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Simulation Based Analysis of Airport Terminal Resilience with a Generic Terminal Model

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Modern societies are based on a high level of mobility and therefore depend on efficient infrastructure systems. Airport terminal systems operating close to their capacity limit are however vulnerable to disruptions such as weather incidents or strikes. We can measure this vulnerability introducing the concept of resilience to airport terminal systems. In this paper, we investigate the resilience of airport terminals using a simulation model in AnyLogic. First, we derive resilience indicators from literature in order to quantify airport terminal resilience. We develop a generic terminal model and simulate the disruptive scenario of a terminal clearance for different operational schedules of selected airports. As a result, we can draw first conclusions on airport terminal resilience depending on the airport characteristics as well as the properties of the disruption scenario. In the future, we aim at deriving recommended actions for airports minimizing the impact of disruptions on the terminal infrastructure.

I. Introduction

A growing interconnectedness leads to an increasing demand for mobility and consequently to an increasing demand in the aviation sector. The International Civil Aviation Organization (ICAO), for example, predicts that passenger volumes will double between 2012 and 2032 [1]. The German Aerospace Center (DLR) expects a comparable increase in passenger volume by a factor of 2.39 between 2016 and 2040 [2]. As the expansion of terminal or runway infrastructures in Europe is limited by national administrative regulations, airport infrastructures are often operating close to their capacity limit today. For 2016, according to [2] already 35 airports are considered as “congested”, those airport handling 19% of global air traffic. An increase of the seat-loading factor can reduce aircraft movements and consequently discharge take-off and landing infrastructures. However, this measure does not reduce the number of passengers in terminal facilities [2]. An understanding of the airport terminal system’s reaction on disruptions such as system outages, staff strikes or passengers passing security without inspection is therefore vital in order to limit the consequences of failures for passengers and airport operators [3].

We use the concept of resilience to develop an understanding on how the airport terminal systems react on failures. The resilience of a system describes the ability to recover from internal or external disruptions. The number of scientific articles dealing with resilience has increased significantly in recent years [4]. In literature, resilience is yet applied to infrastructure systems such as road or rail networks [5,6]. We use this research as a basis to introduce resilience indicators for an airport terminal system in order to be able to quantify airport terminal resilience. Moreover, we build a generic terminal model in AnyLogic to apply the resilience indicators to specific disruption scenarios. With this strategy, we aim at understanding the reaction of the system to the disturbance and at developing effective strategies against disruptive events.

In Section II, we describe our methodology including the resilience indicators, the model setup as well as the input parameter selection. We present and discuss first simulation results in Section III and Section IV. Section V will close the paper with a conclusion about the key findings and an outlook for further actions.

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II. Methodology

A. Definition of Resilience Indicators

As there is no research about airport terminal resilience in literature yet, we derive resilience indicators from current research in different application areas. The term "resilience" comes from the Latin word "resilire" and means "to bounce back". Further definitions can be found depending on the field of application, including psychology, material science, ecology, economy and engineering. A detailed literature overview has already been presented in [7]. From the different definitions in literature, we can extract various concepts to quantify resilience with indicators.

We define airport terminal resilience as the ability of the terminal system to respond to an internal or external disturbance with robustness and rapidity [8–11]. This ability, we quantify by measuring the minimum system performance after a disruption (p_{min}), see Eqn. (1), and by measuring the recovery time of the system after the disruption [8,9,12]. As system performance measure, we use the passenger system time without disturbance in relation to the passenger system time with a disturbance. This relative measure is referred to as the "system quality" in the following and theoretically can take values between 0 for infinite system times after a disruption and 1 for identical system times with and without the disruption. We define the recovery time ($t_{recovery}$) as the time between the start of the disturbance and the time at which the original performance level is reached. To measure the rapidity, the recovery time is set in relation to the time of disruption $t_{disruption}$ (see Eqn. (2)). Moreover, we use the system performance over time as a third resilience indicator. The system performance over time is calculated by the integral of the system performance ($p(t)$) during the simulated time interval [t_0, t_{end}], see Eqn. (3). All three resilience indicators are relative measures with values between 0 implying a low and 1 implying a high resilience.

$$Robustness = p_{min} \tag{1}$$

$$Rapidity = t_{disruption}/t_{recovery} \tag{2}$$

$$System\ performance\ over\ time = \int_{t_0}^{t_{end}} p(t)\,dt \tag{3}$$

Additionally, we define ranges of values for the indicators in order to distinguish between a low, a medium and a high resilience. A high resilience is reached if an indicator is larger or equal to 0.5. Consequently, a system is regarded as highly resilient under the following conditions. Concerning the robustness, a high resilience implies that after the disturbance, the minimum system performance equals at least at half of the performance level reached before. A high rapidity means that the recovery time is at most double as long as the time of disruption. A high system performance over time requires that during the simulated time interval, on average half of the performance compared to the normal operations is reached. A system is highly resilient if all three dimensions show indicator values larger than or equal to 0.5.

A low resilience shall apply if an indicator is smaller than 0.1 and a medium resilience consequently implies an indicator value of larger or equal than 0.1 and smaller than 0.5. Hence, a system is to be considered as low resilient under the following conditions. Concerning the robustness, the system shows low resilience if the minimum performance indicator is reduced to a factor of more than 10 as a result of the disturbance. A low rapidity means that the recovery time is more than 10 times as long as the time of disruption. A low system performance over time requires that during the simulated time, on average less than 10% of the performance compared to the normal operations is reached. A system shows low resilience if all three dimensions show indicator values smaller than 0.1. Moreover, we specify that an indicator value of 0 stands for no resilience. We use all three presented dimensions to evaluate the resilience of airport terminal systems.

B. Development of a Generic Terminal Model

According to "DUDEN", the word "generic" describes that something is "used in a generally valid sense". A "specific" terminal model usually describes the infrastructure of a particular airport terminal. A generic terminal model, on the other hand, describes a general model. We can use the model with input parameters of selected airports or a class of airports. In this paper, we use a generic model with a flight plan of Frankfurt Airport as a big European hub airport accommodating mainly network carriers and a flight plan of Cologne Bonn airport, which is a typical point-to-point airport accommodating mainly low cost carriers.

For the simulation, we can use different modelling approaches [13]. We can distinguish between system dynamics modeling, event- or process-oriented modeling (discrete event modeling) and agent-based modeling. In this case, we use a discrete event simulation in AnyLogic. In event- or process-oriented modelling, systems and their system states are modeled in connection with discrete points in time [14]. AnyLogic is a multi-method simulation tool developed by The AnyLogic Company. We do not consider spatial parameters and we only consider the departure flow. The terminal model consequently includes the process stations check-in desk or machine, bag drop, boarding pass control, security control and passport control. A 24 hours period of operations is simulated. As some input parameters are subject to a percentage distribution, we conduct several simulation runs in order to display the stochastic nature of the terminal model. The results in Section III consequently represent average values over all simulations runs.

C. Input Parameter Selection

The input and output parameters of the model are shown in Fig. 1. In order to define an appropriate number of process stations, we assume that the Level of service category "Optimum" shall be satisfied for a "busy day" according to [15]. A first approximation of the number of process stations in calculated analytically based on the number of passengers in the peak hour of the busy day according to the equations specified in [15]. We need the passenger arrival rate during the day for this calculation. For Frankfurt airport, the peak hour starts at 12 pm. For Cologne Bonn airport, the peak hour starts at 6 am. We iteratively determine the final number of process stations with simulations of the busy day for Frankfurt airport and Cologne Bonn airport in AnyLogic, reviewing the maximum waiting times to ensure the Level of service category "Optimum".

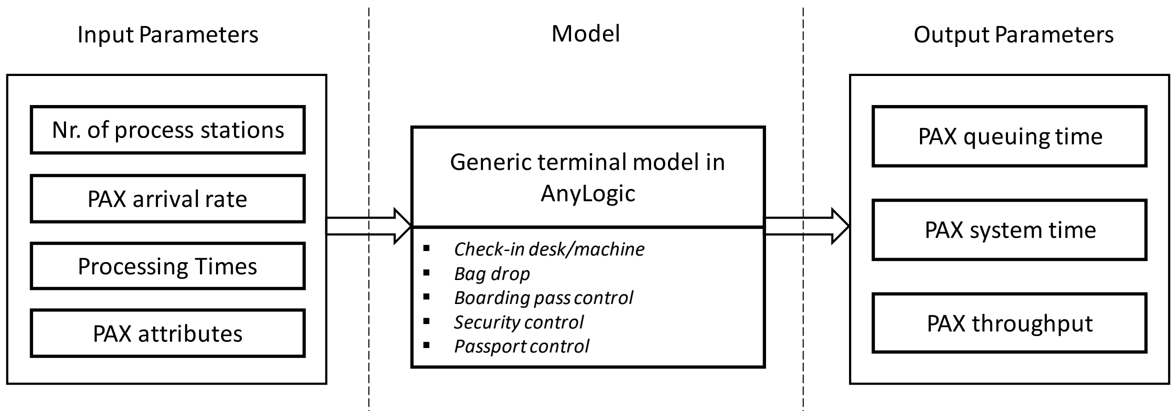

Fig. 1 Simulation input and output parameters

In order to determine the passenger arrival rate, we use the respective flight plan of Frankfurt airport and Cologne Bonn airport at a busy day 2019. The busy day 2019 is identified based on an analysis of the passenger numbers of the year 2019. We calculate the arrival rate from the passenger arrival profiles according to [16] as well as the flight plan for the busy day extracted from Flightradar24. The resulting curve of arriving passengers during the day for Frankfurt airport and Cologne Bonn airport is shown in Fig. 2.

The processing times are derived from a literature research. Concerning the attributes of the passengers, we consider the Schengen status as well as the check-in type. We distinguish between a check-in online, at a machine or at a desk. Moreover, we consider if the passengers have to visit the bag drop or not. The distributions for the bag drop status as well as the check-in type are again extracted from a literature study. We gain the information on every passenger's Schengen status from the flight destinations, which are part of the flight plan.

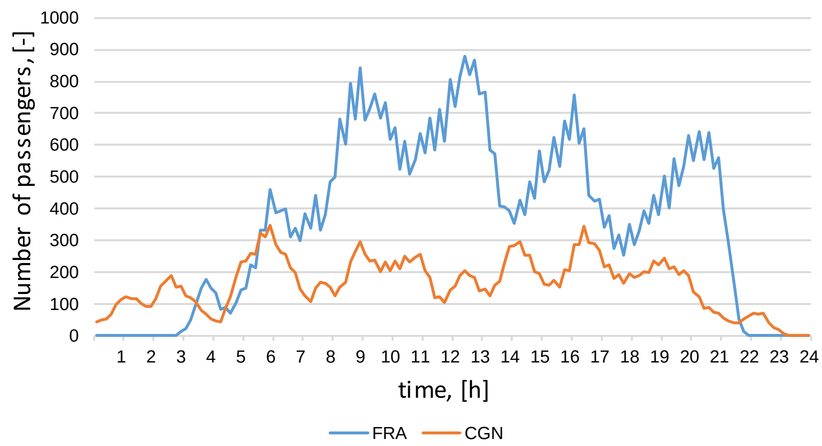

Fig. 2 Number of passengers arriving during the day

As output parameters of the simulation, we can extract the queuing times at each process station as well as the overall system time of each passenger. With this information, we can furthermore determine the passenger throughput of the terminal system. For the calculation of the resilience indicators, we use the system quality. We determine the system quality considering the passenger system time during the simulated period of 24 hours without a disturbance compared to the simulated period of 24 hours with a disturbance.

D. Disturbance Scenario Definition

As disturbance scenario, we chose a terminal clearance being one of the most frequent disturbance events in an airport terminal system. In order to come to this conclusion, all disturbances at the six major German airports have been analyzed for the years 2017 and 2018. A terminal clearance is usually caused by a violation of security requirements in the airside area of an airport terminal, for example when passengers accidentally pass through the security area without having been checked before. All passengers who are already in the airside terminal area at the time of the incident have to return to the landside, public terminal area. Consequently, those passengers must pass through the security control again after the airside terminal area is released.

For the simulation of the disruption scenario "terminal clearance", the start time and the duration of the disruption are varied. The literature search identified a total of 11 terminal evacuations lasting from 45 minutes to just under 5 hours. For the simulation, we assume a duration of 60 min, 90 min and 120 min. The incident starts at 6 am, 12 pm or 6 pm.

To investigate the resilience of airport terminal facilities, the disturbance scenario "terminal clearance" is applied to the three different operational schedules, depicting an average day 2018, the busy day 2019 as well as an estimated busy day 2025. The passenger numbers for the average day 2018 are extracted from [17]. The passenger numbers for the busy day 2019 are derived from the respective flight plan of that day, which was extracted from Flightradar24. The passenger numbers for the busy day 2025 are based on IATA assumptions regarding the expected growth in air traffic, assuming an annual growth of 3.5% concerning passenger numbers [18]. Extrapolated to the year 2025, this results in an increase in passenger numbers to 122.93% compared to the busy day 2019.

An overview about all simulated scenarios is shown in Table 1. Consequently, we will be able to analyze the influence of the start time and duration of the disturbance as well as the operational schedule on the resilience of the terminal system. Moreover, we can identify the impact of the flight plans of Frankfurt airport as well as Cologne Bonn airport on the airport terminal resilience

Table 1 Overview about all scenarios simulated for a model with the flight plan of Frankfurt airport and Cologne Bonn airport

<table>
<tr><td rowspan="2">Operational Scenario</td><td colspan="10">Start time and duration of disturbance</td></tr>
<tr><td>No disturbance</td><td colspan="3">6am</td><td colspan="3">12pm</td><td colspan="3">6pm</td></tr>
<tr><td>Average Day 2018</td><td rowspan="3">-</td><td rowspan="3">60 min</td><td rowspan="3">90 min</td><td rowspan="3">120 min</td><td rowspan="3">60 min</td><td rowspan="3">90 min</td><td rowspan="3">120 min</td><td rowspan="3">60 min</td><td rowspan="3">90 min</td><td rowspan="3">120 min</td></tr>
<tr><td>Busy Day 2019</td></tr>
<tr><td>Busy Day 2025</td></tr>
</table>

III. Results

A. Presentation of the results

Every simulated scenario leads to results concerning the robustness and the rapidity of the terminal system as well as the system performance over time. The output of the simulations on the example of a 60 minute disturbance at 6 am at Cologne Bonn airport on the busy day 2019 is depicted in Fig. 3. The minimum system quality after the disturbance, which corresponds to the robustness of the system, equals 0.0184 around 5 am. As the terminal system is not fully recovering until about 5:30 pm, the time until full recovery equals 11.64 hours. The rapidity indicator is calculated to 0.0859. The indicator considering the system performance over time is calculated to 0.084.

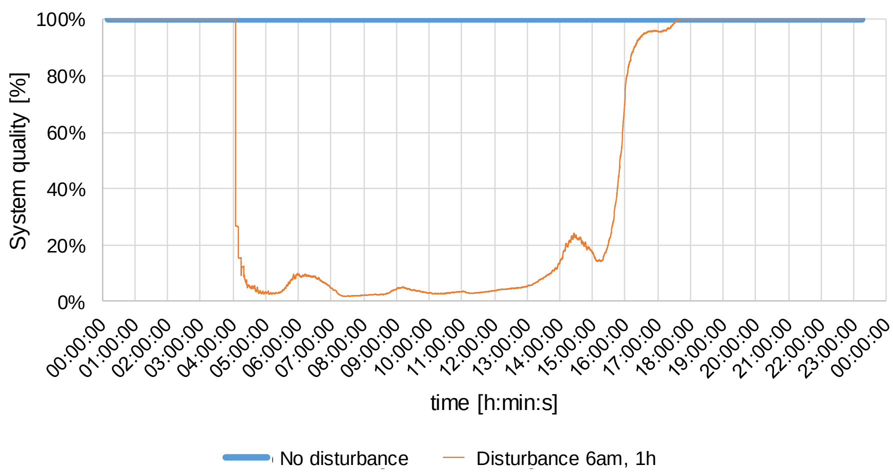

Fig. 3 System quality for a busy day 2019 with and without a terminal clearance

Consequently, in this case we observe a low resilience concerning the robustness, the rapidity and the performance over time of the system. We can conclude a low system resilience for a terminal clearance of 60 minutes at 6 am at Cologne Bonn airport. In the following subchapter, we will describe the results for all simulated scenarios.

B. Resilience Assessment

The resilience indicators for all simulated scenarios are shown in Fig. 4. The simulated terminal models with the flight plan of Frankfurt airport and Cologne Bonn airport show a low robustness in nearly all simulated scenarios. The only exception forms the busy day 2025 scenario in the Frankfurt airport model for a disturbance at 12 pm and 6 pm, where we can observe a medium robustness. Concerning the rapidity, we observe medium indicator values for the average day scenario for both flight plans, with the exception of no resilience in the Frankfurt airport model for disturbances of 90 min and 120 min at 6 pm. In these scenarios, the system is not recovering anymore before the end of the simulation, which leads to a value of 0 for the rapidity indicator. For the busy day 2019 scenario, we observe a low rapidity for a 60 min disturbance at 6 am and no rapidity starting at a 90 min disturbance at 12 pm for Frankfurt airport or at a 90 min disturbance at 6 pm for Cologne Bonn airport. In between, we note a medium rapidity. For the busy day 2025 scenario, there is no rapidity for all simulated disturbance scenarios. Concerning the system performance over time, we observe the highest values compared to the other indicators. For the average day 2018 and the busy day 2019, we note a medium or low resilience depending on the time and duration of disturbance as well as the flight plan. For the busy day 2025, we observe a low system performance over time regarding disturbances at 6 am and 12 am for Frankfurt airport and all simulated disturbances for Cologne Bonn Airport. For disturbances at 6 pm at Frankfurt Airport, we not a high system performance over time.

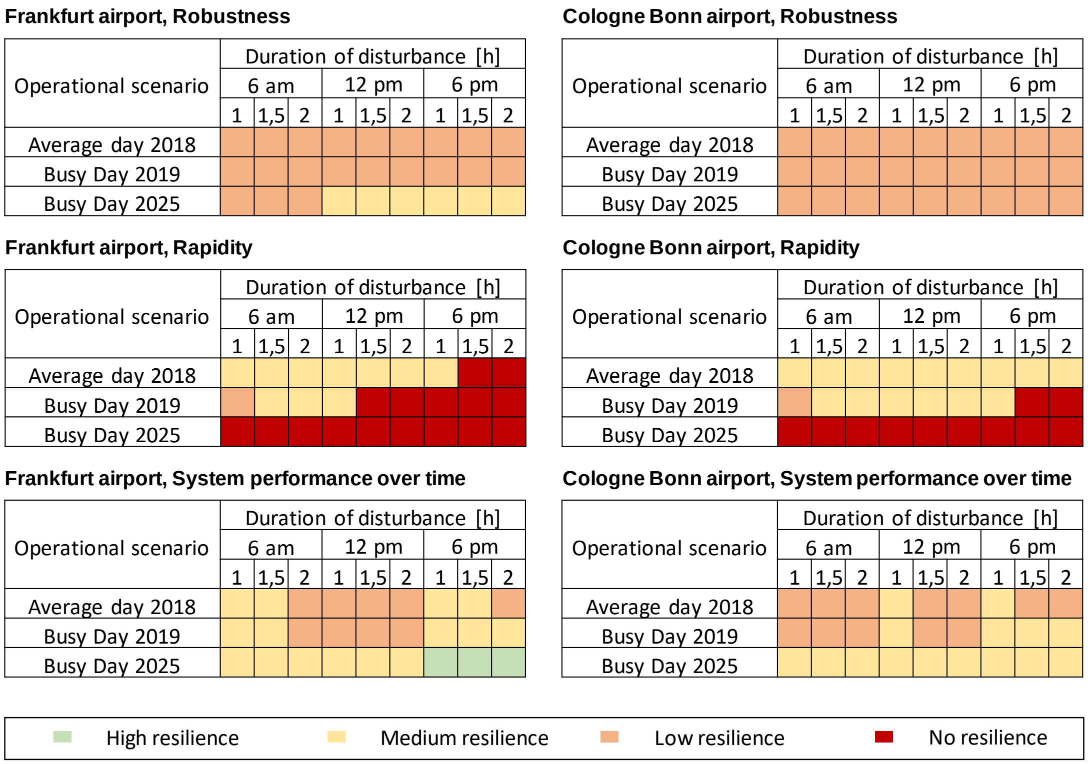

Fig. 4 Evaluation of the resilience indicators for a terminal clearance depending on the flight plan, the time and duration of disturbance as well as the operational scenario

C. Correlations between Input Parameters and Resilience

After evaluating the resilience for the simulated operational and disturbance scenarios, we analyze the effect of the varied input parameters on the airport terminal resilience. Parameters influencing the airport terminal resilience are the occupation of the terminal, which corresponds to the operational schedule, the average day 2018 implying the lowest and the busy day 2025 implying the highest occupation. The start of the disturbance also relates to the occupation and influences the time remaining for a system recovery. Concerning the relation of occupancy and start time of the disturbance, we have to consider both airport models separately, as the peak hour of Frankfurt airport starts at 12 pm while the peak hour of Cologne Bonn airport starts at 6 am. The duration of the disturbance forms another possible influencing factor concerning the airport terminal resilience. Finally, the flight plan of the considered airports remains as an input variable with a potential impact on the indicator values.

Examining again Fig. 4, we observe a slightly higher robustness for the operational schedule busy day 2025. While for the average day 2018 and the busy day 2019, the robustness is low, for the busy day 2025, we note a medium robustness for disturbances starting at 12 pm and 6 pm in the Frankfurt airport terminal model. Consequently, the robustness of the Frankfurt airport model is also slightly higher compared to the robustness of the Cologne Bonn airport model. We cannot detect an influence of the start of the disturbance (including the peak hour) or of the duration of the disturbance on the robustness.

Concerning the rapidity of the airport terminal model, we observe a negative influence of the occupancy. There is no rapidity for the busy day 2025 schedule concerning both simulated airport models. The average day 2018 schedule shows the highest rapidity, which is medium except for the 90 min and the 120 min disturbance in the Frankfurt airport model. Furthermore, we note that an early start of the disturbance leads to comparably higher rapidity values. An increasing duration of disturbance generates comparably lower rapidity values. Finally, the rapidity of the Frankfurt airport model is lower compared to the rapidity of the Cologne Bonn airport model.

The system performance over time indicator shows higher values when the occupation of the model is increasing, the busy day 2025 schedule showing the highest resilience values. Moreover, a disturbance in the peak hour leads to a comparably lower performance over time for both airport models. The disturbance at 6 pm leads to the highest performance over time compared to the disturbance at 6 am or at 12 pm. An increasing duration of disturbance generates comparably lower system performance over time values. Moreover, we observe higher system performances over time for the Frankfurt airport model compared to the Cologne airport model.

IV. Discussion

We include several aspects in this discussion. First, we discuss the resilience assessment and the correlations between input parameters and the resilience of the terminal system. This includes a critical questioning of the plausibility of the results. Afterwards, we will discuss if we can derive possible strategies from the results in order to increase airport terminal resilience.

The robustness of almost every simulated terminal clearance scenarios is low. Consequently, we can identify a need for action to increase airport terminal resilience in terms of robustness for the terminal clearance scenario. However, the comparably higher robustness for the busy day 2025 scenario in the Frankfurt airport model seems unrealistic and reveals a weakness of the relative performance function. For example, very high initial system times due to a high occupancy result in a low sensitivity of the robustness indicator. Only the relative increase in system time is captured and not the absolute increase in system time. Consequently, we could modify the system performance measure $p(t)$ and consider the absolute system time. However, the resilience assessment based on the range of values between 0 and 1 does not hold anymore in this case. We therefore recommend using both the relative indicator and the initial system time in order to draw realistic conclusions.

With regard to the rapidity, both flight plans show medium or no resilience due to the terminal clearance. On an average day, both models can mostly recover from the terminal clearance during the day. On a busy day, however, depending on the time the disruption occurs, there is too little reserve capacity at the security control to handle the large number of passengers who will have to pass through again as a result of the evacuation. For the Frankfurt airport model, we identify a need for actions for disruptions longer than 60 min at 12 pm or for disruptions in the evening. For the Cologne Bonn airport model, we identify a need for actions for disruptions longer than 60 min at 6 pm. In this case, the indicator can help to identify critical time spots, where the terminal system cannot recover from a terminal clearance anymore.

Concerning the system performance over time, we observe comparably higher indicator values. This means that the average system performance does not drop as much as the system performance at a certain time, especially for evening disturbances. However, we note that comparably low or over-utilised systems can lead to misunderstandings. As already observed for the robustness indicator, systems with very high system times in their original state experience proportionally lower increases in system times, so that the indicator suggests a high resilience despite of high waiting times. The relative character of the indicators thus leads to a positive assessment of the system, which is questionable. We observe this effect especially for the busy day 2025 scenario.

The operational schedule, the start time of the disturbance and the flight plan form the most influencing factors on the airport terminal resilience. As the occurrence of the terminal clearance itself already leads to a large number of passengers queuing at the security control, the duration of the clearance has a comparably lower effect on the system performance. The observed correlations concerning the input parameters might therefore be different for other disturbance scenarios.

Concerning strategies to increase airport terminal resilience, we can conclude that reserve capacities especially during peak hours and in the evening might increase the rapidity. Since both airports show the lowest rapidity in their peak hours, the provision of additional resources is particularly advantageous in this time window. The cancellation of flights would increase the system times of the remaining passengers, but would not allow the system to return to its original state. A recovery according to the definition of the key figures would no longer be possible.

V. Conclusion and Outlook

In this paper, we created a basis to assess airport terminal resilience by using three different resilience indicators. The discrete, event-oriented simulations revealed that the indicator system is not fully applicable to all simulation scenarios yet and that boundary conditions such as initial system times need to be considered. Applying the indicator system to other flight plans or to more detailed terminal models can quantify, evaluate and compare the resilience of airports concerning selected disruptions scenarios. Based on the results of this work we can, for example, conclude that the systems investigated mostly show little or no resilience concerning the scenario of a terminal clearance. The operational schedule, the start time of the clearance as well as the flight plan represent the most influencing factors in this case. We can use the same generic model and simulate other disruption scenarios to compare the resilience of the terminal clearance scenario with those other scenarios.

In order to derive airport-specific statements, the generic model can be adapted to a specialized model. For example, to be able to quantify specific measures for a certain airport, the level of detail should be adjusted. Terminal geometries, passenger arrival profiles and processing times should be tailored to the airport. Furthermore, no delays of departures have been included in the analysis so far, but individual passenger system times have been measured. The integration of departure delays into the resilience analysis is a further possibility to refine the representation of real airport operations and to realistically depict the effects of different management strategies. In this context, a monetarization of delays and additional resources can enable an economic evaluation in order to use reserve capacities in an effective manner. A probability analysis of the occurrence of a disruption scenario can further supplement this evaluation.

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