Airport traffic optimisation and airdrome analysis using mathematical modelling

Douae Zbakh[1], Marwane Benhadou[2], Abderrahmane Benkacem[1], Abdelouahid Lyhyaoui[1]
[1]National School of Applied Science, Innovative Technology Laboratory, University Abdelmalek Essaadi, Tangier, Morocco
[2]Faculty of Economics and Management, Laboratory of Research in Management and Development, University Hassan I Settat, Settat, Morocco

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ABSTRACT

An airport is considered to be a complex system, so managers nowadays are looking for verifiable solutions that could be tested and virtually simulated, in order to optimize safety, improve regularity, and reduce delays and risks of collision. To respond to this dilemma, many solutions were tested using safe simulation methods. The specific problem tackled in this paper refers to aerodrome capacity optimization, and specialy arcrafts mouvements. For this purpose, we introduce a mathematical model that was applied to Mohamed V Casablanca Airport, and the corresponding event actualization and graph was constructed taking into account uncertainty in flight schedules, aircraft types and their stand. Finally, the airdrome model was simulated using a special parameter in Arena tool.

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Corresponding Author:

Douae Zbakh
National School of Applied Science, Innovative Technology Laboratory, University Abdelmalek Essaadi Tangier, Morocco
Email: douae.zbakh@gmail.com

1. INTRODUCTION

Travelling through an international airport is a stressful experience for both passengers and airport decision makers; it affects many aspects such as management, safety and security, and passenger's satisfaction. In an aerodrome which occupies 80% to 95% of the airports' superficies, the airport efficiency is particularly important to prevent delays and risks of collision, especially since the cost of the workforce and security is increasing. To solve these problems, managers should test many solution scenarios of using safe simulation methods. Indeed, simulation is an accessible method to test all processes in a virtual way, with the possibility of editing parameters and adding constraints to obtain instantaneous results. This simulation offers a method to fully explore the resources with lower costs and without security breach [1], [2].

Systems modelling is based on the construction of a virtual model from real world data. This model must be easy to simulate in such a way that the management of the airports can be improved by testing many hypotheses and using airport model simulation to prevent system damages and additional costs. Simulation is a useful means to plan maintenance works or to assess the level of efficiency of functional systems, as well as monitoring systems' complexities and failures [3].

Traffic optimization in aerodromes is a crucial aspect of airport operations. With the increasing volume of air traffic, there is a growing need to efficiently manage aircraft movements on the runway, taxiways, and parking areas. Optimization of traffic flow can improve safety, reduce delays, and increase capacity, which ultimately translates into improved operational efficiency and cost savings. To achieve this, various approaches have been proposed, ranging from traditional methods such as deterministic scheduling and queuing theory to dynamic optimization techniques based on machine learning and intelligent algorithms. These methods take into account various factors, such as weather conditions, flight schedules, aircraft type, and ground vehicle movements. The use of simulation models and real-time data analysis further enhances the effectiveness of traffic optimization.

So, this paper is about the Mohamed V Airport mathematical; it concerns landing, take-off, and taxi-in/out processes, using mathematical modelling and a static method to optimize aerodrome. The approach simulation uses Arena tool. The paper is structured as follows; after the introduction section we address literature reviews of basic methods used to optimize airdromes. Section 3 presents the mathematical model of Mohamed V International Airport of Casablanca using event succession tables and graph. Section 4 deal with Mohamed V Casablanca Airport mathematical simulation of landing, take-off and taxi-in/out processes based on Arena tool. The section 5 is devoted for conclusion and perspectives.

2. LITERATURE REVIEW

Previous studies reported in literature review propose optimizations algorithms to reduces delays and manage congestion in airports using Arena tool. The literature was divided in two groups, the first one concerns statistical methods and the second focus on dynamic models. This paragraph was devoted to statistical methods related works, such as queuing models [4], statistical regression approaches [5], fuzzy rule-based systems [6]. Khanmohammadi *et al*. [7] expose a method approach for scheduling aircraft landings at John F. Kennedy (JFK) Airport in New York City for optimizing airport runway capacity. Bouras *et al*. [8] provides an overview of the airport gate assignment problem (AGAP), which involves the allocation of airport gates to arriving and departing flights, it is covers various aspects of the AGAP, including mathematical models, optimization techniques, and solution approaches. Ravizza *et al*. [9] highlighted the importance of accurate taxi time estimations in reducing delays and improving the efficiency of airport operations. They noted that current estimation methods were often inaccurate and did not account for the variability in ground movement patterns [9]. The authors propose a static method for optimizing airport surface operations, such as aircraft movement at Tokyo International Airport [10], [11]. Queuing models are also used to optimize traffic management at airports, authors use their model to evaluate different traffic management strategies and find the approach that could reduce delays and improve efficiency [4], [12].

Many dynamics methods were adopted in aviation to deliver available time to fly, eliminate collision and optimize airdrome. Such as genetic algorithm used to optimize the runway and reduce aircraft waiting times and improve runway capacity, the created model takes into account capacity constraints (aircraft types, weather conditions, gate capacities and airline preferences [13], [14]. The authors highlighted the importance of accurate wind speed prediction for various applications, such as renewable energy generation and air pollution control. They noted that conventional prediction methods often suffer from low accuracy and limited generalization ability [15], [16]. Balakrishna *et al*. [17] proposes a dynamic optimization approach for airport surface traffic based on a multi-agent system. The method considers various factors such as aircraft size, speed, and parking location, and uses a simulation model to test the approach and show that it can significantly reduce taxiing time and fuel consumption. Stochastic mathematical models are used to optimize airport runway operations by sequencing and scheduling flights and taking into account uncertainty in flight schedules and weather conditions [6], [18]–[21]. Yin *et al*. [22] propose a framework to study the Shanghai Pudong Airport Taxi-in/out processes, using macroscopic distribution network and machine learning methods.

3. METHOD

The Mohamed V Casablanca Airport is the principal airport in Morocco, and it is the only place where aircraft move. It has its own adapted structure and is composed of different zones, each with its own specifications. It is mainly comprised of three terminals and a tow runway (17L/35R). The study hereto revolves around data collected using the runway 35R [23].

Air traffic management is linked to available resources. To optimise the aircraft waiting times, it is necessary to model the airport. This chapter is an overview of the Mohamed V Airport modelisation. The modelling of our airport is done by mathematical simulation, including the event actualization and the event graph, and it depends on aircraft types and the airport's resources. The model is constituted of landing, taxi-in, take-off and taxi-out. This paragraph covers all types of variables needed to build the model, and also the event actualizations and the resulting graph.

3.1. Casablanca airport mathematical model

To simplify the study, the airdrome must be modelled based on the previous section that dealt with the airport infrastructure [24], [25]. The model is constituted of landing, taxi-in, take-off and taxi-out. This paragraph covers all types of variables needed to build the model, and also the event actualizations and the resulting graph. The mathematical simulation is used to model the Mohamed V Airport.

3.1.1. Variables and state variables study

In mathematical modeling, variables are used to represent quantities that can take on different values and they are typically used to capture the behavior of the process. On the other hand, state variables are a specific type of variable that describe the current state of a system and they are typically used in dynamic models to keep track of the system's behavior over time. This section shows and explains the variables and state variables needed to model the Mohamed V Casablanca Airport [26]. Tables 1 and 2 are dedicated to variables, however Table 3 is reserved to state variables.

3.1.2. Variables' actualization and event graph

The variables and state variables studied in the previous paragraph (Tables 1, 2, and 3) will be used in our event actualization and graph. This paragraph shows the landing, take-off and taxi-in/out processes in Mohamed V airdrome. Tables 4 and 5 are used to explain the steps and conditions needed to model those processes [27]. Figure 1 represents the Mohamed V Casablanca Airport event graph. The landing process is started with an arrival queue and characterized with an arrival time variable. The aircraft realize landing after testing the availability of the runway, and finally join the stand using the suitable taxiway. Concerning the take-off process, the aircraft realize the taxi-out which is made of a rolling phase and an alignment phase. The first one is done from the stand using the congruent taxiway and the second one is done on the runway after testing availability, and finally the aircraft realizes the take-off on the same runway.

Table 1. Landing variables

Process	Variables	Explication
Landing	$T_{Arrival}$	Arrival time
	$T_{Start\_Landing}$	Start landing time
	$T_{End\_Landing}$	End landing time, also called runway occupation
	$Q_{Arrival}$	Arrival queue
Taxi-in	$T_{Start\_Taxi-in}$	Start taxi-in
	$T_{End\_Taxi-in}$	End taxi-in

Table 2. Take-off variables

Process	Variables	Explication
Taxi-out	$T_{Departure}$	Departure time
	$T_{Start\_Rolling}$	Start rolling time equivalent to start taxi-out
	$T_{End\_Rolling}$	End rolling time
	$T_{Start\_Alignment}$	Start alignment time before take-off using runway
	$T_{End\_Alignment}$	End alignment time before take-off and it is equivalent to end taxi-out
	$Q_{Departure}$	Queue departure
Take-off	$T_{Start\_Take-off}$	Start take-off
	$T_{End\_Take-off}$	End take-off
	$Q_{Take-off}$	Queue take-off

Table 3. Airdrome modelling state variables

Variable	Explication
$Q_{Departure}$ (0, 1……………….)	State variable, characterizes the number of aircraft in departure queue. + 1 for every new aircraft departure
$Q_{Take-off}$ (0, 1……………….)	State variable, characterizes the number of aircraft in take-off queue. + 1 for every new aircraft desiring to take-off
$Q_{Arrival}$ (0, 1……………….)	State variable, characterizes the number of aircraft in arrival queue. + 1 for every new aircraft arrival
A_{Vi} (1,2,3)	Aircraft type: i=1, - super heavy i=2, - medium i=3, - heavy
A_{Free_Runway} (0,1)	Only one runway is available, The runway is available: A_{Free_runway}= 1 The runway is occupied: A_{Free_runway}= 0
$A_{Free\_Taxiway\_i}$ (0,1)	5 taxiways are used in the taxi-in/out process, The taxiway is available: $A_{Free\_Tawiway\_j}$= 1 The taxiway is occupied: $A_{Free\_Tawiway\_j}$= 0
$A_{Free\_Stand\_k}$ (0,1)	The test concerns the stand k (aircraft stand). The stand is available: $A_{Free\_Stand\_k}$= 1 The stand is occupied: $A_{Free\_Stand\_k}$= 0

Table 4. Events actualisation of aircraft landing process

Events	Variables actualisation	Remarks
Aircraft arrival	$T_{Arrival}$	New aircraft arrival is characterized with the arrival time variable
	$Q_{Arrival} = Q_{Arrival} + 1$	Count (+1) is made for each new aircraft arrival
	$A_{Free\text{-}Runway} == 1$	The availability of the runway is a condition to start landing.
Start landing	$T_{Start\_Landing}$	Variable that characterises the start landing time
	$Q_{Arrival} = Q_{Arrival} -1$	The aircraft is removed from the queue because of the start landing
	$A_{Free\text{-}Runway} = 0$	The runway is occupied
End landing	$T_{End\_Landing}$	The end landing time variable
	$A_{Free\_Taxiway\_j} ==1$	The availability of the taxiway j used to attain the stand is a condition of start taxi-in
Start Taxi-in	$A_{Free\text{-}Runway} = 1$	When the taxi-in is started, the runway is available
	$T_{Start\_Taxi\text{-}in}$	The start taxi-in variable
	$A_{Free\_Taxiway\_j} = 0$	The taxiway j is occupied by the aircraft that realise taxi-in
End Taxi-in	$T_{End\_Taxi\text{-}in}$	The end taxi-in time variable
	$A_{Free\_Taxiway\_j} = 1$	When the aircraft attains the stand, the taxiway is unoccupied

Table 5. Events actualisation of aircraft take-off process

Events	Variables actualisation	Remarks
Aircraft departure	$T_{Departure}$	The departure time variable
	$Q_{Departure}=Q_{Departure}+1$	Count (+1) is made for each new aircraft departure
	$A_{Free\_Taxiway\_j} ==1$	The availability of the taxiway j used to attain the stand is a condition of start taxi-out (rolling)
Start Taxi-out	$Q_{Departure}=Q_{Departure}-1$	The aircraft is removed from the queue because of the start taxi-out
	$T_{Start\_Taxi\text{-}out} =T_{Start\_Rolling}$	Start taxi-out variable that characterises start rolling to the runway
	$A_{Free\_Taxiway\_j}=0$	The taxiway j is occupied by the aircraft that realise taxi-out
	$T_{End\_Rolling}$	End rolling variable
	$A_{Free\text{-}Runway}== 1$	The availability of the runway is a condition to start alignment.
	$T_{Start\_Alignment}$	Start alignment variable using runway
	$A_{Free\text{-}runway}= 0$	The runway is occupied
	$A_{Free\_Taxiway\_j}=1$	When the aircraft starts the alignment using the runway, the taxiway is unoccupied
End Taxi-out	$T_{End\_Taxi\text{-}in} =T_{End\_Alignment}$	The end taxi-out time for an aircraft is equivalent to end alignment
	$Q_{Take\text{-}off} =Q_{Take\text{-}off} +1$	The take-off queue is added with +1 preparing the process
Start Take-off	$T_{Start\_Take\text{-}off}$	The start take-off time variable
	$Q_{Take\text{-}off} =Q_{Take\text{-}off} -1$	The aircraft is removed from the queue because of the start take-off
End Take-off	$T_{End\_Take\text{-}off}$	The end take-off time variable
	$A_{Free\text{-}runway}=1$	When the take-off process ends, the runway is unoccupied

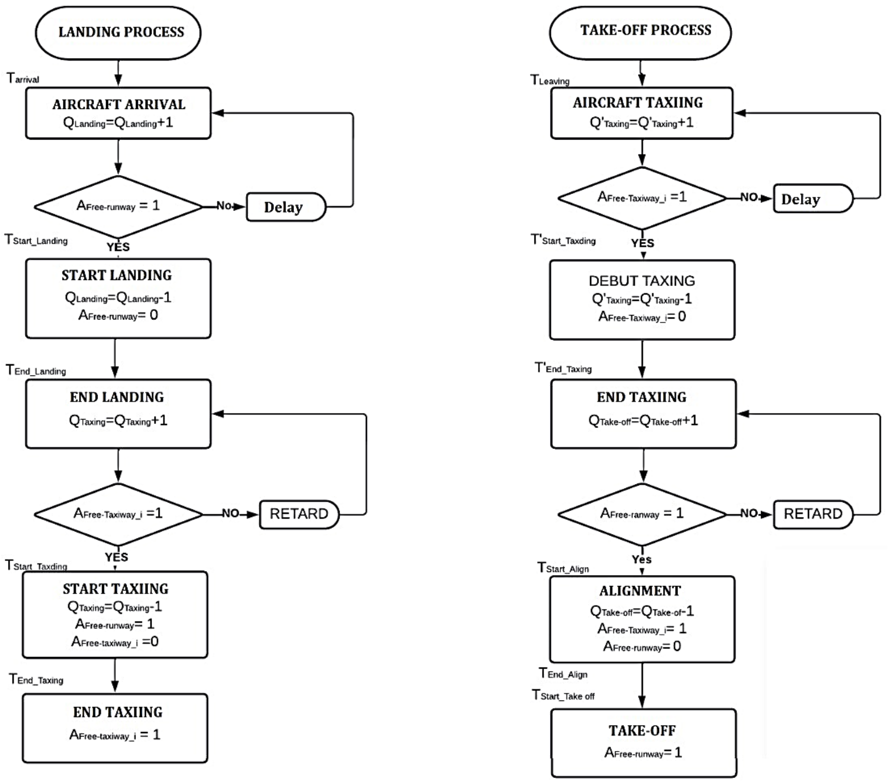

Figure 1. Airport Mohamed V event graph

4. RESULTS AND DISCUSSION

As the mathematical simulation uses a discrete or a continuous model, the appropriate choice between them depends on the specific aim of the studies. Discrete event simulation is applicable on systems that evolve over time, while their variables change the state instantaneously at separate points of time. The cost minimization of the check-in and the security control gate of passengers in an airport is an example of discrete event systems [28]. Also, discrete event simulation is widely used to analyses the detailed behavior of manufacturing systems, logistic systems, traffic modelling and healthcare systems for estimating their major performance measures [29].

Discrete event simulation allows us to analyse the behaviour of a system or a process over time without any financial implication, as well testing new procedures without disrupting the current system. This section will be devoted to simulating the landing take-off and taxi-in/out processes using Arena simulator. The simulation of a model based on discrete events offers the possibility of studying, analysing, and testing new scenarios for a system in complete safety without disturbing the main system. To optimize traffic in an aerodrome such as Mohamed V Airport, a test of multiple scenarios remains essential for better results [30]. So, this part is aircraft landing modelling and analysis. The trajectory is predefined thanks to the type of the aircraft and therefore the location of its stand.

4.1. Statistics analyse

To imete the real system, the simulation model parametring is a very important step after modelling. To this end, we use the landing and take-off processes' statistics. So that we use the input analyser from ARENA simulator to have the data distribution used in the simulation parametric.

Aircraft operational taxi data are extracted from recorded runway scheduler data that have been provided by Mohamed V Airport. The data used in our simulation was collected for 20 days of taxi-in and landing including peak hours. The input data were converted to minutes and then were imported in the input data area to generate the input analyser. The Figure 2 is a presentation of actual landing and off block time distribution. The actual landing time inputs data distribution is about LOGNORMAL function using the LOGN (6.95, 6.57) expression, and the square error (between histogram and the function) is around 0.019525. The off-block time input data distribution is GAMMA function that uses the GAMM (7.43, 0.898) expression, and the square error (between histogram and the function) is around 0.000831.

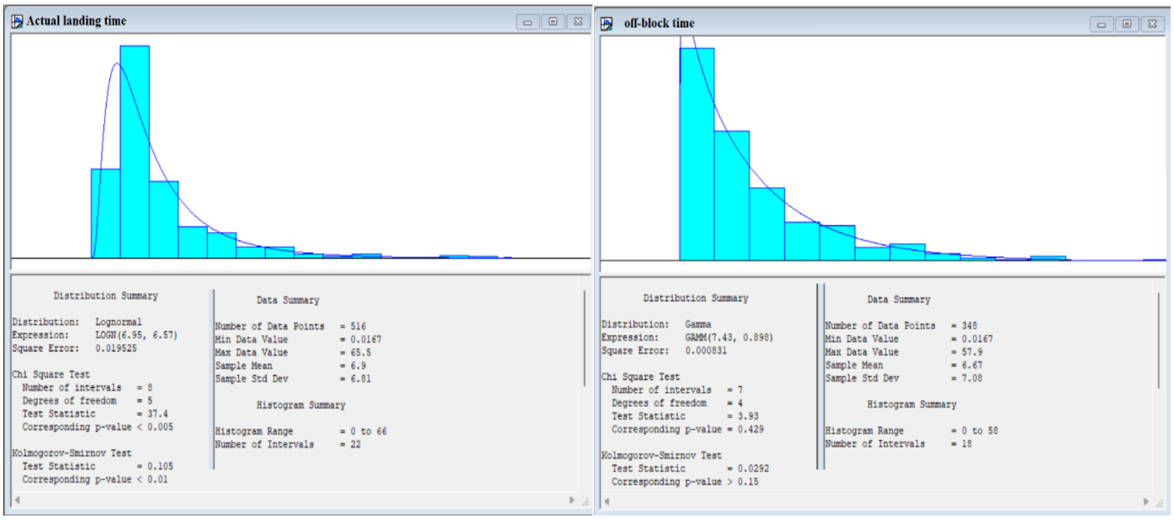

Figure 2. Actual landing and off-block time distribution and analysis

4.2. Landing process

4.2.1. Landing main menu

To model the landing traffic in Arena tool, we first realize the main menu that includes specific processes. Figure 3 summarizes this menu and shows the procedure that starts with aircraft arrival until reaching the stands, through landing and taxi-in processes. The sequence of steps is ensured by testing the availability of runway and taxiways. The trajectory needed to attain the stand is predefined and depends on apron location and aircraft type.

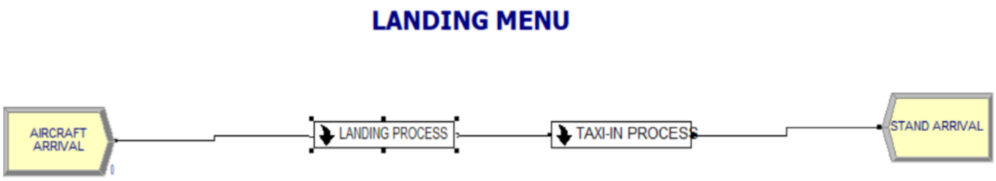

Figure 3. Landing process: main menu

4.2.2. Landing process

The landing process refers to the sequence of events that occur when an aircraft approaches and touches down the runway. The process is modelled using Figure 4 and it a subsidiary of landing menu exposed before with Figure 3. The process starts with testing the availability of the runway while being in the landing queue, then the aircraft realize landing using the runway.

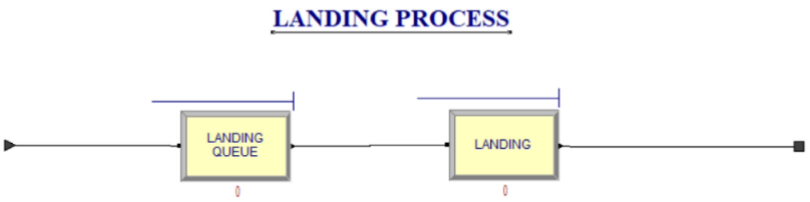

Figure 4. Aerodrome simulation: landing process

4.2.3. Taxi-in process

The taxi-in process is more complicated than the landing one, and the Figure 5 explains the process which starts with testing the aircraft type (super heavy, heavy, and medium). This test gives the possibility to specify the trajectory to attain the stand. While the aircraft is located in the taxi-in queue, the availability of the taxiway needed to join the stand is tested, then the aircraft join the specified stand. The configuration of this part is carried out in the same way as the previous processes.

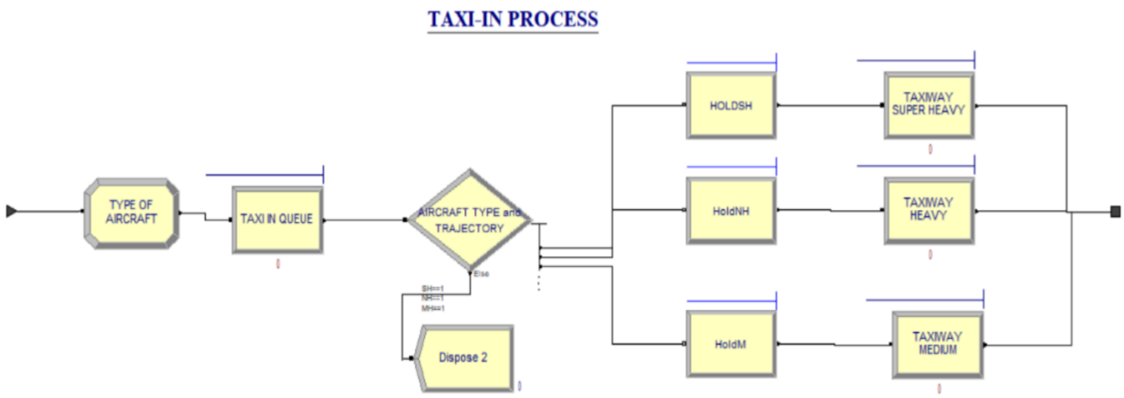

Figure 5. Aerodrome simulation: taxi-in process

4.2.4. Results

The simulation of the landing process is used for 1 replication. As the Figure 6 exposes, the results show that landing queue have the most time as an average however landing is the menor time and the instantaneous utilization show the PISTE resources of landing processes is used at 8.5% or taxiway is used at 100%. This result show that if we want to improve our system landing and optimize the total time, we should act on taxiway resources that present the main constraint of the process. So that, the optimization concerns the target taxi-in time (TXIT).

LANDING

Replications: 1 Time Units : Minutes

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
LANDING	1.3884	0,028870145	0.7504	2.8412
LANDING QUEUE	3.7459	0,042013791	2.6145	5.6907
TAXI IN QUEUE	2.3825	(Insufficient)	0.3146	6.3674
TAXIWAY SUPER HEAVY	3.0908	(Insufficient)	2.9434	3.3729

Wait Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
LANDING	4.9638	(Correlated)	0.00	22.8722
LANDING QUEUE	3.7161	(Correlated)	0.00	21.2072
TAXI IN QUEUE	0.00	(Insufficient)	0.00	0.00
TAXIWAY SUPER HEAVY	0.00	(Insufficient)	0.00	0.00

Total Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
LANDING	6.3521	(Correlated)	0.8411	24.3689
LANDING QUEUE	7.4620	(Correlated)	2.7573	24.4193
TAXI IN QUEUE	2.3825	(Insufficient)	0.3146	6.3674
TAXIWAY SUPER HEAVY	3.0908	(Insufficient)	2.9434	3.3729

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
HOLDSH.Queue	0.9007	(Insufficient)	0.00	2.3998
LANDING QUEUE.Queue	3.7161	(Correlated)	0.00	21.2072
LANDING.Queue	4.9638	(Correlated)	0.00	22.8722
TAXI IN QUEUE.Queue	0.00	(Insufficient)	0.00	0.00
TAXIWAY SUPER HEAVY.Queue	0.00	(Insufficient)	0.00	0.00

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
PISTE	0.08557047	(Insufficient)	0.00	1.0000
TAXIWAY	0.9995	(Insufficient)	0.00	1.0000
taxiwayM	0.00	(Insufficient)	0.00	0.00
taxiwayNH	0.00	(Insufficient)	0.00	0.00
taxiwaysh	0.00032196	(Insufficient)	0.00	1.0000

Number Busy	Average	Half Width	Minimum Value	Maximum Value
PISTE	0.08557047	(Insufficient)	0.00	1.0000
TAXIWAY	2.9986	(Insufficient)	0.00	3.0000
taxiwayM	0.00	(Insufficient)	0.00	0.00
taxiwayNH	0.00	(Insufficient)	0.00	0.00
taxiwaysh	0.00032196	(Insufficient)	0.00	1.0000

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
PISTE	1.0000	(Insufficient)	1.0000	1.0000
TAXIWAY	3.0000	(Insufficient)	3.0000	3.0000
taxiwayM	1.0000	(Insufficient)	1.0000	1.0000
taxiwayNH	1.0000	(Insufficient)	1.0000	1.0000
taxiwaysh	1.0000	(Insufficient)	1.0000	1.0000

Figure 6. Landing simulation report: processes, resources and queue

4.3. Take-off process

4.3.1. Take-off main menu

The principal menu is composed of two steps as shown in the Figure 7: taxi-out and take-off processes. The following paragraph summarizes the verified steps to fulfil the taxi-out and the take-off in good conditions. It starts with the departure time definition, then the taxiway availability test is necessary to attain the runway. to realise rolling phase, a runway availability test is also important. Finally, the aircraft take-offs and clear the runway.

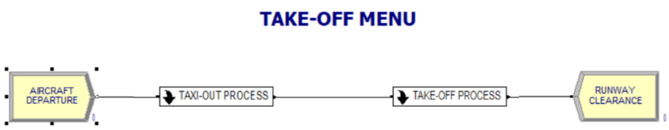

Figure 7. Take-off process: main menu

4.3.2. Take-off and taxi-out simulation

Figure 8 explains the taxi-out process. After specifying the off-block time, the aircraft joins the departure queue. To ensure the rolling trajectory, an aircraft type test is applied. When the aircraft attains the runway entry, a test of its availability is imposed. Finally, the aircraft release alignment for preparing take-off. Figure 9 is dedicated to the take-off process. The aircraft joins the take-off waiting line, then the availability of the runway is tested to release to the take-off. If necessary, the aircraft takes some delay before restarting the test.

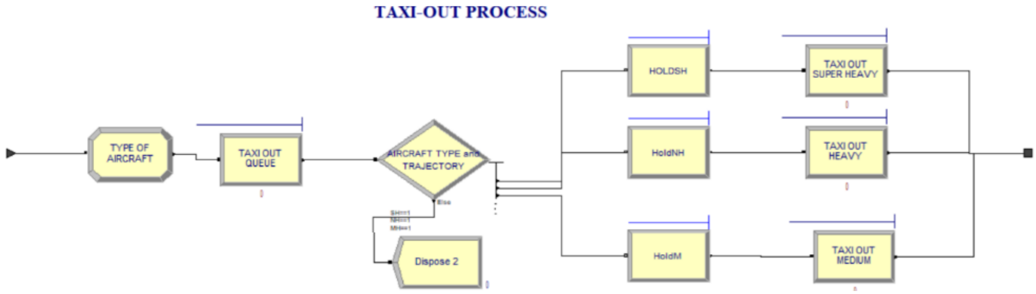

Figure 8. Airdrome simulation: taxi-out process

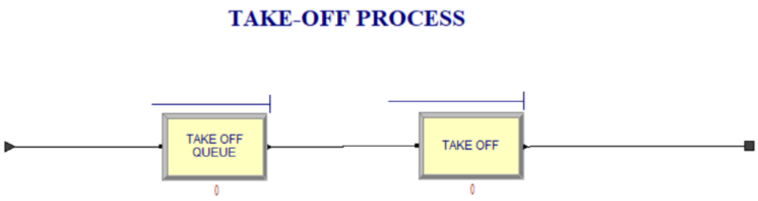

Figure 9. Airdrome simulation: take-off process

4.3.3. Results

The simulation of the take-off process is used for 1 replication as shown in Figure 10, and the time units is minutes. The figure shows that the superheavy taxi out time is important comparing it with other aircraft type taxi out times, however instantaneous utilization of resources shows that the super heavy taxiway is the lest used. The results show that the taxiways are used 99% as resources. So that to improve taxi out process we should optimize total time. To optimize aerodrome, we have to optimize target taxi-out time (TXOT).

TAKE-OFF

Replications: 1 Time Units: Minutes

Process

Time per Entity

VA Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
TAKE OFF	0.6068	(Insufficient)	0.5523	0.6384
TAKE OFF QUEUE	0.5366	(Insufficient)	0.0954	1.1920
TAXI OUT QUEUE	2.2479	(Insufficient)	1.9509	2.8403
TAXI OUT SUPER HEAVY	14.2336	(Insufficient)	9.7165	20.6265

Wait Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
TAKE OFF	0.00	(Insufficient)	0.00	0.00
TAKE OFF QUEUE	0.00	(Insufficient)	0.00	0.00
TAXI OUT QUEUE	0.00	(Insufficient)	0.00	0.00
TAXI OUT SUPER HEAVY	0.00	(Insufficient)	0.00	0.00

Total Time Per Entity	Average	Half Width	Minimum Value	Maximum Value
TAKE OFF	0.6068	(Insufficient)	0.5523	0.6384
TAKE OFF QUEUE	0.5366	(Insufficient)	0.0954	1.1920
TAXI OUT QUEUE	2.2479	(Insufficient)	1.9509	2.8403
TAXI OUT SUPER HEAVY	14.2336	(Insufficient)	9.7165	20.6265

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
PISTE	0.00011911	(Insufficient)	0.00	1.0000
TAXIWAY	0.9996	(Insufficient)	0.00	1.0000
taxiwayM	0.00	(Insufficient)	0.00	0.00
taxiwayNH	0.00	(Insufficient)	0.00	0.00
taxiwaysh	0.00148267	(Insufficient)	0.00	1.0000

Number Busy	Average	Half Width	Minimum Value	Maximum Value
PISTE	0.00011911	(Insufficient)	0.00	1.0000
TAXIWAY	2.9988	(Insufficient)	0.00	3.0000
taxiwayM	0.00	(Insufficient)	0.00	0.00
taxiwayNH	0.00	(Insufficient)	0.00	0.00
taxiwaysh	0.00148267	(Insufficient)	0.00	1.0000

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
PISTE	1.0000	(Insufficient)	1.0000	1.0000
TAXIWAY	3.0000	(Insufficient)	3.0000	3.0000
taxiwayM	1.0000	(Insufficient)	1.0000	1.0000
taxiwayNH	1.0000	(Insufficient)	1.0000	1.0000
taxiwaysh	1.0000	(Insufficient)	1.0000	1.0000

Figure 10. Take-off simulation report: process and resources usage

5. CONCLUSION

A system can be modelled either physically or mathematically, depending on the type of issues involved. In fact, the vast majority of these systems are represented in two forms: as a simulation, generally used as a testing tool, or as an analytical solution, which defines the constraints of the system. This paper presents a mathematical model of an airport traffic flow. The model was proposed by considering the traffic as a discrete event. The simulation focuses on aircraft movements during taxi-in/out, departure, and landing. This paper deals with the Mohamed V Airport model as a concrete example, by first choosing the variables, updating the events and then generating the event graph. Using Arena software and Mohamed V Airport data, the airfield simulation has been proposed for arrivals and departure processes.

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BIOGRAPHIES OF AUTHORS

Douae Zbakh is Ph.D. student at the National School of Applied Sciences of Tangier, Morocco. State Engineer in Telecommunications Systems and Networks Engineering. Here research areas are data science, artificial intelligence, modelisation an optimization, in innovative technologies laboratory. She has participated in several national and international research projects and conferences. She can be contacted at email: douae.zbakh@gmail.com.

Marwane Benhadou is an assistant professor of informatics in Hassan first University, Morocco. His research interest includes telecommunications, mathematical modeling and computing, traffic engineering, and sustainable mobility. He can be contacted at email: marwane.feg.info@gmail.com.

Abderrahmane Benkacem is an Senior Consultant in Industrial Engineering and Logistics Ph.D. in Industrial Engineering and Logistics. His research interest includes modeling, imulation, machine learning, and artificial intelligence. Hospital logistic and industry 4.0. He can be contacted at email: a.benkacem@uae.ac.ma.

Abdelouahid Lyhyaoui is full professor at the National School of Applied Sciences of Tangier. He holds the Ph.D. degree in Telecommunications Engineering from the Escuela Politecnica Superior, Universidad Carlos III de MADRID. His research interests include data science, artificial intelligence, and smart city. He is the founder and president of the Moroccan Society for Technological Development and Innovation. He has participated in several national and international research projects, and has more than 150 scientific publications. He is a member of scientific committees of several national and international conferences and journals. He is strongly involved in university life, having served as director of the Innovative Technologies Laboratory, head of the Telecom and Electronics Department, elected member of the Scientific Council, the Board of Directors, the Pedagogical Commission of the University, and a member of the jury for the recruitment contest for doctoral students at Abdelmalek Esaadi University. He can be contacted at email: lyhyaoui@gmail.com.