Agent-based modeling to support collaborative decision making in predictable airport ground operations

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***Abstract*—Inside the complex air traffic network, delay occurring at the aircraft stand and related ground processes has the potential to propagate and so increase. This "butterfly effect" typically has a significant negative impact on the downstream flights and airports. Efficient aircraft ground operations can help stabilize the in- and outbound aircraft operations and, in some cases, reduce knock-on effects. Reliably forecasting possible bottlenecks at a dedicated airport and its management is key to optimally using resources and applying appropriate strategies. In this research, we implement the digital twin of a selected airport section, Pier H of Amsterdam Schiphol airport, to simulate the aircraft ground operations throughout the course of a single day using an agent-based model. The agents' behavior representing various ground handling operators is considered for an optimized collaborative decision making process. The consequences derived from operational needs will be demonstrated, and the remedies to reduce operational stress will be put to the test. The findings and lessons offer the possibilities for predictable airport ground operations, both in terms of strategic and tactical planning as well as operations.**

***Keywords*—aircraft ground operations, airport collaborative decision making, agent-based model and simulation, digital twin.**

I. Introduction

Efficient aircraft ground handling at airports is vital to ensure performance operations in the overall air traffic network. Close cooperation between all involved stakeholders (e.g., airport operators, airlines, ground handlers, air navigation service providers) positively improves punctuality and predictability of the aircraft turnaround process. Aircraft generally earn revenue only when in-flight [1]. The airlines consequently aim at constantly minimizing ground times for stand operations at airports.

Airport collaborative decision making (A-CDM) is a concept adopted by ICAO that consists of sharing information of the complex airport system between stakeholders to provide a common situational awareness and to enable mutual strategies to solve operational challenges. It was developed in establishing operational milestones from arrival to departure in order to improve the efficiency and predictability of airport operations and air traffic management indirectly [2]. A performance-based airport environment is needed to enable full A-CDM benefits (e.g., enhanced use of airport resources or reliable scheduling) since airport stakeholders can collectively (and dynamically) work on the agreed performance targets during the day of operations [3]. Integrated management is embodied in an airport operations center (APOC) concept, where all parties involved coordinate tasks to monitor and maintain the agreed performance targets in their respective areas of responsibility to enable total airport management (TAM) [4] following an Airport Operations Plan (AOP). A reliable and fast turnaround process is one of the performance targets, which requires the airport to coordinate all related ground resources properly [5].

In the wake of the COVID-19 pandemic, the aviation industry is gradually regaining its former prosperity. According to a EUROCONTROL's impact assessment before COVID-19 in 2018, a 660 million euros loss per year was computed for the ECAC area due to delays generated by airport ground operations. Thus, any improvements in the aircraft turnaround process, such as improved use of existing airport ground resources or reliable ground support equipment (GSE) scheduling, would contribute to this goal down to a day-to-day operational perspective.

Current airport management mainly contributes to ensuring the requirements of the airlines and the air traffic flow management (ATFM). Ground handlers usually stay in reactive positions. Therefore, the main research is dedicated to investigate the airport ground operations from the ground handlers' perspective. A digital twin of aircraft ground operations and its environment will be developed by means of an agent-based model (ABM) to provide reliable predictions on the aircraft turnaround process. Actual A-CDM milestones do not provide any further information about turnaround processes during the time between in-block and off-block. We will restore the complicated aircraft ground activities to provide explicit hints to APOC and precise e.g., off-block time prediction. Achieving the ability to identify potential bottlenecks in airport ground handling is another purpose of our research.

The paper is organized as follows. Section II provides state of the art on aircraft ground operations research. Section III introduces how the digital twin of a real airport ground environment is implemented by means of agent-based model, and the definitions of the agents inside of it. Section IV describes the simulation design and analyzes the results. Finally, Section V discusses the added value of our approach in the airport environment and the potential extensions on the subject.

II. State of the Art

The airport ground handling activities, as part of the aircraft trajectory over the day of operations, must be part of optimization strategies for minimizing flight delays and ensuring flight connection considering operational uncertainties. The aircraft turnaround is considered to finish when all ground support equipments are disconnected, all doors of the aircraft are closed, the aircraft is ready to leave and the chocks are removed [6]. In this context, a reliable turnaround that depends on buffer time can absorb inbound delays and could enhance slot adherence at airports or mitigate problems of push-back scheduling [7]–[9]. Some research focuses on the critical path of the aircraft turnaround and exhibits that both land- and airside processes can be bottlenecks [10]. The turnaround time refers to the sum of all the activities of the turnaround critical path [11], in such a way that any delay of one of these activities will result in the total turnaround delay. Whenever these processes are part of the critical turnaround path, the effects could also propagate an accumulating delay through the ATM network [12], [13].

Investigations on the reliability of aircraft ground operations show significant improvement potentials in standardization, data quality and availability, process design, integrated planning, and optimization [14]. By giving airport stakeholders access to data from different sources, airports are able to make more accurate predictions about their operational progress in the next planning horizon [15]. In the course of generalizing digitalization in aviation, airports are trying to predict the aircraft turnaround time by machine learning methods with reliable robustness in their operations of day [16]. At the current stage, data can be captured and analyzed from many aspects of airport operations (i.e., weather impact [17]) which are used to monitor the system performance and to identify areas of improvement. With the interpretable Shapley values, a method from coalitional game theory that tells us how to fairly distribute the "payout" among the features, it is possible to analyze the full turnaround time prediction, which would infer the contribution of each sub-process to the total duration [18].

To deal with the complex airport system, simulation method is another option, where agent-based modeling is one of the appropriate tools. These simulations help to observe the emergence of macro-level behaviours but further, the impact of the different micro-level decisions or rules on the whole system, such as, the study of how additional COVID-19 restrictions can affect the terminal operations [19], and the analysis of smart passengers behaviors' impacts on the departure passenger flow at airports [20], etc. Another research [21] built an agent-based model to optimize the number of GSE allocated for airport service planning. In the manufacturing environment, which is similar to the case of the airport ground operations, the multi-agent-based approach has been applied to set feasible working schedules using negotiation/bidding mechanisms between agents [22], [23].

Both the machine learning methods utilized to the aircraft turnaround process and modeling ground operations with simulation can assess predictability. In our research, we plan to build the simulation environment of a real use case, the digital twin of Pier H of Schiphol airport with the aid of ABM to forecast the potential operation situations, which form the foundation of today's situational awareness to all airport stakeholders for real-time monitoring and collaborative decision making. Schiphol airport has applied the computer vision techniques at the aircraft stands to monitor and collect information about the ongoing turnarounds.

III. Methodology

The total turnaround consists of multiple ground operations that can partly take place independently of each other, while others are linked to constraints (e.g., fueling while boarding). This forms the basic model structure for the anticipated agent-based model. The specific aircraft ground operations thus will be described first. Then, we will present the definition and potential of agent-based modeling and digital twin. The properties of the relevant agents of the airport ground operations environment will be described. Finally, the data analysis of Schiphol Pier H and model implementation will be demonstrated.

A. Aircraft ground operations

It is crucial first to understand what occurs on each stand during the turnaround process to create an airport model that accounts for interactions throughout the whole airport on multiple stands. This is a bottom-up method. A concatenation of micro-level behavior constructs that occur at macro-level. Several ground operations contribute to the processes taking place between in-block time and off-block time, which typically consists of the parallel processes of fueling, cleaning, catering, and the sequential processes of the passenger deboarding, boarding as well as the baggage unloading and loading. Many aviation associations and researchers have investigated the technical content in detail [8], [9], [14].

The first process is deboarding, and the last is boarding. Nearly none of the other operations can be completed at the same time. Fueling is too risky for the passengers, and physically deboarding and boarding are hard to proceed while cleaning and catering. The only simultaneous operations allowed are unloading and loading of baggage. Next, most of the aircraft need to be fueled during the turnaround. The amount of fuel depends on the distance to the destination airports and the flight holdings (number of passengers, cargo weight, etc.). Sometimes the fueling is conducted while the passengers are deboarding to shorten the turnaround time. In this case, a fire brigade must be there to monitor the fueling process to ensure the safety of the passengers. Cleaning includes many various jobs like seat cleaning, galley cleaning, toilet cleaning, etc. This procedure is often carried out by a service company. Not every flight requires the completion of all of these requirements. Catering consists of all the tasks related to the loading of food, products and service utilities for passengers to improve the cabin service level. In the unloading and loading processes, normally luggage, containers and mail are handled with two load types of bulk and containers. They can be done in parallel with all other procedures.

We are aware that there are several additional turnaround activities such as ground power supply or ambulifting. However, those are not (yet) taken into account as their influence on the prediction is considered marginal. Deicing, in turn, can produce a major impact on predictability during winter operations [24]. This aspect will be considered at a later stage of our research.

B. Agent-based model and digital twin

An agent-based model is a computing model for simulating the behaviors and interactions of multiple agents (both individual and collective entities, such as organizations or groups), with the goal of better understanding how a system behaves and what factors influence its results, attempting to re-create and predict the appearance of complex phenomena [25]. It includes three key elements:

- Agents: Also known as entities, which make decisions based on the current conditions and interact with each other and with the environment;
- Interaction rules: Define how agents act and interact;
- Environment: The space or case where agents interact.

ABM works like a process of emergence, where complex behaviors (i.e., macro-scale state changing at the whole system level) are produced by simple ones (i.e., agents acting by rules in micro-scale scope) [26]. The entire ABM environment must have a global clock that provides the time reference for all the agents' interactions.

The digital twin can be referred to as a virtual representation of real-world entities and processes, which is applied to simulate performance and develop improvements for the physical equivalent [27]. Fig. 1 presents the definition of the digital twin. Based on the data from the real space, the twin model is built in virtual space in such a way that it can provide the findings and feedback to its physical object after some operations of simulation, diagnosis, optimization, etc. Working with the data connected to the real world, combined with other sources of information, we are allowed to perform the tasks in the digital twin model in advance so that it can help us not only understand the present, but also predict the future.

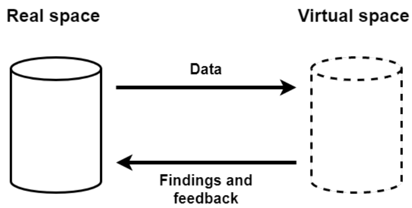


Figure 1. Digital twin model.

Digital twin can improve the behavior of the system or processes, which generally means improving their performance. In the airport environment, the case of ground operations around the aircraft stand positions can just be built to its digital twin with the help of agent-based model, where the ground handling stakeholders and serving objects are considered as the agents.

C. Agents

The components that interact with one another in the environment of airport ground handling are referred to as agents. The different interactions are conducted during the turnarounds when the different crews interact with the aircraft to carry out the corresponding ground operations with the specific equipment. As a result, both the crew members and the GSE are equal in our concept. There are three agent categories considered in our model, which are the agent of airport ground manager, the one of aircraft and the ones of GSE:

- The main role of the ground manager agent is to coordinate the availability of the GSE agents with the aircraft service requests. Different from the other agents, the ground manager agent has a wider knowledge of the whole environment and takes charge of the communication between all the agents. The concrete interactions are depicted in Fig. 2, where the ground manager agent operates and shares information, and the GSE agents perform the service activities to the aircraft agents.

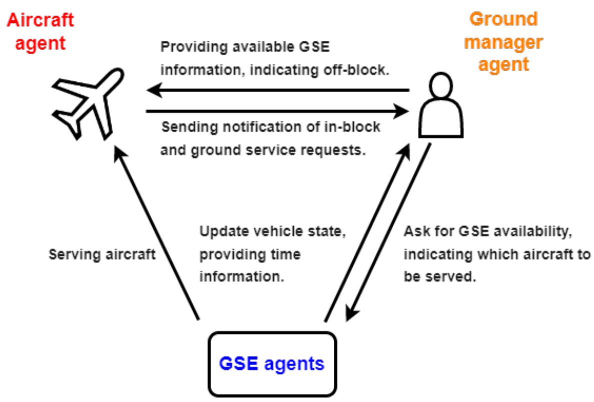


Figure 2. Interactions between the agents.

- The aircraft agents act following the flight arrival plan, and they would send the ground service requests to the ground manager agent.
- For the GSE agents, we will mainly consider the normal movable ground operations. Fig. 3 illustrates the aircraft turnaround workflow in Schiphol Pier H, where nine different ground operations are considered. However, as mentioned in Section III-A, the ground power supply almost accompanies the total turnaround time, and the ambulift service is not always performed. We therefore focus on the ground vehicles serving for deboarding, boarding, fueling, catering, watering, unloading and loading operations. Watering refers to potable water and toilet water services, which needs a specific watering truck.

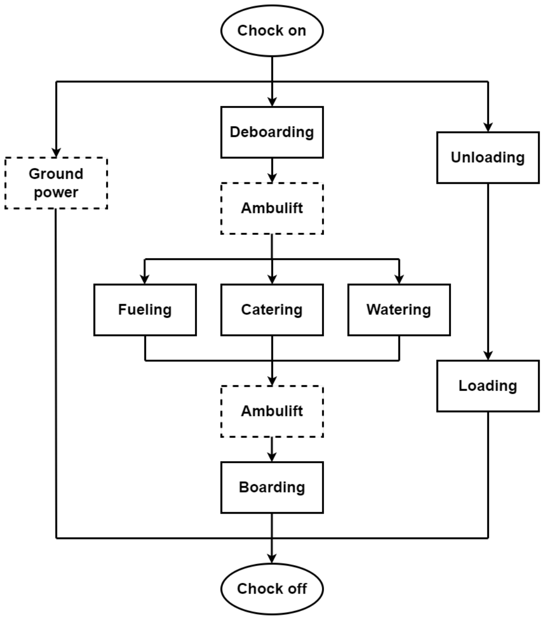


Figure 3. Aircraft turnaround workflow in Schiphol Pier H.

Schiphol Pier H includes docking stands only, where passengers can therefore board aircraft directly when they leave the terminal. In this case, ramps are selected for the agents that are used in deboarding and boarding. Tractors will be the GSE agents for unloading and loading operations. Fueling, catering and watering have their own specific GSE agent types, respectively, which are the fueling truck, catering truck and watering truck. In a word, a total of seven agent types need to be set in the model. They are the ground manager agent, aircraft agent, ramp agent, fueling agent, catering agent, watering agent and tractor agent.

D. Data analysis

The actual dataset used for our research was collected during a busy time span of 2021 summer and autumn, and provided the operations data specifically at Pier H of Amsterdam Schiphol airport. Schiphol is equipped with an aircraft stand monitoring system and applies advanced computer vision technologies to catch the specific GSE movements so that all the operations around the aircraft can be monitored. At the same time, some indicative time stamps of the actions, such as the presence, connection, disconnection, disappearance of GSE, opening and closing of doors, etc., will be automatically recorded. Because of our focus on the aircraft turnaround process, aircraft parking for a longer time up to overnight stand occupancy is taken out of the assessment.

The recorded aircraft ground operations data reflects well the seven activities, which are deboarding, boarding, fueling, catering, watering, unloading and loading. Additionally, some corresponding domain knowledge, like aircraft type, airline company, stand number, etc., can be obtained as well. Fig. 4 shows the time structure of the ground operations for two aircraft series A320 and A319, based on the median value of the relative time stamps. The start and end timestamps of each turnaround sub-process are calculated relative to the actual in-block time (AIBT). We find that 3 minutes after the AIBT, both A320 and A319 start passenger deboarding and their boarding activities finish 34 minutes later. No significant difference in the duration of each ground operation can be observed between the two aircraft series. Only it seems that the A319 catering and watering operations proceed earlier than A320. And in A319 ground operations, there is an overlap of deboarding and watering that should not occur in real-world situations usually. However, this is acceptable from the perspective of the various median value statistic of a dataset.

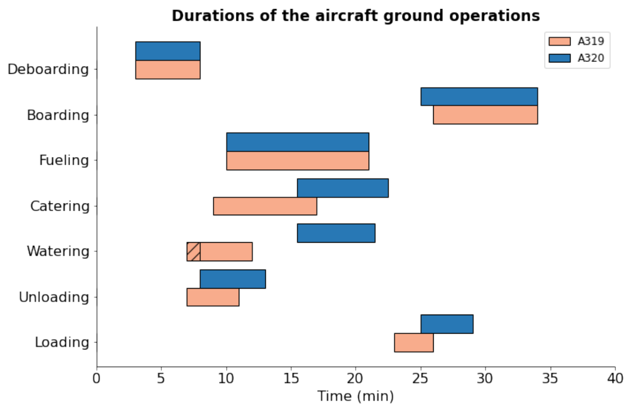
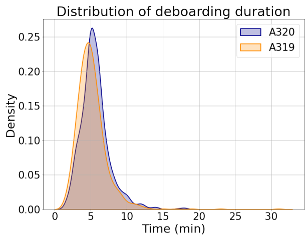
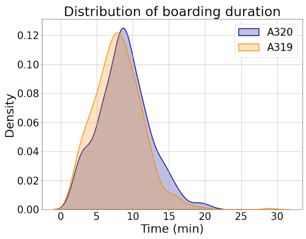


Figure 4. Time structure of the aircraft ground operations based on data median value in Schiphol Pier H.

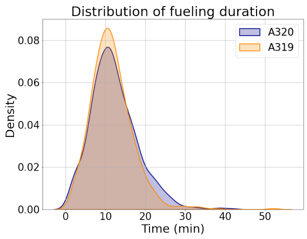
For a real-world aircraft turnaround, the start time of most activities can be handled flexibly by the flight crew. Therefore, investigating the durations of aircraft ground operations would provide more insights. Fig. 5 summarizes the duration distribution of each aircraft ground operation in Schiphol Pier H. Except for unloading, the other operation duration distributions of both A320 and A319 are similar. The durations of A319 unloading are more aggregated compared to A320. In terms of these real data distributions, we typically find the best fit with Weibull or Gaussian distributions.



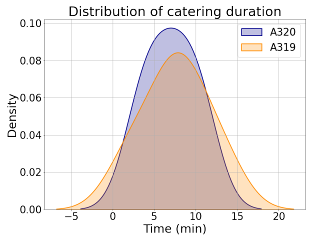
(a) Deboarding.



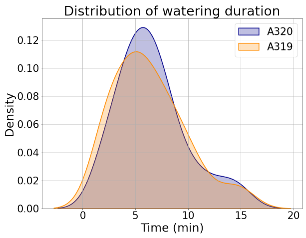
(b) Boarding.



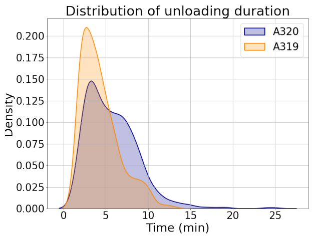
(c) Fueling.



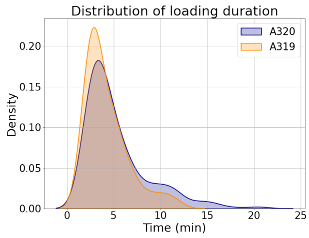
(d) Catering.



(e) Watering.



(f) Unloading.



(g) Loading.

Figure 5. Duration distributions of different ground operations in Schiphol Pier H.

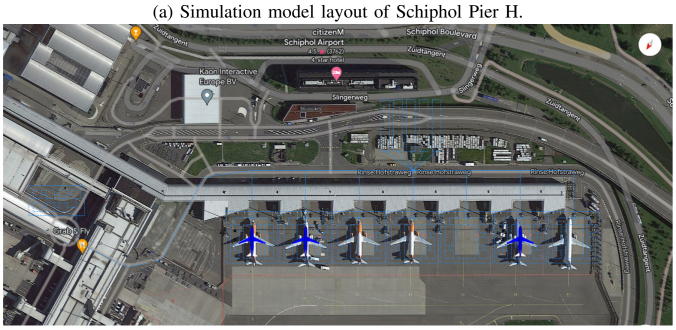
E. Model implementation

This section describes the digital twin implementation of Schiphol Pier H with the help of the defined agents, which will be applied to emulate ground operations. It can be regarded as the test bench for some new technologies, policies, service rules, or advanced ground equipment by changing the parameters or creating new agents before their applications in reality. The simulations will help us forecast the possible operation consequences.

The digital twin model of Schiphol Pier H is built via the platform *AnyLogic*[1]. *AnyLogic* is a multi-method simulation modeling tool, which has a function of visualization so that we can follow the movements of the GSE agents inside the simulation environment. It also supports multiple cores running that can reduce the simulation time significantly. Fig. 6a illustrates the simulation model layout, and Fig. 6b shows the simulation environment on its real geographical background. There are seven aircraft stands, H1 to H7, located from left to right. According to the information confirmed by Schiphol airport, GSEs usually stay in positions near the aircraft stands they are supposed to serve, so we assume in our model that they park centrally near the middle of the H4 stand. The Schiphol main terminals are located on the left, so the baggage take and drop position for loading and unloading operations is assumed to be located on the left. The aircraft stands, GSE parking position and baggage take and drop position are connected following real-world paths.

In our simulation, the ground manager agent tells the GSE agents when the aircraft agents chock on, and the GSE agents will move to the aircraft stands to start their services. The simulation environment is scaled to the layout of real Schiphol Pier H, where we can directly set the GSE moving speed to

(a) Simulation model layout of Schiphol Pier H.



(b) Simulation environment on geographical background.

Figure 6. Preliminary digital twin model of Schiphol Pier H. Background pictures resource: Google Maps, Imagery 2022 Aerodata International Surveys, Maxar Technologies, Map data 2022. Google Maps permits to be used in research papers[2].

the value in the real world. GSE speed is limited to 10 Km/h, as per Schiphol Group Operations Manuals [28].

Table I presents the time-related characteristics of the aircraft ground operations in our basic model. Firstly, we choose a Gaussian distribution to fit the service times of A320 and A319. As illustrated in Fig. 7, the ground operations usually cannot be performed immediately after the completion of the previous one, and the buffer times in between should be taken

[1]https://www.anylogic.com/
[2]https://www.google.com/intl/en-GB_ALL/permissions/geoguidelines/

TABLE I. TIME RELATED CHARACTERISTICS OF THE AIRCRAFT GROUND OPERATIONS [MIN]: GAUSSIAN DISTRIBUTION (μ, σ).

Ground operations	A320 service time	A319 service time	Buffer time	Preparing time
Deboarding	Gaussian (5, 2)	Gaussian (5, 2)	Gaussian (5, 2)	-
Boarding	Gaussian (9, 3)	Gaussian (8, 3)	-	-
Fueling	Gaussian (11, 5)	Gaussian (11, 5)	Gaussian (5, 2)	Gaussian (15, 2)
Catering	Gaussian (7, 4)	Gaussian (8, 5)	Gaussian (10, 2)	Gaussian (15, 2)
Watering	Gaussian (6, 3)	Gaussian (5, 3)	Gaussian (10, 2)	Gaussian (15, 2)
Unloading	Gaussian (5, 3)	Gaussian (4, 2)	Gaussian (15, 5)	-
Loading	Gaussian (4, 2)	Gaussian (3, 1)	-	-

into account. Besides, the fueling, catering and watering trucks need to do some preparations between two aircraft turnaround processes, such as, to refuel the fueling truck, and to settle down the catering and watering trucks, etc. Therefore, the buffer time and preparing time are also considered in the model.

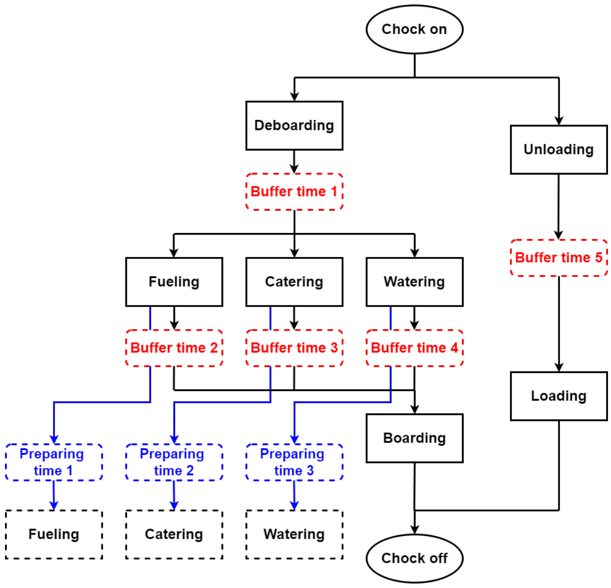


Figure 7. Turnaround process considered buffer times and preparing times in Schiphol Pier H.

As expected, infinite GSEs will always lead to a minimal total turnaround time (MTTT) in aircraft ground operations. We should limit the GSE numbers and set the required GSEs for one turnaround. Table II describes the assumed GSE agent fleet size and service required GSE amounts.

TABLE II. GSE AGENT FLEET SIZE AND SERVICE REQUIRED GSE AMOUNTS.

GSE agent	Fleet size	Service required amounts
Ramp agent	4	Required 2 ramps for deboarding and boarding, respectively.
Fueling agent	2	Required 1 fueling truck for fueling.
Catering agent	2	Required 1 catering truck for catering.
Watering agent	2	Required 1 watering truck for watering.
Tractor agent	3	Required 1 tractor for unloading. and loading, respectively.

IV. SIMULATION DESIGN AND RESULTS

The flow of flight arrivals at Schiphol Pier H varied regularly during the week, so we would choose one busy day to simulate the aircraft turnaround process. After eliminating the overnight aircraft, 29 flights, or aircraft agents, remain in our simulation. The aircraft arrival and departure flight plans are shown in Fig. 8a and Fig. 8b in every 15 minutes. Fig. 8c illustrates the cumulative arrival and departure flights on the day of the operation, where the space in between indicates the number of the occupying aircraft stands (or the aircraft in service) at each time point. We will apply the "first come, first served" rule, which means that the early arriving aircraft will receive the GSE service earlier than others. How to determine whether a departure aircraft is delayed, is a challenge in our simulation, since we do not have a reliable reference for the departure time requested by the airport manager. Therefore, we assume that, the actual in-block time of each aircraft would be regarded as the reference starts of their turnaround processes, while the actual off-block times would be the required turnaround ends. Obviously, we will evaluate the aircraft turnaround punctuality as the metrics.

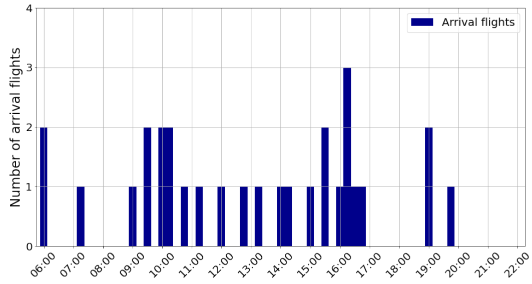
The basic model has been introduced in Section III-E with all its parameters. To mitigate the potential aircraft outbound delays in our simulation, we have also developed four policies, which are:

- **Policy 1**: Increasing the GSE numbers to provide more service resources, the new GSE fleet sizes are shown in Table III;

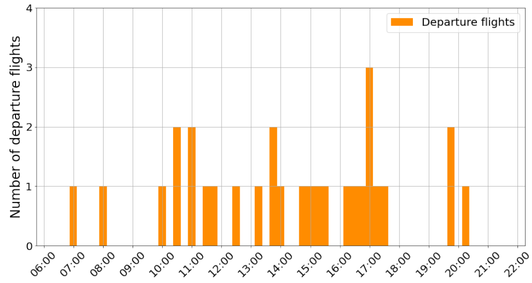
TABLE III. UPDATED GSE AGENT FLEET SIZE.

GSE agent	Fleet size
Ramp agent	8
Fueling agent	4
Catering agent	4
Watering agent	3
Tractor agent	4

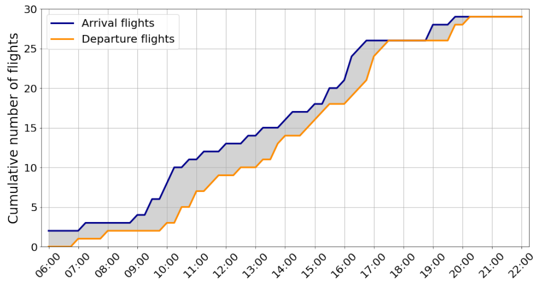
- **Policy 2**: Removing (reducing) the buffer times in between for the delayed aircraft;
- **Policy 3**: Indicating the aircraft agent in-block time to the GSE agents 10 minutes prior to the start of the turnaround so that the GSE agents can act in advance, which is what usually happens in real operations thanks to the A-CDM concept;
- **Policy 4**: Combining Policy 2 and Policy 3.



(a) Arrival plan.



(b) Departure plan.



(c) Cumulative arrival and departure flights on the day of the operation.

Figure 8. Arrival and departure flights over one day in Schiphol Pier H.

At first, the simulation results of the basic model compared with the reference turnaround time are reviewed, what is performed in Fig. 9. From an air traffic management perspective, if the aircraft can meet the planned off-block time in the scope of $[-5, 10]$ minutes, a new airport slot does not need to be released so that the departure can be regarded on time. Nevertheless, any aircraft with a departure difference of over 10 minutes will be considered a delayed flight. We also count the aircraft number in the difference intervals of $(-\infty, -20)$ and $[-20, -5)$ minutes, which means that these aircraft can finish their ground operations much earlier than the planned off-block times. This statistical data will help to check the residuals of aircraft turnaround time, which can be further used in the following steps to improve airport resource arrangement. In the basic simulation, there were eight aircraft delayed. The analysis of the concrete start and end service time stamps of each GSE inside every turnaround process showed that two main bottlenecks contribute to this result: (i) the assumed GSE numbers are insufficient to handle the aircraft during peak hours, especially with the lack of ramp, fueling and catering service capacities; and (ii) the buffer times between the services are not reduced or canceled in tight turnaround time windows.

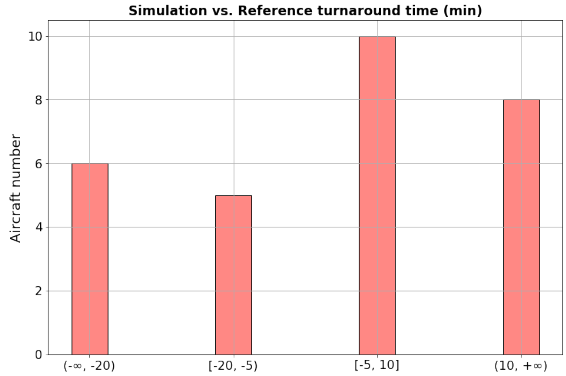


Figure 9. Comparison results of simulation and reference turnaround time in basic model.

Fig. 10 illustrates the delay for different predefined tactics. By increasing the available GSE numbers in Policy 1, we find that the delayed aircraft number is reduced to five. Most of the turnaround times of these delayed aircraft are only around 35 minutes but in the afternoon peak hours, where they require some additional operations to cut down the delays. Policy 2 removes the buffer times, and the GSE fleet sizes remain unchanged. It performs better solution measures showing only two delayed aircraft, which result from the late fueling services. In Policy 3, we neither add more GSE resources nor reduce buffer times but anticipate the ground handling by informing the GSE agents of the guess of the aircraft in-block time in advance, allowing them to provide services as soon as the aircraft chock on. In this case, the aircraft delayed number is four without any actual increase in GSE workloads, but still, the delays are mitigated, demonstrating the benefits of A-CDM information sharing for aircraft ground operations. Policy 4 combines Policy 2 and Policy 3 together, which can avoid delays completely. It provides useful advice in low-latency aircraft ground operations and exhibits the model's ability to simulate some complex combined strategies.

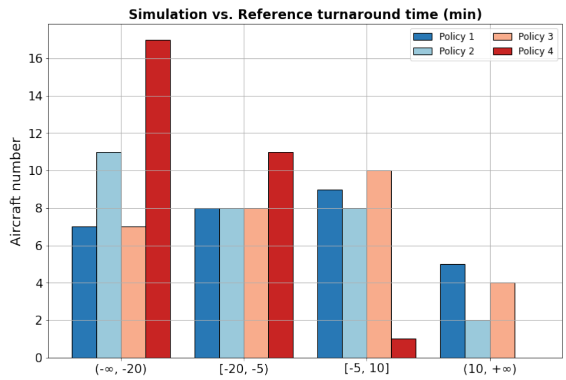


Figure 10. Comparison results of simulation and reference turnaround time in different applied policies.

V. Conclusions and Recommendations

In this paper, we introduced the definitions of the agent-based model and digital twin, and their potential benefits for airport ground operations and total airport management. In order to implement the digital twin of an actual airport airside environment by means of ABM, three agent categories of airport ground manager, aircraft and GSE were described. In general, the ground manager agent coordinates and shares information, and the GSE agents serve the aircraft agents. Through the collaboration of all these agents, the system contributed to making the decisions for the uniform to reduce aircraft departure delays and provide concrete insights on the GSE units. Next, the real use case of the digital twin of Schiphol Pier H was built on the platform *AnyLogic* to simulate the airport ground operations. The results revealed the possible bottleneck positions before the exact operations, which could be the limited GSE resource or the non-required buffer times. The digital twin of the airport airside environment, with the aid of ABM, enabled us to simulate some delay mitigation policies and evaluate the outcomes in advance, which would be difficult to achieve in actual operations. Due to the limitations of my in hand *AnyLogic* edition, Monte-Carlo-Simulation is not currently supported. However, it can be conducted with a higher software version to provide robustness of the simulation.

Our approach could be beneficial to all the parties involved in ground handling and airport operations. For example, ground managers can use it as a reference to airport resource planning, and ground handlers can obtain operation advice as well. It has the advantage of predicting and identifying the potential situations that would give the preconditions to strengthen the cooperation significantly in the scope of the airport. This work offers new research avenues that the authors will investigate in the future, such as that we can rearrange airport resources considering the priority of the aircraft. From the perspective of ground handling, various service rules can be simulated. In addition, the number of ground resources will be optimized depending on the operational tasks and objective functions. Combined with reinforcement learning methods, we can give agents real “business intelligence”.

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