SSKs, as reflected by the relation $(v, v+g)$ = (3, 4) in Table 4, with a value of 0.2. This implies that the remaining 80% of passengers in this group are directly routed to MBCs. Such traffic management necessitates the engagement of 2 auxiliary staff members to oversee the process. In contrast, for EU passengers being directed to e-Gates, no redirection to MBC is applied. It means that 100% of EU nationals passengers are directed to e-Gates, as indicated by $(v, v+g)$ = (6, 7) in Table 4, with a value of 1. Consequently, there is no need to involve auxiliary staff at this stage for managing passenger flows. These staff members are also not engaged in queue balancing – this option is not active in any decision node, neither for $(v, v+g)$ = (4, 5), nor for $(v, v+g)$ = (7, 9), as indicated by the value 0 in Table 4. To evaluate the quality of the recommended solution, additional experiments have been conducted under the following assumptions:

– Scenario o1: All three types of devices, i.e., MBC as MBLs, SSKs, and e-Gates, are used exclusively with default passenger routing (no redirection options are applied);

– Scenario o2: Only traditional manual border control lanes (MBLs) are used, with default routing of all passenger types to these servers.

The results of the simulations are summarized in Table 6. All alternative scenarios o1, o2 and the recommended variant (24) guarantee service for at least 99.4% of passengers within a maximum time of 10 minutes. Solution o2 requires less space for passengers waiting in the queues in front of the servers than variant 24, i.e., 149 m² vs. 167 m², but it demands more servers, i.e., 13 vs. 10 items, and a higher number of border guards, i.e., 13 vs. 10 staff. Solution o1 performs worse in all dimensions compared to the recommended variant 24.

A comparison has been also made between the results obtained using the holistic process design methodology and the current state presented in the first row of Table 6. If 39% of all passengers are subject to border control procedures that take 10–120% longer than before the EES implementation, the recommended variant 24 requires a total of 2 more servers than the current state. Their composition is different with the same number of border guards and 31% less space needed for passengers waiting in the queues. The efficiency of the current solution is more than 3 percentage points lower than the recommended solution.

6. Conclusion

This paper addresses the problem of shaping specialised service processes conducted in passenger terminals, with a particular focus on new technical and organisational solutions. The authors assumed that the development of a target process flow should be supported by a detailed analysis of both technical and organisational solutions and assessed from many points of view to provide wide perspective. At this stage, as demonstrated by the experimental results, it is crucial to seek a compromise solution – one that guarantees both rationalisation of the human and technical resources involved and efficiency of the implemented processes, primarily perceived by passengers. In this sense, the authors refer to the developed methodology as a holistic approach.

The paper outlines the methodological foundations for designing passenger service processes concerning the BCP as a distinct part of the passenger terminal. It consists of six key stages, starting with the analysis and evaluation of existing solutions, through the development of a multi-criteria mathematical model, its implementation in a simulation environment, the selection and application of a decision aiding method, and concluding with the identification of the recommended compromise solution. The first stage of the methodology makes it universal, assuming that it can be applied both in the case of redesigning an existing terminal and designing a new facility. The authors also assumed that the methodology has comprehensive applications from the perspective of the transport sector, making it applicable to airport, road, rail, and maritime terminals. The paper, however, verifies the methodology concerning the BCP at an airport passenger terminal. The experimental verification presented in Chapter 5 allows the formulation of generalised conclusions, including practical applications:

– A synergy effect has been achieved between the composition of equipment (different types and numbers of technical means) and the control of passenger flows within the BCP. This resulted in tangible benefits, such as a reduction in the space allocated for passengers waiting for border checks compared to the current state, a slight increase in the number of servers, and a similar number of engaged border guards.

Table 6. Summary of alternative solutions in comparison with the current state (As is) and recommended variant 24 (authors' own work)

Variants	Decision variables							Values of criteria				
	d_5 (item)	d_8 (item)	d_9 (item)	ξ^s for $(v, v+g)$ (3,4) (-)	ξ^s for $(v, v+g)$ (6,7) (-)	ξ^d dla $(v, v+g)$ (4,5) (-)	ξ^d dla $(v, v+g)$ (7,9) (-)	C_1 (%)	C_2 (item)	C_3 (pers.)	C_4 (pers.)	C_5 (m²)
As is	0	8	0	n/a	n/a	n/a	n/a	97.0	8	8	0	239
24	2	4	4	.2	1	0	0	99.4	10	8	2	167
o1	13	4	4	1	1	0	0	99.7	21	9	0	173
o2	0	13	0	n/a	n/a	n/a	n/a	99.9	13	13	0	149

- The level of efficiency of passenger service processes has been increased, as measured by the number of passengers served in a relatively short time. This is influenced by the engagement of passengers in the border control process through pre-enrolment using SSKs and the automatic control performed for selected groups of passengers, i.e., using e-Gates. The use of these types of devices significantly reduces the involvement of highly qualified staff, such as border guards.
- Sensitivity analysis demonstrated that for a level of efficiency close to the recommended one, it is possible to maintain the BCP's operation in a layout similar to the current one, i.e., using only one type of server and without redirecting passengers to different service points, see scenario o1. However, to meet the requirements of the EES system, the number of such server would need to increase from 8 MBLs to 13 MBLs, along with an increase in the number of border guards from 8 to 13. Another considered option was to utilise all types of servers without redirecting passengers to other than their initially designated service points, e.g., based on queue length. This scenario (o2) can be related to the recommended solution due to the considered types of servers, i.e., MBLs, SSKs, and e-Gates. Consequently, the number of border guards, SSKs, and the space required for passengers waiting in the queues for border checks is higher than in the recommended solution, i.e., variant 24.
- The static control of passenger flow assumes that the percentage of passengers allocated to various servers may differ per each variant and is fixed in each variant. It offers a flexible adjustment of different passenger types to the technical devices. The dynamic control of passenger flow leads to greater flexibility of the modelled process and reflects a situation close to the reality.

The authors emphasise also the following elements as methodological conclusions:

- The natural feature of the proposed methodology is the design of multi-stage and optional passenger service processes, wherein numerous configuration options exist, both in static terms, i.e., fixed proportions of selected passenger types' paths, and dynamic terms, i.e., redirection of selected passenger types based on current queue lengths.
- The methodology is universal which means: i) it accommodates optional border control using traditional MBC devices as well as contemporary technologies such as SSKs and e-Gates; ii) the representation of BCP in the form of a graph, with default routing values $f_{(v,v+g),p,r,t}$ allows for a variant configuration of the BCP, including the use of MBCs only, MBCs and e-Gates, or all types of the servers, i.e., MBCs, SSKs, and e-Gates; iii) the multi-criteria mathematical model considers various aspects of the border control process, allowing for a comprehensive evaluation; iv) the use of an algorithm for selecting a decision aiding method enhances the reliability of the obtained result and the recommended BCP organisation; v) the proposed pseudocode for process simulation can be implemented in any simulation environment, with its structure considering the multi-stage nature of the border control process.
- The methodology incorporates many aspects of BCP operations, combining operational considerations based on passenger flow data from a selected day, with tactical aspects, such as planning the number of staff with appropriate qualifications assigned to tasks, and strategic considerations, such as recommending BCP type and number of equipment and the required area for passengers waiting in the queues at the BCP. Due to its multi-stage and complex nature, implementing the methodology is time consuming.

The utility and methodological conclusions suggest that the intended goal of the study has been achieved. However, there is considerable scope for further research, and the authors highlight the following areas:

- Conducting an analysis of the impact of disruptions in the passenger arrival schedule at the BCP on the configuration of passenger service processes. This analysis should consider the effects of different arrival patterns and passenger structures on the stability of the designed border control process.
- Expanding the graph structure to include the possibility of implementing the latest technological advancements in mobile devices used in passenger control. This pertains to both the use

of mobile passenger applications on smartphones and mobile devices used by border guards.
- Testing the developed methodology for border control of passengers starting or continuing their journey from the analysed passenger terminal. Comprehensive analyses on arrivals and departures should also be conducted for terminals in other transport sectors, i.e., road, rail, and maritime.
- Adapting the process design methodology to enable simulation optimisation, which would replace the iterative multi-variant simulations. The results should be compared not only in terms of criteria values and process design but also in computational time.
- Considering the inclusion of additional criteria related to energy efficiency and conducting comparative assessments with the results obtained using the current set of criteria.
- Conducting a stochastic analysis of solutions, accounting for the variability range of results obtained from variant simulations using methods specifically designed for such decision-aiding applications.

Nomenclature

Indices and sets:

E – set of edges (arcs) in the graph G, $G = (V, E)$;
g, h – indices of sequential numbers of nodes in the graph G, $g, h = 1, 2, \ldots, V \wedge g \neq h$
i – index of transportation means arriving at PSF, $i \in I$;
j – index of a sequential order of border guard groups depending on the number of servers in use, $j \in J$;
k – index of a decision node, $k, k+1, \ldots, K$, $K \in V^d$;
n – index of a border control node, representing a homogeneous group of servers, $n, n+g, n+h \ldots, N \in V^c$;
m – index of an ending node, $m \in V^m$;
p – index of a passenger, $p \in P$;
r – index of a passenger classification, i.e., type of a passenger, $r \in R$;
R – set of different passengers r-types, $r \in R \wedge R = \{R_1, R_2, \ldots, R_a\}$;
s – index of a starting node, $s \in V^s$;
t – index of a time moment, $t \in [0, T]$;
v – index of a node in the graph representing a transportation system, $v: v, v+g, v+h, \ldots, \mathcal{V} \in V$; $v = (s, k, n, m)$;
w – index of the range of variations of the servers operating at the BCP, i.e., interval, $w \in [1, W]$;
T – set of time moments t, i.e., simulation time;
V – set of arcs in the graph G, $v: v, v+g, v+h, \ldots, \mathcal{V} \in V \wedge V \subseteq N \times N$.

Parameters:

$b_{v,t,j}$ – number of border guards involved in the operation of control servers in v-node, $v \in V^c$, at t-time, in j sequential order, $j \in J$ dependent on the number of deployed devices, (pers.);
$D_{v,w}^{\min}$ – minimum number of servers belonging to the control devices in v-node, $v \in V^c$, within the range of variation w, $w \in [1, W]$, of the servers operating at the BCP, (items);
$D_{v,w}^{\max}$ – maximum number of servers belonging to the control devices in v- node, $v \in V^c$, within the range of variation w, $w \in [1, W]$, of the servers operating at the BCP, (items);
P – total number of passengers to be border checked for 24 hours, (pers./24h);
P_i – number of passengers on board of an i-th transportation mean, (pers.);
t_p^{a} – arrival time of a p-passenger to the PSF, (min);
t_p^{w}– transition, i.e., walking time of the p-passenger from the transportation mean to the BCP, expressed as a non-deterministic value, (min);
$t_{(v,v+g),p,r}$ – processing time for the p-passenger of r-type using a control server in node $v+g$, dependent on the passenger's routing from node $v: v \in V$, to node $v+g: v+g \in V^c$, (s);
T – simulation time, (min);
T^{acc} – acceptable total time for border control of each passenger at the BCP including waiting time in front of the server, indicating the efficiency of organizational solutions, (min);
$T^{\max}$ – maximum total time for border control of each passenger at the BCP including

waiting time in front of the server, (min);

u_v – unit space occupied by a p-passenger, required to maintain comfortable conditions for waiting in front of the v-node control servers, (m²/pers.).

Values determined during simulations:

$b_{v,t}$ – number of border guards employed to operate servers in v-node, $v \in V^{\mathrm{c}}$, at a t-time, $t \in [0,T]$, (pers.);

$c_{(v,v+g),p,r,t}$ – control function for the p-passenger of r-type at a t-time using a server in $v+g$ node being moved from node $v \in V^{\mathrm{d}}$, to node $v+g \in V^{\mathrm{c}}$, (pers.);

$d^{\mathrm{b}}_{v,t}$ – number of servers in v-node, $v \in V^{\mathrm{c}}$, being busy at a t-time, $t \in [0,T]$, (items);

$d^{\mathrm{c}}_{v,t}$ – number of servers in v-node, $v \in V^{\mathrm{c}}$, where p-passenger control begins at t-time, $t \in [0,T]$; it is equivalent to the number of passengers leaving the queue in front of the servers at a t-time, (items);

$d^{\mathrm{i}}_{v,t}$ – number of servers in v-node, $v \in V^{\mathrm{c}}$, being idle at a t-time, $t \in [0,T]$, (items);

$d_{v,0}$ – initial number of available servers in v-node v: $v \in V^c$, (items);

p^{out} – number of passengers exiting the BCP, i.e., after border check completion, (pers.);

$\tau^{\mathrm{q}}_{v+g,p}$ – time of arrival of p-passenger at the queue in front of the servers in node $v+g$, $v+g \in V^{\mathrm{c}}$, (s);

$\tau^{\mathrm{c}}_{v+g,p}$ – time of starting control for p-passenger conducted within the servers in $v+g$-node, $v+g \in V^{\mathrm{c}}$, (s);

$q_{v,t}$ – total number of passengers waiting in the queue in front of the control server in v-node at a t-time, (pers.);

$q_{v+h,t}$ – total number of passengers waiting in the queue in front of the control server in node $v+h$ at a t-time, (pers.);

$q_{v+h,t-1}$ – total number of passengers waiting in the queue in front of the control server in node $v+h$ at a time t-1, (pers.);

$q_{v+g,t}$ – total number of passengers waiting in the queue in front of the control server in node $v+g$ at a t-time, (pers.);

$q_{v+g,t-1}$ – total number of passengers waiting in the queue in front of the control server in node $v+g$ at a time $t-1$, (pers.);

$w_{v,p,r,t}$ – number of auxiliary staff employed in the BCP area at the v-decision node, v: $v \in V^{\mathrm{d}}$, where potential redirection of p-passengers of r-type at t-time occurs, (pers.)

Decision variables:

$d_{v,t}$ – number of servers in v-node, $v \in V^{\mathrm{c}}$, available at a t-time, $t \in [0,T]$, (items);

$f_{(v,v+g),p,r,t}$ – binary variable to determine the default path of a p-passenger of r-type in the BCP area on the arc $(v, v+g)$: $v, v+g \in V$, at a t-time, (-);

$f_{(v,v+h),p,r,t}$ – binary variable to determine the alternative path of a p-passenger of r-type in the BCP area on the arc $(v, v+h)$ instead of the arc $(v, v+g)$, where $g \neq h$, $v, v+g$, $v+h \in V$, at a t-time, (-);

$\varrho_{(v,v+g),p,r,t}$ – auxiliary binary variable indicating whether a p-passenger of r-type remains on the arc $(v, v+g)$ of the default path or is redirected to the arc $(v, v+h)$ of the alternative path, where $v \in V^{\mathrm{d}}$, $v+g, v+h \in V$, $g \neq h$, at a t-time, $t \in [0,T]$, (-);

$\xi^{s}_{(v,v+g),p,r,t}$ – static control threshold value used to decide whether a p-passenger of r-type remains on the arc $(v, v+g)$ of the default path or is redirected to the arc $(v, v+h)$ of the alternative path, where $v, v+g, v+h \in V$; $g \neq h$, at a t-time, $t \in [0,T]$, (-);

$\xi^{\mathrm{d}}_{v+g,v+h,t}$ – multiplicity of a queue length in front of the servers in $v+g$-node, relative to the queue length in front of the servers in $v+h$-node, where $v+g, v+h \in V^c$; it is used for a dynamic control of the p-passenger of r-type at a t-time $t \in [0,T]$, (-).

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Conflict of interest
The authors declare that the research was conducted in the absence of any commercial or financial relations that could be construed as a conflict of interest.

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Appendix A

For the computational part of the paper, a following arrivals schedule is adopted, see Section 4. Each flight is anonymized.

Table 7. Flight schedule[1] for a considered BCP

No.	t_p^{a} [hh:mm]	P_i (pers.)	No.	t_p^{a} [hh:mm]	P_i (pers.)
01	00:10	181	18	14:30	132
02	00:50	196	19	15:25	187
03	01:15	190	20	15:40	162
04	02:10	169	21	15:55	176
05	05:50	182	22	16:45	177
06	06:55	254	23	17:20	203
07	07:15	261	24	17:35	172
08	08:50	178	25	18:15	193
09	09:45	166	26	18:35	220
10	10:30	101	27	19:20	266
11	11:40	227	28	20:30	153
12	11:50	171	29	21:05	236
13	12:15	187	30	21:25	171
14	12:50	178	31	21:35	150
15	13:05	170	32	21:55	129
16	13:15	217	33	22:10	79
17	13:30	335	34	23:35	187

[1] Flight schedule is based on empirical data

Appendix B

Within this Appendix, the pseudocode for the simulation conducted as part of Stage 3 is presented. It provides a more detailed representation of the diagram shown in Section 3.4, in Figure 4.

```
INPUT DATA:
  p ≔ p ∈ P; v: v ∈ V ∧ (V^s, V^c, V^d, V^m) ∈ N; v: v, v+g, v+h, …, 𝒱; v: v = s ∈ V^s; v: v = k ∈ V^d; v: v = n ∈ V^c;
  v: v = m ∈ V^m; d_{v,t}; ξ^s_{(v,v+g),p,r,t}; ξ^d_{v+g,v+h,t}; f_{(v,v+g),p,r,t}; ϱ_{(v,v+g),p,r,t}; t_{(v,v+g),p,r}; t^a_p; t^w_p, T.

OUTPUT:
  Value of criteria: C_1, …, C_5

FUNCTIONS:
Function {add_passenger_to_queue()}:
  s := the only source node v: v = s ∈ V^s
  while p has not reached the destination v: v ∈ V^m do
    #Check if the passenger should move from node v to v+g
    if f_{(v,v+g),p,r,t} = 1 then #Passenger p moves from v to v+g, where (v,v+g) ∈ V
      if v: v ∈ V^d ∧ ξ^s_{(v,v+g),p,r,t} > 0 then #Check if it is a dec. node and ξ^s_{(v,v+g),p,r,t} > 0
        draw random los() ∈ [0,1] #Random value los() for comparison with ξ^s_{(v,v+g),p,r,t}
        if los() ≤ ξ^s_{(v,v+g),p,r,t} then
          v ≔ v+g ∧ f_{(v,v+g),p,r,t} = 1 #Pass. p stays on the default path from v to v + g
        else
          v ≔ v+h ∧ (f_{(v,v+g),p,r,t} = 0, f_{(v,v+h),p,r,t} = 1) #Pass. p is redirected from v to v+h
        end if
```

```
    else if $v: v \in V^{\mathrm{d}} \wedge \xi^{\mathrm{d}}_{v+g,v+h,p,r,t} > 0$ then #Check if it is a dec. node and $\xi^{\mathrm{d}}_{v+g,v+h,t} > 0$
      call {process_passenger()}  #Process the $p$ at the server
      if $q_{v+h,t} > \xi^{\mathrm{d}}_{v+g,v+h,t} \cdot q_{v+h,t}$ at time $t$ then
        $v := v+g \wedge f_{(v,v+g),p,r,t} = 1$  #Passenger $p$ stays on the default path from $v$ to $v+g$
      else
        $v := v+h \wedge \left(\mathrm{f}_{(v,v+g),p,r,t} = 0,\ \mathrm{f}_{(v,v+h),p,r,t} = 1\right)$ #Pass. $p$ is redirected from $v$ to $v+h$
      end if
    else if $v: v \in V^{c}$ then
      $q_{v,t} := q_{v,t}+1$ #Increase no. of pass. entering the queue prior to the server $v$: $v \in V^{c}$
      $v := n$  #Update the $v$-node to the border control node $n$
      call {process_passenger()}  #Process the $p$ in front of the control server
      if $f_{(v,v+g),p,r,t} = 1$ for $v, v+g \in \mathrm{V}$ then  #Check if $p$ should go from $v$ to $v+g$
        $v := v+g$ #Redirect $p$ to the next node $v+g$
      end if
    end if
  else
    $v \coloneqq m \in V^{m}$ #Exit node is set, no queue, $p$ reaches the exit node
    $p^{\mathrm{out}} \coloneqq p^{\mathrm{out}}+1$ #Increase the count of $p$ exiting the system
  end if
end while

Function {process_passenger()}:
  $d_{v,0} \coloneqq d_{v,t}$ #Initial no. of avbl servers equals the max no. of servers in $v: v = n \in V^{d}$
  while $q_{v,t} \neq \emptyset \wedge d_{v,t} > 0 \wedge t < T$ do #While there are passengers in the queue, servers are
  available, and simulation time has not ended
    $p \coloneqq$ first element from $q_{v,t}$ #Get first $p$ from the queue in front of node $v: v = n \in V^{d}$
    $\tau^{c}_{v,p} \coloneqq$ current time #Record the start time of processing the $p$-passenger
    $q_{v,t} \coloneqq q_{v,t} - 1$ #Remove the $p$ from the queue at the beginning of processing at $t$-time
    $d^{c}_{v,t} \coloneqq d^{c}_{v,t}+1$ #Increase the count of $p$ leaving the queue in front of the $v$-node
    $\tau^{c}_{v,p} - \tau^{q}_{v,p}$ #Calculate the waiting time in the queue in front of the v for the p
    $d_{v,0} \coloneqq d_{v,0} - 1$ #Reduce the number of available servers at time $t = 0$
    finish processing passenger $p$ after $t_{(v,v+g),p,r}$  #Process $p$ of $r$ at the server in $v+g$
  end while
  $d_{v,0} \coloneqq \min\left(d_{v,0}+1, d_{v,t}\right)$  #Increase the number of avbl servers after processing of $p$ at $t$

Function {generate_arrivals()}:
  for $p$ from 1 to $P$ do
    $t^{a}_{p} \coloneqq T_{\mathrm{arrival}(p)}$  #Determine the arrival time based on schedule
    at $t$ call {arrival_at_BCP()}  #Schedule $p$ arrival at the BCP at $t$
  end for

Function {arrival_at_BCP()}:
  $t^{w}_{p} \coloneqq T_{\mathrm{walk}(p)}$ #Random transition time for $p$-passenger
  wait $t^{w}_{p}$ units of time
  call {add_passenger_to_queue()}:  #After transition, $p$ enters queue prior to $v$

Function {run_simulation()}:
 call {generate_arrivals()} #Schedule $p$-passenger arrivals according to $t^{a}_{p}$
 while $p < P$ and $t < T$ do #Loop continues while $p < P$ and simulation time is $t < T$
   for $t = 1,2,\ldots$ do
     if $p$ is scheduled to arrive at $t$ then
     call {arrival_at_BCP()} #Passenger $p$ begins transition to the BCP
     end if
   end for
   for each $v: v \in V^{c}$ do  #Simultaneously process $p$ at all types of servers in $v$
   call {process_passenger()}  #Process passengers in queue $q_{v,t}$ for each $v \in V^{c}$
```

```
    end for
  end while
  while there exists v ∈ V^c, where q_{v,t} ≠ 0 do #Process until queues are empty
    for each v ∈ V^c do
      if q_{v,t} ≠ 0 then  #Check if the queue is not empty
      call {process_passenger()}
      end if
    end for
  end while
END
```