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DOI
10.1504/IJSPM.2017.10010587
Publication date
2017
Document Version
Proof
Published in
International Journal of Simulation and Process Modelling

Link to publication

Citation for published version (APA):
Scala, P., Mujica Mota, M., & de Bock, N. (2017). A divide and conquer approach for simulating an airport system. *International Journal of Simulation and Process Modelling*, *12*(6). https://doi.org/10.1504/IJSPM.2017.10010587

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A Divide and Conquer Approach for Simulating an Airport System

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Abstract: Airport capacity, expressed as the maximum number of air traffic movements that can be accommodated during a given period of time under given conditions, has become a hard constraint to the air transportation, due to the scarce amount of resources on the ground and restrictions in the airspace. Usually the problem of capacity at airports is studied separating airspace operations from ground operations, but it is evident that the two areas are tied to each other. This work aims at developing a simulation model that takes into account both airspace and ground operations. The approach used is a divide and conquer approach, which allows the combination of four different models. The four models refer to the airside, and airspace operations. This approach allows to evaluate the system from different angles depending on the scope of the study, the results show the analytic potential of this approach.

Keywords: simulation model; airport ground operations; airspace operations; divide and conquer approach; data driven decisions.

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1 Introduction

As many authors stated, the runway system at airports is the main bottleneck of the global air transportation (Idris et al., 1998). Looking at the trends for the next coming years, it is expected that the demand of traffic will increase, therefore, the study of an efficient use of

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the resources involved in air transport operations is a key aspect. The actors involved in the air transportation industry come up with different solutions to cope with the problem of lack of capacity. For instance, a solution could be the expansion of current facilities such as new runways or new gates, other solutions regard the optimization of the existing resources in order to improve the efficiency of the various processes involved in airport operations. The former solution seems to be the most natural one, but it is the worst in terms of time and investments needed, on the other hand, the latter seems to be a challenging one in which techniques from operations research gain importance due to the type of problems to be solved. Another solution could be the development of the so called multi-airport system (De Neufville and Odoni, 2003), in which capacity is spread on a network of airports constituted by a main airport (hub) and some secondary airports (non-hub). The purpose of the multi-airport system is to relieve capacity at the main airport (hub) and increase the capacity of the overall system in order to satisfy the demand of their catchment area. Airports included in a multi-airport system need to be close to each other and well connected to each other in order to make the choice of the airport from/to which depart/arrive irrelevant.

In this context, the analysis of airport operations assumes an important role in the short-term capacity planning and forecast. Airport operators require to be aware of the capacity limit of the airport using the given facilities and resources. Due to the increase in the air traffic demand, airspace is getting busier and it affects also the workload of air traffic controllers. Airlines, from their perspective, want to increase the number of their destinations and they are putting pressure on the airport operators asking for more slots. In such a context it is noticeable that all the main stakeholders involved in the air transportation are affected by the lack of capacity. A solution should be given to them in order to cope with all their different objectives. This leads to look for solution where the airport system is considered as a whole, not only focusing on a specific part but making a global analysis taking into all different components. The first thing to consider when making a global analysis of the airport system is the interactions between the airspace and ground operations. These interactions are more evident when the ground is congested, because then the airspace is asked to to absorb this congestion accommodating as much aircraft as possible in order to avoid disruptions of the service. If the airspace has not the capability of absorbing the congestion occurred on the ground, a chain effect is triggered, with delays imposed by air traffic control to the aircraft in the airspace (e.g holding pattern procedures, alternative routes, speed control). On the contrary, delays occurred to aircraft in the airspace (e.g. due to weather conditions) are translated on the ground as well. This fact drove the study presented in this paper taking a holistic perspective, therefore, in this work an integrated model of airspace (Terminal Manoeuvring Area) and ground operations was developed.

The objective of this work is to evaluate the interactions of the different subsystems and also the performance of the entire system more accurately. Based on our review we found simulation as the only tool able to cope with the particularities of the aforementioned problem, since simulation approach allows us to be more flexible in representing the different processes which are characterized by being concurrent, dynamic and stochastic. This approach is widely used in many different fields of research, for instance, in manufacturing, Tajini et al. (2014) used simulation approach for decomposing the production system, and coming up with a general and modular model for the production processes. In the maritime field, Nicoletti et al. (2014) developed a hybrid model for optimizing the turnaround time for vessels at sea port terminal container employing simulation together with genetic algorithms. In the aviation field we find also the work of Mujica (2015a) who presented a coloured petri net formalism in order to cope with the check-in allocation. Concerning road transportation, Pekel and Kara (2016) proposed a simulation model for the scheduling of the fleet for public transportation. Moreover, in the work of Piera et al. (2014) coloured petri nets and a multi-agent system were used for developing a collaborative decision making related to social dynamics. These problems could not be approached with analytical techniques due to the rigid representations required for obtaining a solution which in most of the cases might be unfeasible or not realistic enough for being implemented.

In this work a simulation model was developed employing a divide and conquer approach in which the airport system was divided in four different models representing the main components of the airport system, and then in a second stage, these models were integrated to obtain a representation of the entire system (Airspace + Ground side) in order to perform a more accurate analysis of the whole system.

The paper is organized as follows, in section 2 a literature review is conducted in order to have a clear idea of what the research community has found so far concerning airport capacity issues. In section 3 the divide and conquer approach is presented, the characteristics of the submodels and the way in which they were combined were described here. In section 4 the different scenarios and the results obtained from the integrated model were presented and compared to the results from each of the submodels, in section 5 some conclusions were drawn.

2 Literature review

Many studies have been made about the improvement of airport capacity, some refer to the optimization of ground operations and others to airspace operations and terminal capacity. Regarding ground operations, most of the studies are related to gate allocation, optimization of taxi-in and taxi-out routes, scheduling of departing aircraft and operations related to the turnaround process. From literature we can see that different methodologies were used for solving these kinds of problems, most of them employ analytical and heuristic solutions. For instance, in the work of Dorndorf et al. (2007) a large survey is provided about various models and solutions techniques utilized for the gate scheduling problem, Bolat (2000) solved the gate assignment problem using a Branch&Bound algorithm, combined with the use of two heuristics. In the work of Narciso and Piera (2015), a colored Petri net formalism was implemented with the objective of calculating the number of aprons necessary in order to absorb the arrival/departure traffic. Other authors proposed models to avoid congestion on the ground using pushback control strategy (Pujet et al., 1999; Simaiakis and Balakrishnan, 2014), (Khadilkar and Balakrishnan, 2014). For the terminal operations, the work of Mujica (2015a) presents the allocation of desks using simulation and optimization techniques. Concerning the airspace, in the specific Terminal Maneuvering Area (TMA), the main findings are related to the sequencing and merging of aircraft flow problems, while other works face the problem of scheduling arrival aircraft. The main objectives of most of the studies are to ensure separation minima and avoid conflicts between aircraft (Michelin et al., 2009; Zuniga et al. 2011-2013), and optimizing the sequence of aircraft in order to decrease delays (Beasley et al., 2000-2001-2004; Balakrishnan and Chandran, 2010; Murca, 2015). Recently scientific community has put attention to discrete event simulation approaches to solve airport capacity issues. For example Mujica et al. (2015b) put focus on the ground operations and also Scala et al. (2015) on airspace operations aiming at evaluating the performance of the systems in terms of capacity. In this framework, the present work aim at analysing the airport system as a whole and evaluating its capacity under different conditions. The main contribution of this work is that it employs a divide and conquer approach where first the main components of the airport system were identified and then modelled. After that the different models were combined into one model representing the wole airport system. Airspace as well as ground operations were taken into account together, coming up with a more reliable analysis. This study was conducted employing a discrete event simulation approach, a valid technique for the performance analysis of a system.

3 DEVELOPMENT OF THE SIMULATION MODEL

In this work, the simulation model of Lelystad airport was developed. Lelystad airport is a regional airport of the Netherlands, currently, it accommodates only general aviation traffic, but in the future it will accommodate commercial traffic (Schiphol Group, 2014). This work takes into account not only ground operations but also airspace (TMA) operations, obtaining an integrated angle of the airport system.

3.1 Integrated model

This section explains how a divide and conquer approach was applied in order to develop an integrated model, including four different sub-models. This approach allows to analyze the airport system as a whole. In line with a divide and conquer approach, dividing the system in different sub-models, each one representing a sub system of the airport, the integration of them has made possible to come up with a unique and integrated model that keeps the characteristics of the sub-models and gives as an output a more accurate and realistic view of the system. If we wanted to analyze the entire system, an integrated approach results better than analyzing separately the sub-models. In real cases, the operation represented in the sub-models, interact each other affecting the performance of the entire system. In order to develop the integrated model it has been used a discrete-event simulation software called SIMIO. It is a general purpose discrete-event simulation software that allows modelling a wide range of systems. When the different models are combined together, some entities are shared, and then the behaviour and properties of these entities are modified due to the interaction with the submodels. Figure 1 represents the architecture of the different submodels.

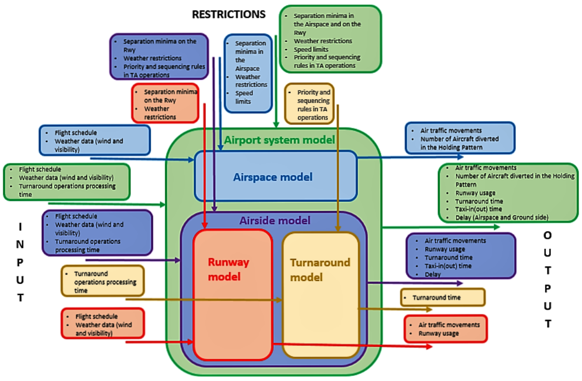

Figure 1 Representation of the interactions between the different submodels in the integrated model

In the integrated model, the entity aircraft is generated from the Airspace submodel, where the logic of that specific model is applied such as separation minima between aircraft, speed limits, effect of the wind and the holding pattern procedure. Then it continues through the airside model where the aircraft entity lands, complete the taxiing-in, turnaround, taxiing-out and take off operations following the logic implemented in that model. In this case the airside model is already an integration of two models, runway and turnaround models, therefore, here the entity implicitly follows the logic implemented in these two models. Finally, after the aircraft crosses the runway for taking off, it enters again in the airspace model following the restrictions given by the logic implemented into the airspace model until it reaches the last point of the model. Table 1 and 2 show the characteristics of the system and the main assumptions taken into account.

Table 1 Characteristics of the Airport system

Number of Runways	1
Number of exitways	1
Taxiway Type	Parallel
Number of Stands	16
Holding Pattern characteristic(number, capacity and speed limit)	1 (for each route), 2 Aircraft, 200 kt
Mix of Aircraft	Code C (B737 - A320)
Number of exitways	1

The different models themselves are self-contained in the sense that different studies can be performed: airspace studies, runway operations, ramp studies. When these models are put together the emergent dynamics are perceived. The main outcomes of the integrated model include the outcomes of the different submodels, the difference is that from the integrated model more accurate values can be obtained since all the components of the system are taken into account simultaneously. The main improvement obtained by the development of an integrated system, is the analysis of the delay, since both airspace and ground delays are taken into account. The evaluation of ground operations performance can be done with more accuracy when the airspace is included than when only the airside is considered, for instance, when aircraft are diverted into the holding pattern, they will land later than the expected causing disruptions on the ground side.

For the modelling of large systems the proposed approach in opinion of the authors is the most appropriate since one can perform the development of subsystems and perform the verification and validation of the subsystem which later can be coupled with other subsystems. Therefore it is a progressive approach in which we end up with the model of complex systems keeping always the control of the fidelity of the model.

Table 2 Main assumptions

Flight Schedule	Built taking into account traffic at Amsterdam Schiphol Airport in the peak hours
Airspace Routes	One route for each of the Runway configuration
Noise	No noise issues were taken into account

3.2 Submodels

Each of the submodels included in the integrated one, represent the following operations:

- Runway operations (Submodel #1); runway occupancy, mix of movements (landings and takeoffs handled) (Mujica et al. 2014).
- Turnaround operations (Submodel #2); boarding/deboarding of passengers, refueling, water service, catering service and baggage in/out. All these operations are made when the aircraft is parked at the apron.
- Airside operations (Submodel #3); landing process, taxiing processes, turnaround process and departing process (Mujica, 2015b).
- Airspace operations (Submodel #4); The main logic applied to the TMA are related to the operations made by aircraft during their approach and departure to and from the runway, they are: separation between aircraft; speed limit; holding pattern procedure; change of runway configuration; effect of wind direction and crosswind (Scala et al. 2015).

In the following paragraphs all the submodels that were used to build the integrated model are presented, providing a description of their main characteristics and their main outcomes. From now on we will refer to the different submodels as: submodel #1, submodel #2, submodel #3, submodel #4.

3.2.1 Submodel #1

In this model all the operations related to the runway system of the airport (Lelystad airport) are represented. In figure 2 input, output and restrictions related to this submodel are represented. Different scenarios were tested based on different volume of traffic and different runway configuration (with normal exitways or with high-speed exitways) (see figure 3). The most relevant results obtained were about number of air traffic movements and runway usage among others. Moreover, it was possible to obtain realistic values about runway occupancy time (see Table 3).

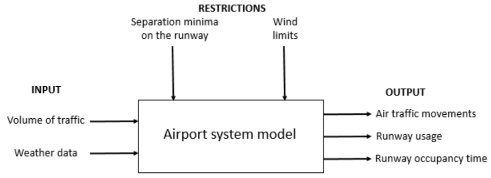

Figure 2 black-box representing input, output and restrictions of submodel#1

Table 3 Results from submodel#1

		Runway configuration with normal exitways	Runway configuration with 2 normal exitways and one high-speed exitway
Flight Schedule 1	Air Traffic Movements	20626	22158
	Runway usage	7.34%	8.05%
	Runway occupancy time [s]	64.47	59,99
Flight Schedule 2	Air Traffic Movements	12293	11781
	Runway usage	2.62%	2.51%
	Runway occupancy time [s]	64.46	59.90
Flight Schedule 3	Air Traffic Movements	36683	36589
	Runway usage	7.55%	7.23%
	Runway occupancy time [s]	64.43	59.96

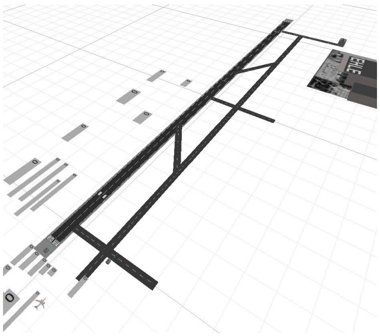

Figure 3 Runway Configuration with high-speed exitways

3.2.2 Submodel #2

This submodel represents the operations at the apron. The main operations are boarding and de-boarding of passengers, loading and unloading baggage, re-fueling, water service, cleanings and catering. Every operation needs a vehicle to be used, therefore we have these different types of vehicles in use: fuel truck, bus for passengers, trucks for baggage loading/unloading, catering service, cleaning service and water service. In figure 4 shows the input, output and restrictions of the submodel. Values about time were represented by random variables and data was gathered from the main manufacturers of aircraft for specific types of aircraft (Boeing 737, Airbus A-320) (see Table 5). Depending on constraints about priority and sequencing rules within the turnaround operations, it was possible to identify the operations that most affect turnaround time. In figure 4 a visualization of the Submodel #2 is presented. Turnaround time values obtained from the model range between a minimum of 39,23 minutes and a maximum of 41,37 minutes with an average of 40,35 minutes.

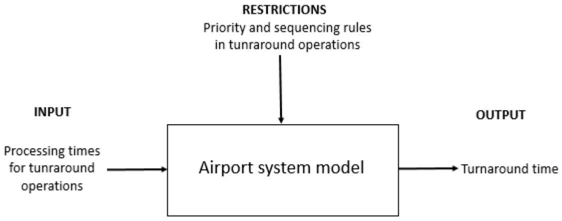

Figure 4 black-box representing input, output and restrictions of submodel#2

Table 4 Times for Turnaround operations

Operation	Distribution	Time
Positioning stairs	Random triangular	90,120,150 (sec)
De-boarding	Random triangular	3,4,5 (min)
Luggage out	Random triangular	5,7,11 (min)
positioning	Random triangular	40,60,80.9 (sec)
Luggage in	Random triangular	5,7,9 (min)
positioning	Random triangular	40,60,80.9 (sec)
Fueling	Random triangular	7,8,9 (min)
positioning	Random triangular	4,5,9 (min)
Cleaning	Random triangular	8,13,16 (min)
positioning	Random triangular	1,2,3 (min)
Water service	Random triangular	4,5,6 (min)
positioning	Random triangular	1,2,3 (min)
Boarding	Random triangular	4,5,6 (min)
Headcount	Random triangular	90,120,130 (sec)

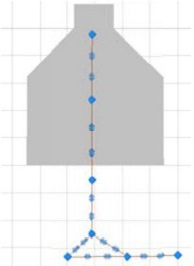

Figure 5 Submodel #2

3.2.3 Submodel #3

In this model, the previous two submodels (submodel #1, submodel #2) were combined. The result is a model that represent the airport airside, including runway operations (landings and takeoffs); taxiing operations; and turnaround operations. The Submodel #1 was linked to the submodel #2 by the taxiway network. In this case we have 16 aprons, in other words, the submodel #2 was replicated 16 times. Figure 6 summarize the main restrictions, input and output applied to the submodel. All the logic concerning the submodel #1 and submodel #2 were kept. In the taxiway network, the logic about speed regulation and path choice was implemented in order to let the aircraft cross the taxiway at the right speed and to go to and from the assigned apron. Once aircraft are landed, they occupy the first apron available from left to the right. The logic implemented make sure that aircraft do not have conflicts during taxiing operations, therefore, it is likely to have aircraft waiting in queues in some parts of the taxiway network, especially when there is high volume of traffic. Different scenarios were based on incoming volume of traffic, different layout of taxiways geometry (see figure 7), different modes of crossing the taxiway (left-right, center-out) and different number of vehicles involved in the turnaround operations. The parameters that characterize the two submodels were used to build the different scenarios, these parameters are: different layout of taxiways and number of vehicles, they refer to submodel #1 and submodel #2, respectively. In tables 5 to 10 the main results such as turnaround time and deviation from off block time (DOBT) are shown. The latter, is an indicator of delay, it calculates the difference between the time when the aircraft has finished all the necessary operations and is ready to leave the apron, and the time when the aircraft physically leaves the apron. Values of DOBT equal to zero mean that the aircraft leave the apron as soon as the turnaround operations are finished, on the other hand, in some situations, the area close to the apron could be very busy, due to the presence of other aircraft and ground vehicles that are involved in the turnaround operations, in this cases we might find positive values of DOBT.

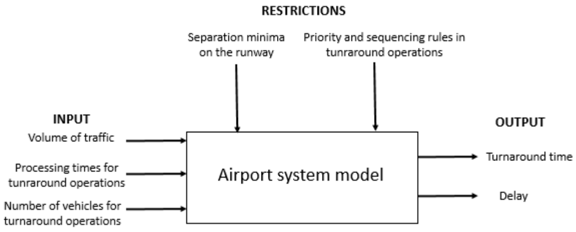

Figure 6 black-box representing input, output and restrictions of submodel#3

The main results from this model are related to taxiing times, turnaround time and delay at the apron due to conflict between vehicles on the taxiway (DOBT). These results refer to the apron and taxi configuration "C", that is the one used in the integrated model. With the integration of these models we can assess the effect of the relationships between the different processes, for instance, traffic congestion could be seen on the taxiway due to unavailability of aprons, and this could be a consequence of high turnaround times, that is, in turn, a consequence of the unavailability of vehicle for turnaround operations. From the results it can be seen that the configuration that gives the best results is the Center-Out with 100% of vehicles (see Table 10), here we find, depending on the traffic, minimum values of turnaround time between 27 ad 28 minutes, average values between 29 ad 30 minutes and maximum values that are around 33 minutes.

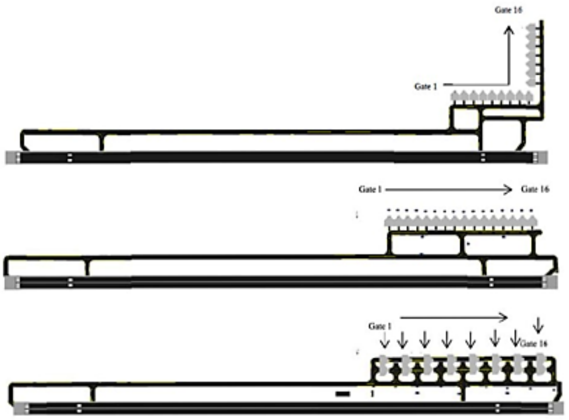

Figure 7 Different configurations of apron and taxiways: from top to bottom configuration A, B and C

Table 5 Results from submodel #3 (Conf. C, Left-Right, 50% vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	32.47	40.03	45.58
DOBT [min]	-	-	-
45K movements	Min	Avg	Max
Turnaround Time [min]	31.72	34.72	37.65
DOBT [min]	-	-	-
50K movements	Min	Avg	Max
Turnaround Time [min]	29.62	33.00	40.18
DOBT [min]	-	-	0.44

Table 6 Results from submodel #3 (Conf. C, Center-Out, 50% vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	28.32	30.69	33.70
DOBT [min]	-	-	0.09
45K movements	Min	Avg	Max
Turnaround Time [min]	28.26	30.60	33.70
DOBT [min]	-	-	0.35
50K movements	Min	Avg	Max
Turnaround Time [min]	31.33	35.16	40.01
DOBT [min]	-	-	-

Table 7 Results from submodel #3 (Conf. C, Left-Right, Flex vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	31.13	37.46	49.57
DOBT [min]	-	-	0.47
45K movements	Min	Avg	Max
Turnaround Time [min]	27.91	31.51	35.38
DOBT [min]	-	-	0.6
50K movements	Min	Avg	Max
Turnaround Time [min]	28.16	32.14	41.95
DOBT [min]	-	-	-

Table 8 Results from submodel #3 (Conf. C, Center-Out, Flex vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	27.49	32.29	38.78
DOBT [min]	-	-	-
45K movements	Min	Avg	Max
Turnaround Time [min]	27.48	31.85	39.78
DOBT [min]	-	-	0.36
50K movements	Min	Avg	Max
Turnaround Time [min]	28.27	32.13	37.65
DOBT [min]	-	-	-

Table 9 Results from submodel #3 (Conf. C, Left-Right, 100% vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	31.09	39.65	48.79
DOBT [min]	-	-	0.34
45K movements	Min	Avg	Max
Turnaround Time [min]	27.85	30.40	34.19
DOBT [min]	-	-	-
50K movements	Min	Avg	Max
Turnaround Time [min]	27.21	29.75	32.35
DOBT [min]	-	-	-

Table 10 Results from submodel #3 (Conf. C, Center-Out, 100% vehicles)

40K movements	Min	Avg	Max
Turnaround Time [min]	27.45	29.70	33.06
DOBT [min]	-	-	0.04
45K movements	Min	Avg	Max
Turnaround Time [min]	27.31	29.66	33.06
DOBT [min]	-	-	0.33
50K movements	Min	Avg	Max
Turnaround Time [min]	28.12	30.56	33.94
DOBT [min]	-	-	0.73

3.2.4 Submodel #4

In this model, the focus was put on the airspace of Lelystad airport, in the specific the TMA. Figure 8 show input, output and restriction related to the submodel #4. The TMA could be could be very congested because of the volume of incoming and outgoing aircraft converging on the runway(s). The TMA is a restricted zone, aircraft should fly following these restrictions, and due to that, the capacity in the TMA is very limited. Below the restrictions applied to the TMA are listed:

- Speed: depending on which segment is flown, there are an upper and a lower bound for speed
- Altitude: it depends on the airspace sector, in each sector there is a minimum and a maximum altitude
- Separation minima between aircraft: longitudinal separation due to wake turbulence. Depending on the leading and trailing aircraft type there are different values of separation
- Weather (crosswind and wind direction): depending on the wind direction, the runway configuration is changed
- Topology of the routes: it depends on the location of the main nodes of the routes. They are the entry and exit point of the TMA, initial approach fix (IAF) and final approach fix (FAF) that are the points where the final approach leg starts and ends, respectively

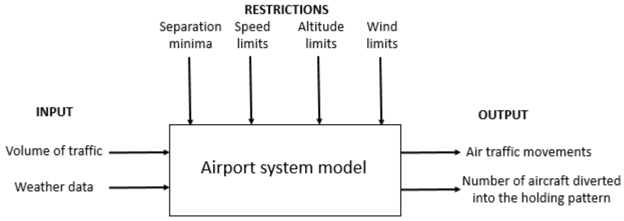

Figure 8 black-box representing input-output and restrictions of submodel#4

In the submodel #4 the aircraft approaching and departing phase to and from the runway was modeled. Another component that characterizes this model is the holding pattern procedure, the holding pattern is an area in the airspace used to divert temporarily aircraft that needs to gain a delay due to congestion on the ground or congestion along the route in the airspace or due to disruptions (crosswind occurrences). The holding pattern has its own capacity, depending on the airspace sector in which it is placed. Moreover, aircraft into the holding pattern should fly at a certain speed, a turn in the holding pattern is assumed to take around four minutes. The airport airside consists of one runway that can be used in both directions, having, in turn, Runway

23 and Runway 05. The airspace topology includes a route for arrivals and departures, for each of the runway configurations, runway 23 and runway 05, respectively. The use of these different runway configurations depend on the wind direction. The routes in the TMA, including the holding pattern, were modeled as a network. In figure 9 it can be seen the topology of the routes and the main nodes of the network.

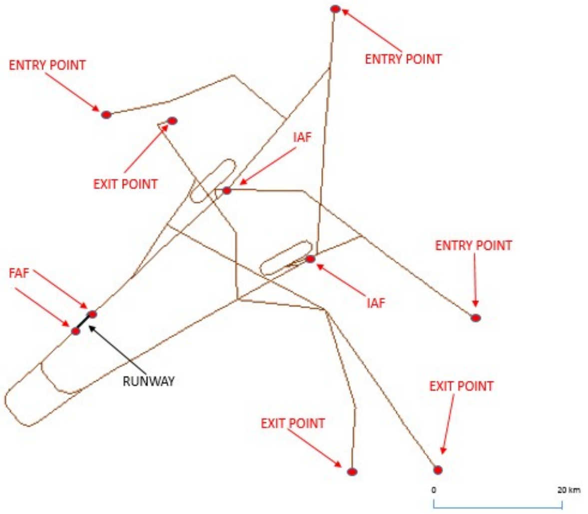

Figure 9 Network representing the routes for Runway 23 and 05

In this network, separation minima between the aircraft and speed limit were checked in each of the nodes of the network, in Table 11 and 12 values for separation minima and speed limits are shown. Below the main logic implemented are explained:

- Separation minima between aircraft (time based), it was fulfilled controlling aircraft speed, accelerating and decelerating in turn.
- The effect of the wind (direction and crosswind), it was modeled referring to data of wind direction and crosswind collected in the 2014 and then translated into the model as probabilities of occurrences.

Table 11 Separation minima (NM) ICAO

		LeadingAircraft		
		Heavy	Medium	Light
Trailing Aircraft	Heavy	4	3	3
	Medium	5	4	3
	Light	6	4	3

Table 12 Aircraft speed range in the TMA

	Upper Bound	Lower Bound
Entry Point	250 kt	160 kt
Initial Approach Fix	160	130 kt
Final Approach Fix	-	130 kt

Table 13, shows results about performance indicators concerning the airspace, they refer to a scenario with high traffic incoming which gives significant results in terms of system congestion rather than other scenarios with less traffic. In average there are 8 aircraft diverted into the holding pattern, and they spend in average 5,32 minutes flying into it. Figures 10 and 11 show how values about aircraft diverted into the holding pattern and amount of time spent by aircraft into the holding pattern are distributed. Figure 10 shows that in the 18% of the occurrences no aircraft are diverted into the holding pattern, in the 78% of the occurrences the number of aircraft diverted into the holding pattern is between 0 and 25, and in the 4% of the occurrences more than 25 aircraft are diverted into the holding pattern. In figure 11 is shown that in the 11% of the occurrences an aircraft make one turn into the holding pattern, and int the 89% of the occurrences an aircraft make two turns. These results suggest that in most of the cases the airspace is not able to handle the incoming demand.

Table 13 Results from Submodel #4

	Min	Avg	Max
Aircraft diverted into the holding pattern	0	8	44
Avg Time spent into the Holding Patter by Aircraft [min.]	0	5.32	8

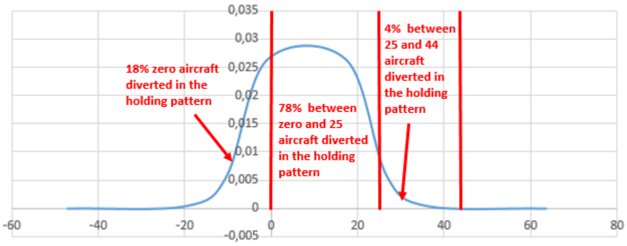

Figure 10 Aircraft diverted into the Holding Pattern values distributed according to a Gaussian distribution

4 SCENARIOS AND RESULTS

The case of study considered on this work, is Lelystad Airport, a general aviation airport of the Netherlands.

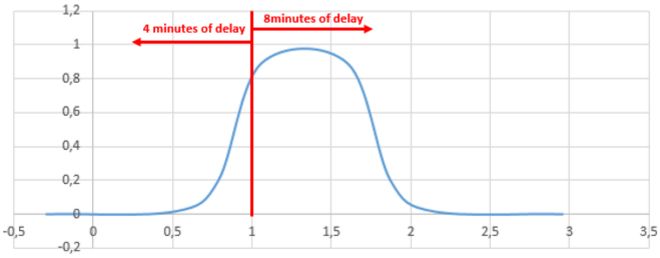

Figure 11 Values of Average time spent by aircraft into the Holding Pattern distributed according to a Gaussian distribution

It has gained importance in the last years because the Dutch government has decided to upgrade it, making it able to accommodate commercial traffic. At the moment they are still in a planning phase that is why this work aim at assessing the potential future capacity for such airport. Due to this fact, it was not possible to conduct a real and complete validation of the simulation model. Historical data is missing and the main assumptions were made based on public information and hypothetical traffic scenarios. In our benchmark study, we chose another airport of the same region (Eindhoven) as test case. Our test case was chosen based on the geometrical characteristic of its layout which are very similar to our case of study. It has been assumed that in the future the airport will accommodate the same amount of traffic as the airport considered as a test case. Different scenarios, based on the volume of incoming traffic and the number of set of vehicles available for the turnaround process were tested. By increasing the amount of traffic as input, we aimed at identifying the maximum capacity that the system was able to handle without incurring in congestion. Delays occurred in the airspace and on the airside were considered as a congestion indicator. From the model, we obtained performance indicators such as incoming and outgoing number of aircraft, number of aircraft diverted into the holding pattern, delay due to airspace operations, turnaround time and ground delay due to taxiway congestion.

4.1 Experimental Scenarios

The experiments were conducted considering different scenarios reflecting different potential situation that can be experienced from the airport in the future. As we have mentioned before the amount of traffic tested is the same as Eindhoven airport. In this manner it was possible to test the model in a realistic potential scenario. According to the future forecasts about the growth of the European air traffic, and also to the different traffic scenarios planned by the authorities in charge of the development of the airport, we have based the different scenarios on a progressive increase of the traffic with the objective of testing the ability of the system to absorb this traffic. Three different flight schedules were tested, they are listed:

- Flight Schedule 1, around 48 movements per day
- Flight Schedule 2, around 67 movements per day
- Flight Schedule 3, around 90 movements per day

Furthermore, another parameter was utilized in order to generate new scenarios, which is the number of set of vehicles involved in the turnaround operations. A set of vehicles includes all the vehicles needed to perform the turnaround operations for an aircraft, therefore, one vehicle for each operation. This parameter is important for the airport operator in order to design the facilities required to perform the turn around operations for the aircraft. It is interesting to see what is the impact of the vehicles on the performance of the system. Theoretically few set of vehicles should generate high delays for aircraft, especially in the peak times when there is high density of traffic on the ground. In this study three different values were utilized, they are listed below:

- 2 set of vehicles available for turnaround operations
- 8 set of vehicles available for turnaround operations
- 16 set of vehicle available for turnaround operations

It was simulated one day of operations and there were made 10 replications for each scenario, Table 14 illustrates the different scenarios that were tested.

Table 14 Scenarios

		Incoming volume of aircraft		
		Flight Schedule 1	Flight Schedule 2	Flight Schedule 3
Number of vehicles	2	Scenario 1	Scenario 4	Scenario 7
	8	Scenario 2	Scenario 5	Scenario 8
	16	Scenario 3	Scenario 6	Scenario 9

4.2 Results

The performance evaluated are a measure of the level of congestion, they are related to airspace congestion like the number of aircraft diverted into the holding pattern and also to airside congestion like turnaround time and DOBT. The following tables summarize the results from the different scenarios:

Looking at the values of the first three scenarios (tables 15 to 17), it can be seen that there are no aircraft diverted into the holding pattern for runway 23 and there is only 1 aircraft diverted for runway 05. Furthermore, turnaround time and DOBT are similar between the three scenarios, this means that with the given amount of incoming traffic, they are not affected by the number of vehicles. The results also suggests that the incoming traffic is not affected and the system is not congested.

Table 15 Results from Scenario 1

Flight Schedule 1 - Number Of Vehicles=2			
	Min	Avg	Max
Incoming aircraft Runway 23	17	21.4	24.5
Incoming aircraft Runway 05	3.5	5.58	8
Outgoing aircraft Runway 23	16	21.05	24.5
Outgoing aircraft Runway 05	4.5	5.41	8.5
Aircraft diverted into the HP (05)	1	1	1
Average number of turns made by each aircraft diverted into the HP (05)	1	1	1
Time spent into the HP (05) [min]	4	4	4
Total Time at the apron (avg) [min]	32.36	39.87	77.49
Turnaround Time (avg) [min]	29.43	30.33	31.34
DOBT (avg) [min]	2.36	9.52	47.10

Table 16 Results from Scenario 2

Flight Schedule 1 - Number Of Vehicles=8			
	Min	Avg	Max
Incoming aircraft Runway 23	21	32.7	48
Incoming aircraft Runway 05	9	17	27
Outgoing aircraft Runway 23	21	33.1	48
Outgoing aircraft Runway 05	8	16.23	26
Aircraft diverted into the HP (05)	1	1	1
Average number of turns made by each aircraft diverted into the HP (05)	1	1	1
Time spent into the HP (05) [min]	4	4	4
Total Time at the apron (avg) [min]	33.57	40.19	52.18
Turnaround Time (avg) [min]	30.54	32.39	35.43
DOBT (avg) [min]	2.06	7.39	19.01

Table 17 Results from Scenario 3

Flight Schedule 1 - Number Of Vehicles=16			
	Min	Avg	Max
Incoming aircraft Runway 23	9	27.2	39
Incoming aircraft Runway 05	9	20.8	39
Outgoing aircraft Runway 23	10	28.5	40
Outgoing aircraft Runway 05	8	19.2	38
Aircraft diverted into the HP (05)	1	1	1
Average number of turns made by each aircraft diverted into the HP (05)	1	1	1
Time spent into the HP (05) [min]	4	4	4
Total Time at the apron (avg) [min]	33.39	39.15	53.21
Turnaround Time (avg) [min]	31.04	32.25	35.50
DOBT (avg) [min]	2.01	6.49	18.54

Table 18 Results from Scenario 4

Flight Schedule 2 - Number Of Vehicles=2			
	Min	Avg	Max
Incoming aircraft Runway 23	9.5	21.2	33.5
Incoming aircraft Runway 05	3.5	11.83	24.5
Outgoing aircraft Runway 23	10	18.25	33
Outgoing aircraft Runway 05	3.5	10.83	22.5
Aircraft diverted into the HP (05)	3.5	3.5	3.5
Aircraft diverted into the HP (23)	2.5	3.25	4
Average number of turns made by each aircraft diverted into the HP (05)	0.79	0.87	1
Average number of turns made by each aircraft diverted into the HP (23)	0.99	1.98	3
Time spent into the HP (05) [min]	3.16	3.48	4
Time spent into the HP (23) [min]	3.96	7.92	12
Total Time at the apron (avg) [min]	32.77	41.38	59.37
Turnaround Time (avg) [min]	30.32	34.63	44.90
DOBT (avg) [min]	1.99	6.75	24.02

Table 19 Results from Scenario 5

Flight Schedule 2 - Number Of Vehicles=8			
	Min	Avg	Max
Incoming aircraft Runway 23	29	47.8	67
Incoming aircraft Runway 05	8	21.33	38
Outgoing aircraft Runway 23	27	46	67
Outgoing aircraft Runway 05	12	21.11	39
Aircraft diverted into the HP (05)	1	1.4	3
Average number of turns made by each aircraft diverted into the HP (05)	1	1.2	2
Time spent into the HP (05) [min]	4	4.48	8
Total Time at the apron (avg) [min]	34.08	46.51	97.38
Turnaround Time (avg) [min]	31.16	32.34	34.19
DOBT (avg) [min]	2.20	13.55	64.09

In tables 18, 19 and 20 there are the values related to the fourth, fifth and sixth scenario, they show that the number of aircraft diverted into the holding pattern is slightly increased together with the average number of turns made by each aircraft into the holding pattern. The latter, in turn, is translated into delay at landing. Turnaround times are in line with the previous scenarios but values of DOBT are increased, we have in average 6.75 min, 13,55 min and 16,40 min for scenario 4, 5 and 6, respectively.

In the last three scenarios presented in tables 21, 22 and 23, under a high inbound traffic, we find again, for both runway 23 and 05, aircraft diverted into the holding pattern. Particularly, looking at the seventh and ninth scenario, it can be seen that they are more congested than eighth scenario. In the seventh scenario there are many more aircraft diverted into the holding pattern, in average 7.72 and 3.48 for the holding pattern of runway 23 and for the holding pattern of runway 05, respectively. In the same scenario values of DOBT assume higher

Table 20 Results from Scenario 6

Flight Schedule 2 - Number Of Vehicles=16			
	Min	Avg	Max
Incoming aircraft Runway 23	25	44	59
Incoming aircraft Runway 05	8	23	42
Outgoing aircraft Runway 23	24	43.4	55
Outgoing aircraft Runway 05	11	225	40
Aircraft diverted into the HP (23)	1	1	1
Aircraft diverted into the HP (05)	1	2	5
Average number of turns made by each aircraft diverted into the HP (23)	2	2	2
Average number of turns made by each aircraft diverted into the HP (05)	1	1.33	2
Time spent into the HP (23) [min]	8	8	8
Time spent into the HP (05) [min]	4	5.19	8
Total Time at the apron (avg) [min]	32.58	50.21	95.57
Turnaround Time (avg) [min]	30.41	31.49	33.56
DOBT (avg) [min]	2.06	16.40	55.54

Table 21 Results from Scenario 7

Flight Schedule 3 - Number Of Vehicles=2			
	Min	Avg	Max
Incoming aircraft Runway 23	15.5	21.9	25.5
Incoming aircraft Runway 05	5.5	6.16	7.5
Outgoing aircraft Runway 23	5.5	7.6	9.5
Outgoing aircraft Runway 05	2.5	2.66	3
Aircraft diverted into the HP (23)	5	14.4	21
Aircraft diverted into the HP (05)	2	9.5	15
Average number of turns made by each aircraft diverted into the HP (23)	1.60	1.93	2.28
Average number of turns made by each aircraft diverted into the HP (05)	0.87	0.87	0.87
Time spent into the HP (23) [min]	6.4	7.72	9.12
Time spent into the HP (05) [min]	3.48	3.48	3.48
Total Time at the apron (avg) [min]	44.91	64.81	97.32
Turnaround Time (avg) [min]	35.25	42.56	53.16
DOBT (avg) [min]	7	22.24	56.13

Table 22 Results from Scenario 8

Flight Schedule 3 - Number Of Vehicles=8			
	Min	Avg	Max
Incoming aircraft Runway 23	38	62.20	90
Incoming aircraft Runway 05	16	26.33	51
Outgoing aircraft Runway 23	38	64.4	87
Outgoing aircraft Runway 05	15	24.55	48
Aircraft diverted into the HP (23)	1	1	1
Aircraft diverted into the HP (05)	1	2.25	6
Average number of turns made by each aircraft diverted into the HP (23)	2	2	2
Average number of turns made by each aircraft diverted into the HP (05)	1	1.48	2
Time spent into the HP (23) [min]	8	8	8
Time spent into the HP (05) [min]	4	5.55	8
Total Time at the apron (avg) [min]	33.37	37.30	45.43
Turnaround Time (avg) [min]	30.33	31.56	33.43
DOBT (avg) [min]	2.34	5.33	13.01

Table 23 Results from Scenario 9

Flight Schedule 3 - Number Of Vehicles=16			
	Min	Avg	Max
Incoming aircraft Runway 23	27	46.4	80
Incoming aircraft Runway 05	3	30.4	56
Outgoing aircraft Runway 23	21	44.47	83
Outgoing aircraft Runway 05	1	27.8	52
Aircraft diverted into the HP (23)	1	1	1
Aircraft diverted into the HP (05)	1	2.28	5
Average number of turns made by each aircraft diverted into the HP (23)	1	1.35	2
Average number of turns made by each aircraft diverted into the HP (05)	2	2	2
Time spent into the HP (23) [min]	4	5.24	8
Time spent into the HP (05) [min]	8	8	8
Total Time at the apron (avg) [min]	112.33	117.10	127.40
Turnaround Time (avg) [min]	30.11	31.19	32.52
DOBT (avg) [min]	81.55	85.58	96.12

values, in average 22.24 min. It can be explained by the fact that the little amount of set of vehicles leads to have slow turnaround operations and as a consequence the increase of delays on the ground. Delays generated on the ground, due to the limited capacity, affect in a small extent also the airspace that needs to hold more aircraft before they are cleared to land by the air traffic controllers. On the other hand, in the ninth scenario, with 16 set od vehicles, high values of DOBT were found. It means that taxiway is over-crowded by vehicles and aircraft at the same time, therefore, aircraft are stuck at the gate for a long time before they are able to reach the runway. This fact leads to think about changing the design of the taxiway in order to have a smooth flow of aircraft on the ground surface and avoid blockages. These results suggest that the best configuration of number of set of vehicles is 8, since in this scenario the system is not affected by long delays and the number of aircraft diverted into the holding pattern is small.

4.3 Comparison of results from integrated model with the ones from the submodels

Looking at turnaround times, submodel #2 evaluates turnaround times (see section 3.2.2) that are bigger than turnaround times evaluated with the submodel #3 (see tables 5 to 10), and the integrated model (see tables 15 to 23), except for the ninth scenario of the integrated model. It means that, representing a more detailed and complete model, as we do when we consider the submodel #3 and then the Integrated model, we find more accurate results than the ones from submodel #2.

Regarding the DOBT between the Submodel #3 (see tables 5 to 10) and the integrated model (see tables 15 to 23), it can be noticed that the latter model has higher values than the former model. This is explained by the fact that, when we add the airspace in the Submodel #3, we add an additional factor that change the dynamic of the system and it affects the the average delay on the taxiway. In some occurrences, the high congestion due to interaction between airspace and ground, produces deadlocks on the taxiway that induce the system to breakdown. Thus the use of the different submodels allowed us to identify the true limits of the system as a whole which could not be identified without the overlaying of the differnt models.

In the submodel #4, we have found aircraft diverted into the Holding Pattern (see Table 13) testing a scenario with high traffic, instead, in the integrated model (see tables 15 to 23), we have found aircraft diverted into the Holding Pattern also when we consider a scenario with less traffic, they increase as the traffic is increased and also changing the number of vehicles available on the airport surface. This fact suggests that in the submodel #4, due to the assumption related to the ground, the system is able to process all the traffic incoming without incurring in congestion problems. When we analyse the integrated model, we take into account new constraints and limited factors like physical capacity of the taxiway, apron and taxiway layout, blockages due to aircraft and vehicles on the airport surface. These limiting factors lead the airspace to act as a buffer in order to make the system able to process all the aircraft incoming, a first consequence is the frequent use of the Holding Pattern as a buffer for the landing aircraft.

5 Conclusions

In this paper, a simulation model that employs a divide and conquer approach is presented. The approach itself allowed us to analyze the different subsystems isolated from the rest and then we could progressively increase the complexity of the model overlaying the different models. This approach allowed to perceive the emergent dynamics of the whole system. The final model integrates the models for the following subsystems: runway, aprons, airspace and taxi network. The model developed was done using a bottom-up approach in which several subsystems were modeled independently and then put together in a model that integrate the different ones airport (runway, aprons, airspace). We could identify several benefits by progressively overlaying models. Two are the main ones: the identification of the limits (practical capacity) for the different subsystems and also of the system as a whole; and the identification of the cause-effect relationships that rule the performance of the system. We encourage the scientific community to use this approach for the study of these systems, since the progressive overlaying of systems impose restrictions which bring as a consequence the reduction of the capacity and one can use this knowledge for improving the performance of the system.

Acknowledgement

The authors would like to thank the Aviation Academy of the Amsterdam University of Applied Sciences for the support to perform this study.

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