

École polytechnique de Louvain

Agent-based modeling in support to collaborative decision-making in airport management

Master thesis

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Abstract

Airports are transportation platforms shared between different parties. All of them have their own objectives to pursue. In this context, they need to do some Collaborative decision-making (CDM) to optimize airport operations and each party's benefits. This thesis aims at developing a tool in support to CDM: an agent-based model aiming to simulate aircraft ground handling tasks. Agent-based modeling is a computational modeling paradigm that aims to study the behaviour of complex systems with computer simulations. The general observed phenomena are consequences of individuals decision-making at the lowest scale. This Master thesis aims at developing this type of model, focusing on all the processes that are performed on an aircraft between the time it arrives at the stand and the time it leaves it. The model should be used as a tool to answer two main objectives. They are to derive confidence intervals on the time the aircraft will leave the stand, and to provide a tool to simulate the realisation of some strategies for decision-making.

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Chapter 1

Introduction

Airports are transport platforms supporting a really large number of companies, coming from a lot of different horizons. They range from airlines companies to traffic controllers, including ground handlers, airport authorities and others, each of them having its own business model and therefore its own strategy and objectives for the different actions taking place within the airport. In order to optimize the benefits of each one, those companies have to work together. If each company decided to make its own strategy choices without taking the others into consideration, they would have a negative impact on each other and none of them would reach its objectives. They have to take decisions that will induce the best possible airport management. This is called collaborative decision-making (CDM) and therefore maximizing the profit of each party simultaneously with guaranteeing the properest possible optimal operation of the airport. All these stakeholders work, among others, together around a global process called turnaround.

Definition 1.0.1 (Turnaround) *The turnaround is a global process including all the processes between the time an aircraft arrives at the stand¹ with passengers (the in-block time) and the time it leaves the stand with new passengers (the off-block time).*

Definition 1.0.2 (Agent) *In this thesis, an agent is considered as a worker or a crew of workers that perform a process on an aircraft between its in-block time and its off-block time.*

All the stakeholders work together from the Airport Operations Plan. It is the plan airports use to let all the operational workers in the airport know everything about all the different flows and operations in the airport. It is supposed to allocate resources (staff and utilities) in an optimized way. However, this plan always has to be reviewed. Indeed, disturbances exist because real life is not deterministic. For example, most of the processes are performed by a workforce consisting of women and men. Also, equipment failures, traffic jams and other unexpected events can happen. Thus, deviations from the schedule exist. These disturbances can have a huge impact on the whole turnaround and induce delays through the whole air traffic network since airport workers work on different turnarounds throughout the day. These delays can sometimes be very problematic. It is

¹Stands are parking places for aircrafts in airports.

known that pilots have a time window in which they are allowed to take-off. This time window is really important for the Air Traffic Controller since it ensures security in the air for all the passengers for each flight. If the off-block time is delayed, the pilot can miss its take-off window. Then, he has to ask the Air Traffic Controller for another window and that induces even more delays. These delays are expensive both for airports and for airlines but they are also problematic for the customers.

In this context, airport operational stakeholders need a tool to pursue two different objectives. First, they need to predict accurately the end of every turnaround to assign well the take-off window and minimize the number of times they are missed. The objective is to have a confidence interval on the off-block time that is the result of a specific operations plan or strategy. Secondly, the tool they need would be used for collaborative decision-making to answer questions like: what is the best strategy to implement in order to satisfy the different parties in the airport ? How to react in case of a disturbance in the planning?

For now, airport operational stakeholders work with a confidence interval of 5 minutes before the scheduled off-block time and 10 minutes after. Thus, its length is 15 minutes. Experienced airport operations experts say that this interval actually works quite well in practice, i.e. it seems large enough. However, better predictions would be even better. Plus, when there is a disturbance in the planning, stakeholders deal with it based on experience and their best guess, not on a scientific simulation model (see [1]). They do have access to time-based and event-based simulation models but they are aircraft-centric: they take into account everything that happens around each aircraft and stand but these models don't see the problem on the right scale since as mentioned before, airport workers work on different stands consecutively. This sequential organization can induce delays on different stands due to a snowball effect and state-of-the-art models don't see it.

Thus, the tool operational agents need is an airport-centric one. It needs to take into account all the interactions that happen on a larger scale than on a stand. A delay for a specific agent on a stand can induce a delay for this agent on the stand where he needs to go afterwards. It is really important for resource planning and the anticipation of the problems planning can induce. Also, a smaller confidence interval on the off-block time seems to be very important for airports. Uncertainty is their enemy, both for logistic and economical reasons.

For this Master's thesis, it has been decided to tackle the problem with agent-based modeling. It is a computational methodology that deals with systems composed of many distributed interacting parts. Its main advantage is that it is suited to model interactions that can happen between different agents. It is a tool for simulation. Thus, the idea is to build the model properly, then use it to simulate what is going to happen with various plannings and strategies. Finally, these simulations can help to derive confidence interval on the off-block times and help to see what the different strategies induce in terms of duration lengths and duration reliability.

At the end of the thesis, the model has been built correctly and works as expected. The objective has been achieved since some exciting results about the confidence intervals on the off-block times have been deducted. Finally, the model has been used to simulate real life situations in different use cases in order to show how airport operational agents could use it.

In order to fit the model perfectly well, some data about what exactly happens during turnarounds would have been needed. Data would have given information about the beginning and end of each task for every turnaround. This dataset has not been available due to the COVID-19 crisis. Indeed, all the civil aviation sector has been working understaffed for months due to travel restrictions. They have not been able to prepare and provide these information. Thus, different assumptions have been made in order to model these tasks durations.

This document is divided into 5 different chapters. Firstly, a state-of-the-art section will be proposed to explain the concepts the model is based on. This includes some information about turnarounds and airports but also about the agent-based modeling paradigm. Then, the model will be described in blocks, containing all the choices and assumptions that have been made. The inputs are detailed, then the description of the model shows how it transforms them, and computes different outputs. Finally, it will be used in different applications to show its power and its ability to fit life-size examples.

The thesis aims at developing the agent-based model and only some illustrations of the tool are shown in this document. Determining precisely optimized solutions according to economic objectives is not part of the thesis. The tool created can be used as a foundation for optimization problems but, in this document, it will only be used in some use cases to show its power and how it could be used by operational stakeholders. The model is focused on the simulation of turnarounds in an airport and does not pretend to be the solution of all airports problems. Also, since it has been created without real data, some adjustment could be necessary to correct some assumptions and represent better real behaviours.

The implementation of the model and the extended results are available on Github[2]: <https://github.com/martintaminiaux/ABM-airport-operations>.

Chapter 2

State-of-the-art

In this chapter, the theoretical material that will be needed for the thesis will be introduced. It includes the turnaround processes, dynamic buffers, the critical path and more importantly, agent-based modeling.

2.1 Processes

To make an airport-centric model that takes into account the interactions across a whole airport on different stands, it is first important to understand what happens on every stand during the turnarounds with the aircraft-centric point of view. It is the bottom-up approach. What happens at a macro-level is only a concatenation of micro-level behaviours. Different actions are performed on the aircraft between its in-block time and its off-block time. They are called processes and will be described in this section. To understand which processes are the most significant, the important concept of critical path will be detailed and its analysis on the specific turnaround case will be pursued. The information comes from different articles: [1], [3], [4], [5], [6] and [7].

2.1.1 Processes

First, a practical definition will be given. Then it will be followed by the probable interactions it has with other processes. The main processes are deboarding, cleaning, catering, fueling and boarding. Luggage and containers unloading and loading are taken into consideration too.

2.1.1.1 Deboarding and boarding

Deboarding is the first process and boarding is the last. Their time estimations are essential because almost none of the other processes can be processed in the same time. Fueling is too dangerous and the cleaning and catering are most of the time impossible to proceed. Only loading and unloading can be performed at the same time.

Airlines have tried to decrease the expectation of the deboarding and boarding durations

to satisfy passengers but also to speed up their turnarounds. However, the strategies also need to decrease the variance of the deboarding and boarding durations to get reliable turnaround times. A lot of strategies can be implemented (families first, back of the plane first, 1 or 2 doors,...) but these processes are passenger dependant. They are influenced by the mutual obstructions between passengers, the number of cabin luggage, etc. The strategy must be easy to implement, robust against disturbances and of minimum time. Most of the time, the aircraft manufacturers give approximations of deboarding and boarding rates [passengers/min].

2.1.1.2 Cleaning

Cleaning includes a lot of different tasks like seat cleaning, galley cleaning, crew resting cabin cleaning, toilet cleaning, etc. This process is really airline-dependent and is usually done by a service company. Not all of these tasks are performed for every flight. Sometimes, it is briefly done by the crew and the big work is done overnight. These logistical decisions mainly depend on the airline standing.

It can't be performed during deboarding for obvious operational reasons. However, the aircraft can be cleaned while it is being fueled, loaded or unloaded.

2.1.1.3 Catering

Catering includes all the tasks related to the loading of food, products and service utilities for passengers. The idea is to improve customer service whilst keeping in mind that excess load and waste are undesirable.

This task is sometimes performed once for multiple flights. This can sometimes ensure a better allocation of the resources for the airlines. The interdependencies with other processes are aircraft dependent. Most of the time, it can't be done while people are deboarding or boarding. As for cleaning, light cleaning can be done and the big work can be done overnight.

2.1.1.4 Fueling

Most of the time, the aircraft needs to be fueled during the turnaround. Some airlines have different strategies, like fueling the aircraft once a day for multiple flights. These logistical choices are made to get a balance between fast turnarounds and efficiency during flights. It is known that aircrafts use more fuel when they carry a large load. The amount of fuel depends on the destination airports, the safety margin airlines take to cope with detours and holdings and the multiple flight strategy or not. Thus, the fueling time depends on the strategy of the airline.

When it is done, this process is essential. Indeed, most of the time deboarding and boarding can not be pursued during fueling for security reasons. Sometimes, to speed-up the turnaround or because of the availability of the resources, the fueling is being done during deboarding. In this case, a fire brigade has to monitor the fueling for the passengers to be safe. Fueling can be pursued by the airline or by a service company. There are

different ways of getting the fuel into the aircraft. It is airport dependent. It can be done either with fuel trucks or with underground pipes.

2.1.1.5 Unloading and loading

Most of the time these two processes are automated. They include luggage, containers and mail handling. These processes are quite technical since the balance of the aircraft is important. The temperature and humidity at which certain items are shipped are also important. There are two types of loads: bulk and containers.

These processes can be done simultaneously with deboarding, catering, cleaning, fueling and boarding. Indeed, it is not dangerous and the location is completely independent of all other processes.

2.1.1.6 Other processes

There are a few other processes that most of the time don't influence the turnaround as much as the ones that have just been described. Moreover, they are not always performed. They include:

- power management: power needed to perform the other processes such as cleaning, catering, loading without turning on the airplane engines.
- anti/de-icing: during winter, the ice can damage the aircraft and alter the visibility of pilots.
- maintenance: it includes both preventive actions and aircraft repairs.
- push-back: the aircraft is pushed backwards away from the stand with an external power (pushback tugs).

2.1.2 Dynamic buffers

Dynamic buffers are time shifts between independent processes which can be used as security buffers. They have been introduced to deal with uncertainty. Indeed, if they are not used or if they are partly used, the scheduling can stay the same. However, if there is no delay and that they are not used, there is a lack of productivity during this time-shift because nothing is happening. Consequently, their duration has to be balanced between maximal delay prevention and minimal time waste.

They usually lie after deboarding and before boarding. On Figure 2.1, one can see that ground handling processes (not including boarding and deboarding) tend to start earlier with respect to the on-block time with increasing inbound arrival delay. It results from the use of these buffers.

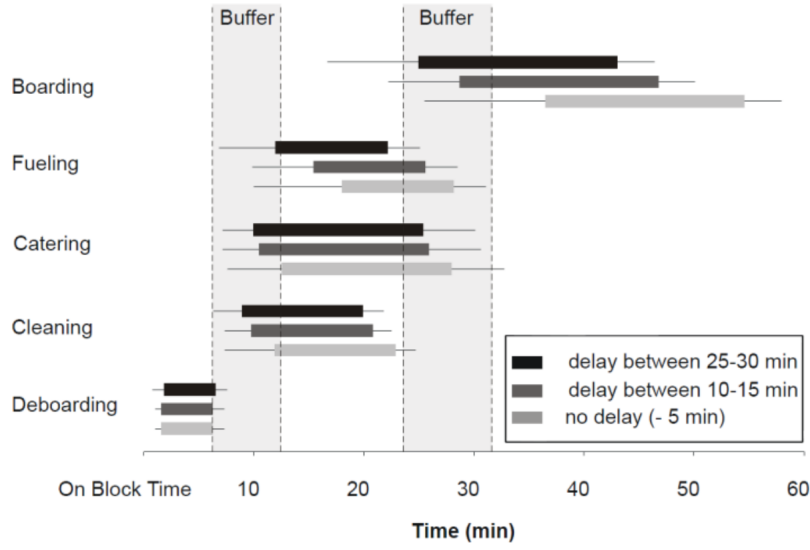


Figure 2.1: Delay compensation due to shift of specific process starting time [8]

2.1.3 Minimum, scheduled and actual turnarounds

To understand further developments in the model description and the use cases, it is important to spot the difference between minimum, scheduled and actual turnarounds. As a reminder, the turnaround is the concatenation of all the processes that happen around an aircraft between its in-block time and its off-block time.

2.1.3.1 Minimum turnaround

This turnaround is the one announced by the aircraft manufacturers. It can be found in the aircraft characteristics document. As it is mentioned in its name, this kind of turnaround supposes that all processes are performed as quickly as possible. It does not mean that processes are shortened, but that processes can be processed sequentially or in parallel with no time buffer or time out. Thus it supposes that resources are unlimited and that the agents performing the processes can be there if they need to be there. Also, it is aligned with the scheduled in-block time. This minimum turnaround is, for example, illustrated by a Gantt chart for an *Airbus A330* on Figure 2.2. Naturally, a lot of assumptions are made so it is quite theoretical and is most of the time not realistic.

2.1.3.2 Scheduled turnaround

This turnaround is the one scheduled officially. It is defined by a scheduled in-block time (SIBT) and a scheduled off-block time (SOBT). The scheduled in-block time is defined as the moment the aircraft is supposed to arrive at the stand after the landing while the scheduled off-block time is defined as the moment the aircraft is supposed to leave the stand just before take-off. The scheduled turnaround is planned as soon as information about the plane arrival and departure is given to the airport. It does not assume an

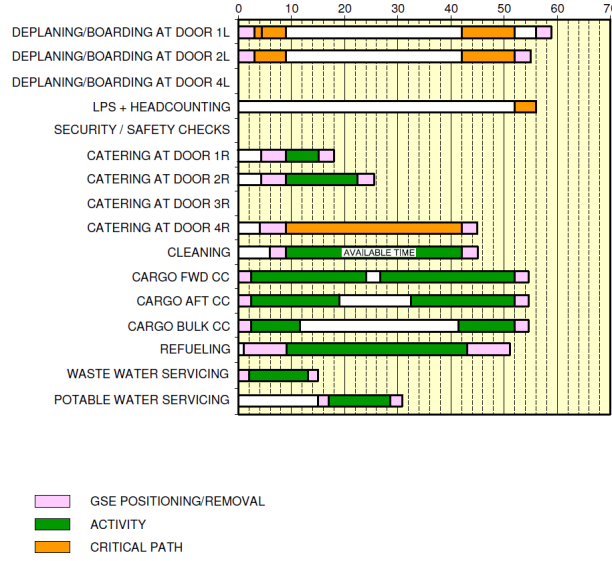


Figure 2.2: Gantt chart illustrating the announced minimum turnaround for an A330

infinite number of resources and agents and is dependent on resource planning. The scheduling works in three stages:

- Schedule the deboarding and the unloading just after the scheduled in-block time
- Schedule the loading and the boarding according to the scheduled off-block time
- Schedule other activities between the end of deboarding and boarding. If the stand occupation duration allows it, some buffers can be planned to cope with uncertainty and with the resources availability.

2.1.3.3 Actual turnaround

This turnaround is the actual realisation of the scheduled turnaround on d-day. They are not equal since reality is not deterministic and the process durations are random. It is defined between the actual in-block time (AIBT) and the actual off-block time (AOBT). The actual in-block time is defined as the moment the aircraft actually arrives at the stand after the landing on d-day while the actual off-block time is defined as the moment the aircraft actually leaves the stand just before take-off on d-day.

2.1.4 Critical path

2.1.4.1 Theoretical description

The critical path is a central concept in resource planning and will be helpful to understand the impact of the interactions between the processes in the next section.

The critical path of a group of activities (such as a turnaround) is the longest sequence of direct dependent activities of the group that takes the most time to complete. It is the longest path between the start of the first activity (the in-block time for a turnaround)

and the end of the last one (the off-block time for a turnaround). Its duration is the shortest possible period needed to realize each activity of the sequence (the shortest possible turnaround duration in the studied case). So it is defined by:

- Its duration: the duration of the total turnaround
- The activities that define it and dependencies between those activities

A delay in one of the activities of the critical path implies a global delay on the turnaround unless some processes (of the critical path) coming after the delayed one are finished faster than scheduled (in a natural way). It implies that dynamic buffers (introduced in Section 2.1.2) can be part of the critical path if they are still observed in practice. Therefore, any disturbance on the critical path causes therefore a disruption in the part of the critical path following the disturbance but that disruption can simply be the use of the buffer to reduce the supposedly delayed turnaround end.

2.1.4.2 Application to turnaround

Since each airport turnaround is different from the other, each of their critical paths can also be different from the other. However, the boarding and deboarding processes are most of the time on the critical path since no main process can be performed simultaneously with one of those two processes except the unloading and loading processes. It implies that most of the processes must wait until the end of deboarding to start, and boarding must wait until the end of most of the other processes to begin. We can often find on the critical path fueling or service processes (cleaning, catering). It depends on the particular time needed for each process. Since fueling, cleaning and catering are often running in parallel, the longer one will often be on the critical path.

This critical path is the most interesting to compute on the scheduled minimum turnarounds. The minimum turnaround is the one announced by the manufacturers. It is aircraft-specific. For example, on Figure 2.2, the critical path includes deboarding, catering and boarding. For other aircraft types than an *Airbus A330*, it can be different.

Sometimes, activities of the critical path are not necessarily successive. A critical path could, for example, be defined by deboarding/fueling/boarding and for a specific reason, the 10' long fueling begins 2' before the end of deboarding with fire brigades that ensure security. Thus we have an overlap but the activities that define the critical path are still deboarding/fueling/boarding. This is called conditional dependencies between activities and is related to a time lag, which is negative (-2 minutes) here.

2.2 Agent-based modeling

2.2.1 Theoretical state-of-the-art

As mentioned in the introduction, this Master thesis focuses on the development of an agent-based model simulating what happens during a turnaround around each aircraft and how agents of the different turnarounds interact with each other at the airport level. However, agent-based modeling is a recent paradigm and needs to be introduced before being used. This section is inspired from [6] and [9].

Humanity has always tried to go further and has pursued a quest for knowledge. In this path, complex systems have been in the centre of research. This terminology *defines systems composed of many distributed interacting parts* ([?]). In these systems, the emergence of different phenomena requires observation. This emergence concept is a bottom-up approach: ordered patterns at a macro-level are obtained from micro-levels rules, structures or interactions between many distributed elements. A key aspect is that these micro-levels rules can be non-deterministic to deal with the complexity of the models. But in the meantime, they can lead to the emergence of specific behaviours at a macro-level.

Apart from agent-based modeling, different tools have been developed. One of them is the equation-based modeling (EBM). However, this very powerful tool is difficult to adapt to very specific and large problems, and is mainly deterministic and adapted to study dynamic systems. It is not suited for modeling the interactions in an airport.

To deal with complex systems, agent-based modeling (ABM) is one of the best tools. It is a computational modeling paradigm or computational methodology. The computational modeling paradigm is a way of programming that takes inputs, treats them with an algorithm, and gives outputs. It is meant to study the behaviour of complex systems with computer simulations. The different observed behaviours are consequences of individuals decision-making. The individuals are agents that interact with each other. They can be humans, cells, organizations, animals, market products, ... It depends on the situation. ABM actually plays the role of an electronic laboratory. These simulations help to observe the emergence of macro-levels behaviours but further, the impact of the different micro-level decisions or rules on the whole system. ABM provides an explicit connection between inputs and emergent behaviours.

In ABM, there is a universal clock. Every time it ticks, agents act within their environment. ABM includes three main elements :

- Agents: they are entities that make decisions and that interact with each other and with their environment.
- Agents relationships: they define how agents lie together in the environment.
- Environment: the space in which agents interact.

These three components are defined below in a general way. They will be defined in Section 3.1 specifically for the context of an airport.

2.2.1.1 Agents

The modeling results from a particular standpoint: the agents. They are the entities that act within the system and interact with each other. They have their own properties that are static and some state variables that describe them at each step of the simulation. The key idea is that they have rules of behaviour that depend on the context they are found in. These rules of behaviour dictate what the agents do every time the clock ticks. The context includes their state variables but also the environment: the global information and the state of their neighbours. In the literature, a global consensus has led to the fact that agents have to respect some properties to be part of an agent-based model:

- **Autonomy** : agents act within their environment. They have information and take decisions in that context. There is no global authority that dictates to taking any action in a given context.
- **Modularity** : agents are identifiable and self-contained. They have to be defined precisely to be able to decide if something is part of an agent or not.
- **Sociality** : agents interact with each other. They have their own rules but can be neighbours and live in the same environment.
- **Conditionality** : agents have a state at a given time. These states are essential since they condition the agents' behaviour. The state of an agent-based model is composed of the states of all agents and the environment.

Finally, they may have goals to pursue and that can drive their behaviours.

2.2.1.2 Environment

It is composed of the global map of the model and the state of the model. The map is meant to define a neighbourhood for each agent (see agents relationships). That map can be a geographical description or network-based. Indeed, agents interact with agents that are near them on the map. Plus, the state of the environment defines the global context in which the agents found themselves. It is defined by global state variables that will be updated or not at each step of the time. The environment is impacted by agents' decisions, moves and actions (see Figure 2.3).

2.2.1.3 Agents relationships

Agents interact with each other. However, these interactions have to be defined and described to be implemented. The action of one agent can have a huge impact on the action of another agent at the next tick. The relationships are contained in the rules of behaviour of each agent.

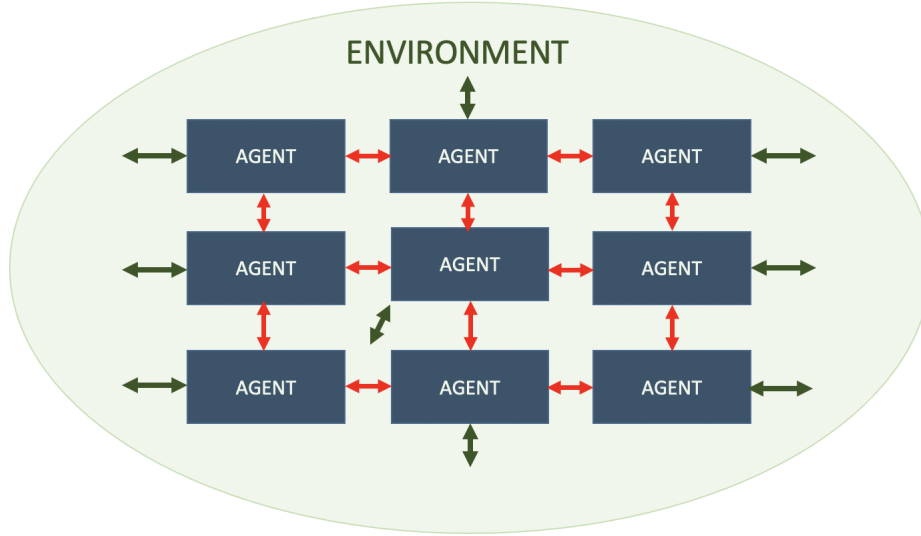


Figure 2.3: Agents interactions with other agents and with the environment

2.2.2 Added value of the ABM

What existed before ABM in turnarounds modeling and simulations? Some time-based and event-based models existed. They are the concatenation of the different time steps of the duration of each process. They are based on a critical path, that most often includes deboarding-fueling-boarding. The way they actually handle disturbances in the processes is mainly based on the experience of stakeholders and on dynamic buffers.

Experience includes all actions that are taken by the stakeholders to minimize the impact of any delay on the whole turnaround. It can be the omission of some cleaning tasks, a faster boarding or the simultaneity of fueling and boarding with fire brigades surveillance. Dynamic time buffers have been introduced in Section 2.1.2. They help to minimize the variance of the turnaround time and ensure the integrity of the flights schedule.

The way ABM will be used in this study case is essential to understanding its added value. In short, ABM will be used to increase the accuracy of the predicted turnaround time and its confidence interval. ABM is part of a computational methodology. It mimics the behaviour of the different agents in particular situations and simulates the scenarios that depend on each agent strategy. With these simulations, the objective can be pursued.

The added value is the simulation of the interactions between agents across the airport. To understand that, it is important to mention the 2 possible points of view:

- aircraft-centric: it consists in considering everything that happens around an aircraft on a specific stand. Time-based and event-based models that already exist are able to model properly what happens on a stand scale. For example, it is able to understand that fueling cannot begin before deboarding. It is done with simple rules.
- airport-centric: it consists in considering everything that is happening simultaneously

on the different stands. Airports contain dozens of stands but a limited number of agents. Thus, it is really important to model the interactions across the different stands. That is where agent-based modeling can be interesting.

For example, it is known that in a classical turnaround, fueling can not be pursued during deboarding. Thus, if the deboarding process on stand n°1 is delayed, then fueling will be too. Time-based and event-based models can illustrate that. However, if the fueling agent needed to go to stand n°2 just after its first fueling to perform another, it will be delayed because of delayed deboarding on stand n°1. The existing models can't see that. Thus, the agent-based model that is about to be described has a huge added value.

If it is used to simulate different strategies or schedules, it might be able to spot where delays will happen and how to cope with them way before they happen. Thus, it can help decrease the dynamic buffers while maintaining a good reliability of the turnaround time.

2.2.3 Software

There are different softwares that are adapted to the implementation of agent-based models. The non-exhaustive list includes *AMP*, *Flame*, *Matlab*, *MetaABM*, *Netlogo*, *Repast*,... However, only one of them has been chosen to implement the agent-based model: *Netlogo*. It is a programming language especially developed for ABM by Uri Wilenski at Northwestern University in Chicago and funded by the National Science Foundation. It is a *Java*-based free and open source programming language. Thousands of biology, social, supply chain models and others have been implemented.

The choose of this software is based on different reasons. First, it is very user-friendly and readable for people from the academic world. Secondly, it is sufficient for the purpose of this Master thesis. An agent-based model can be implemented on any programming language. However, even if it can be faster to run the model on a classical object-oriented programming language like *Java*, the development time will be considerably larger. Since the thesis is more a proof-of-concept than a commercial development, *Netlogo* is sufficient. Plus, the speed of the other programming languages is necessary for ABM with millions of agents. In an airport, there are only hundreds of agents.

Chapter 3

Model

The main part of this thesis concerns the modeling of aircraft turnarounds thanks to agent based-modeling (ABM). The model created allows to simulate a large number of successive (or simultaneous) turnarounds taking place in an airport, meaning sharing replenishment trucks and stands between each other. After passing inputs through the model, the Montecarlo method is used in order to estimate as accurately as possible the actual off-block time (AOBT) of each plane, i.e. the moment at which its turnaround is fully done. This section therefore describes how the off-block times predictions are done.

The modeling has been done based on some hypotheses about the real turnarounds behaviour. All those hypotheses are justified and based either on the literature or on the advice of an airport operations expert¹. Globally, every hypotheses has been modeled such that it is easy to modify it (if not the case, it will be clearly specified).

Such a development has been described in four parts :

1. The ABM approach of the model : it introduces the model by describing its ABM characteristics, namely the environment, the different agents, theirs properties and the way they interact with each other.
2. The complete model description : this part includes everything that composes the model such as all the choices and hypotheses, the building method and blocks description, the different inputs supported by the model and the fully described way in which it has been modeled. In short, it fully describes the input and the model itself.
3. The output computation using the Montecarlo method : the agent-based model is built to get reliable confidence intervals on the off-block time of each aircraft. This part explains the path from simulations to results.
4. The demonstration of the ABM power for the model: the agent-based model can simulate interactions across the airport that other models could not do. The objective is to highlight them to value the development of the model.

¹Bruno Desart, supervisor of this thesis.

3.1 ABM to model airport turnarounds

The first step towards modeling is to imagine how to represent a succession of aircraft turnarounds using agent-based modeling. This means thinking about what is the environment, what composes it and what are the agents interacting in it, respecting the characteristics and properties of agent-based modeling detailed in Section 2.2.1. It also means describing what those interactions consist in, and what are their properties. All this information constitutes a strong basis for building the model. It is its core since it consists in simulating a succession of agents actions and movements in their environment.

3.1.1 The environment

As explained in Section 2.2.1.2, the environment is the global map of the model. The map incorporating all the turnarounds is a geographical description covering everything the model can simulate.

First of all, since the model has been designed to evaluate the moment turnarounds end, it considers aircrafts only when they are at stands. Indeed, as a recall, an aircraft turnaround starts when the aircraft arrives at the stand, and ends when it leaves it. The movements of aircrafts inside the airport (from the runway to the stand and from the stand to the runway) have no influence on the turnarounds duration². Since the modeling only considers planes parked at stands but not their different moves such as take-off, landing, or even travels between stands or towards taxiways and airstrips, those elements (taxiways and airstrips) are therefore not part of the environment of the model.

However, the model considers the movements of different trucks which go from stand to stand to perform part of the turnarounds, like fueling or loading. Those movements have an impact on turnarounds durations since those trucks have to be present at different moments along the full turnaround duration. If a truck is in movement, it is not at the stand and cannot perform its turnaround part. Therefore, the distance between the different stands is considered, but also the distances towards the different facilities useful for trucks between the different turnarounds such as the fuel depot to refill fuel tankers, or the terminal to load/unload luggage.

In summary, the environment is composed of all the airport stands and of the different roads between them, useful for the different trucks to move around. It also includes the different facilities needed for each truck to fully perform its action. Geographically, it is therefore a part of an airport similar to the part which is not shaded on the synthesised airport plan of Figure 3.1. Of course, this geographic area depends on the airport itself.

²they can however produce delays (positive or negative) for the start of the turnaround but delays are taken into consideration later in this chapter

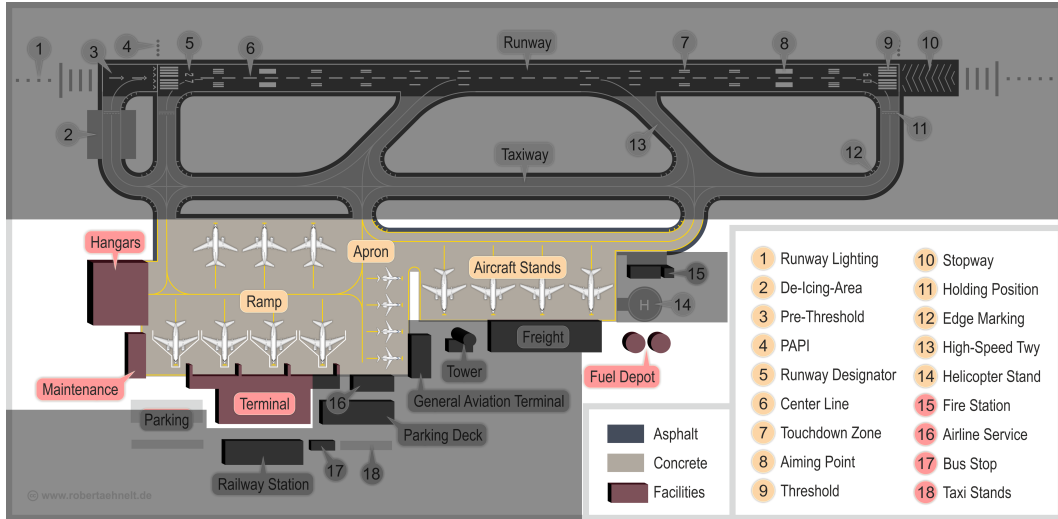


Figure 3.1: Environment : airport illustration [10]

In agent-based modeling, the notion of neighbourhood is really important. Agents act (at least partly) according to the state of the agents in their neighbourhood. In the environment, two agents will be considered as neighbours if they are at the same stand. Indeed, some processes are performed only if the corresponding truck is present at the stand and, vice versa, trucks only act if the plane is at the stand and if no other similar truck is doing the same action on the same plane. This notion will be more clearly explained once all the agents have been defined.

The environment has just been defined as the airport (a part of it) in which the turnarounds are performed. As in every agent-based model, the state of this environment determines the global context of the agents. The environment is indeed defined by all the information about the succession of turnarounds that will occur and what impacts them, from the number of trucks available and their travel distances from stand to stand, to the schedule of the turnarounds, their stand assignment and the airplane types. In fact, these environment characteristics are defined by the input of the model, as explained in Section 3.2.4.1.

3.1.2 The agents

Now the environment is defined, it is necessary to determine the different agents that interact in it. The first step in this determination is to define what are the elements in the environment which interact with each other. The different interactions are done during the turnarounds when the different crews interact with the plane in order to carry out the turnaround processes, such as fueling or cleaning. Those crews are represented by their main equipment. For example, a fueling truck represents the full fueling crew, i.e. the people working on it and the equipment. The hypothesis that people can be represented by their equipment holds if the whole is acting accordingly, meaning for example the absence of the crew members in real life is represented by the absence of the equipment itself in the model. In short, crew members and equipment are one and the same.

For the processes modeled (see the selection in Section 3.2.1), it means five types of agents : fueling trucks, catering trucks, cleaning trucks, ULD³ trains and bulk trains. The last two are responsible of the loading and unloading of the containers and luggage. Each type of agent has a number of occurrences defined by the initial state of the environment, i.e. the equipment of the airport. The number of trucks of each type is therefore dependent on the airport itself.

With a modeling point of view, each agent holds some information about its actions, meaning its state is define by the progress and characteristics of its actions. As previously mentioned, the mobile agents interact with the different aircrafts in order to perform the turnarounds. However, since they move from plane to plane to perform different turnarounds, it could be complicated to collect all the information about a complete turnaround, since it means access pieces of information detained by each agent that is involved in it, and therefore requesting that which agent has been involved in each action is always known. For example, to know if the fueling process is done, the information must be collected from the fueling truck that has performed it, it is therefore always needed to keep track of this fueling truck. Moreover, this information can be needed several times, since as it will be explained later, it is often important for the fueling to be over before allowing people to board or declaring the end of a turnaround. The information is therefore needed all the time before the end of the processes (in order to know when it occurs), which means it is susceptible to be collected a lot of time.

To avoid such a collect of information, it is possible to consider aircrafts as the agents, interacting with all other mobile agents, which centralize all the information about their turnarounds in order not to have to collect them from the different mobile agents at each time. However, it has been defined that the aircraft moves in the airports are not considered, and therefore that the aircrafts are either at their stand or not (in the modeling point of view). Interacting with a plane when it is at its stand is therefore the same as interacting with a stand when the plane is at it. It can be noticed that, in big turnaround periods, there are many more planes effectuating turnarounds than stands supporting those turnarounds (most of the stands see multiple different turnarounds each day, hundreds of them each year). Moreover, planes are not specific to the environment and go in and out of it, contrarily to the stands which are connected to the airport. It has therefore been decided that the last agent type would be the stands, representing the different planes which will pass through them. This choice is also useful since the number of stands is supposed to stay constant (changing it is simply changing the environment, like changing the airport itself) while the number of plane changes over each period of turnaround successions. Once again, the number of stands is defined by the airport that is taken into account.

Therefore, to obtain a good modeling, the stand agents are the ones performing the turnarounds. As it will be explained later, they will be the ones performing the different processes in the model. Of course, in real life, those processes are carried out by the different mobile crews, but from a modeling point of view, the turnarounds will be performed by stand agents (according to the presence or not of the real processes performers). Such a modeling choice allows to centralize all the information of a turnaround in one agent, and to keep that information once the mobile agents have left.

³Unit Load Device

To summarize this, the agent types are the following :

- 5 mobile agent types : they represent the crew and their equipment that are responsible for different specific processes (i.e. fueling trucks for refueling, cleaning trucks for the cleaning, catering trucks for the catering and bulk trains and ULD trains for the loading and unloading).
- 1 fix agent type : the stands, they are active when planes are present at the stand and interact with the mobile agents in order to perform the turnaround. They centralize the information about the different turnarounds. They are the agents performing it.

3.1.3 Interactions

Since the main added value of agent-based modeling is to model interactions, it is important to define them. They will define the rules of behaviour of the agents. Two big types of interactions can be described :

- the ones between stands and the different types of mobile agents
- the ones between mobile agents of the same type.

The first one occurs during the different turnarounds. For the stand to perform some processes of the turnaround, it needs the corresponding truck to be present. For example, if the fueling truck is not at the stand, the fueling process cannot be performed. The turnaround state, and therefore the stand state, is thus dependent on the presence of mobile trucks : the stands interact with the mobile agents. And vice-versa, since the stands detain all the information about the turnarounds, the interactions between stand and mobile agents allow the mobile agents to know when the process they are responsible for is over. The interactions provide them with information about the stand state, i.e. the turnaround state, and enable them to know when they are free to go and perform their next action.

The second interaction type considers mobile agents interacting with agents of the same type. They interact together in the turnaround allocations, since a mobile agent has an action assigned if no other agent already has this action assigned. This behaviour is described more accurately in Section 3.2.4.1.

3.1.4 Properties of the ABM

The agent-based modeling basis described in the previous subsections makes it possible to create a model representing an environment in which agents, fix and mobile, interact with each other. To perfectly fit agent-based modeling, the model must consider an universal clock. Agents must act in their environment and interact with the others at each tick of this clock. In this case, it is : at each tick, stands where a plane is present perform the turnaround according to the presence or not of the different mobile agents. Also, at each

time step, mobile agents either go to a stand, wait, or perform their process. Algorithm 1 and Algorithm 2 reflect this universal clock of the model very well. They will be fully described in Section 3.2.4.2.

Also, the agents fully respect the different properties of agent-based modeling (see Section 2.2.1.1), namely :

1. **Autonomy** : each agent acts on its own in the environment. Their actions are dependent on the information they receive, and there is no global authority imposing on them what to do at each tick of the clock. For example, mobile agents act based on the information they receive about the turnaround but those information are not orders, agents have their own rules of behaviour depending on the situation.
2. **Modularity** : since they are physical equipments (stands, fueling trucks, catering trucks, ...), agents are identifiable and precisely defined. A fueling truck is something very specific and distinguishable, as all the other agents are. It is easy to determine if an object/entity belongs to one of the agent types or not.
3. **Sociality** : each agent type interacts well with others in the environment, as explained in Section 3.1.3.
4. **Conditionality** : each agent has a state depending on the time. Mobile agents are either moving towards stands, waiting or performing their action. Stand agents are either performing a turnaround or not (the turnaround has itself different states depending on its advancement).

3.2 Model choices and building

Section 3.1 brings the foundation of the modeling. This one fully describes the model itself. It begins with the choices of the different processes to implement, then defines the inputs and how time distributions have been built. Next, the model is detailed by blocks (the outputs are described in Section 3.3). The different hypotheses and choices are explained in this section.

3.2.1 Processes choices and constitutions

To know exactly what to model, it is important to determine each process to model, and to know if some of those processes were themselves divided into other sub-processes i.e. to investigate the possible characteristics of a turnaround. For know, the model concentrates itself on passengers planes, but the application to cargo planes is just an adaptation of the processes. Two main sources are used in this determination : on the one hand, the literature summed up in Section 2.1, on the other hand the turnaround description for 11 different aircraft types. Those aircraft types are the main types encountered in the available data. As a reminder, almost no private data were provided for this thesis, but the hypotheses has been made that the characteristics of this selection of common aircraft types cover a large panel of other types of characteristics, since they contain a lot of turnaround possibilities. The list of those aircraft types can be found in Section 4.1.1. Their characteristics come from manufacturers' documentation, see [11], [12] and [13]. All the characteristics from those documents make it possible to build Gantt charts similar to the one on Figure 3.2.

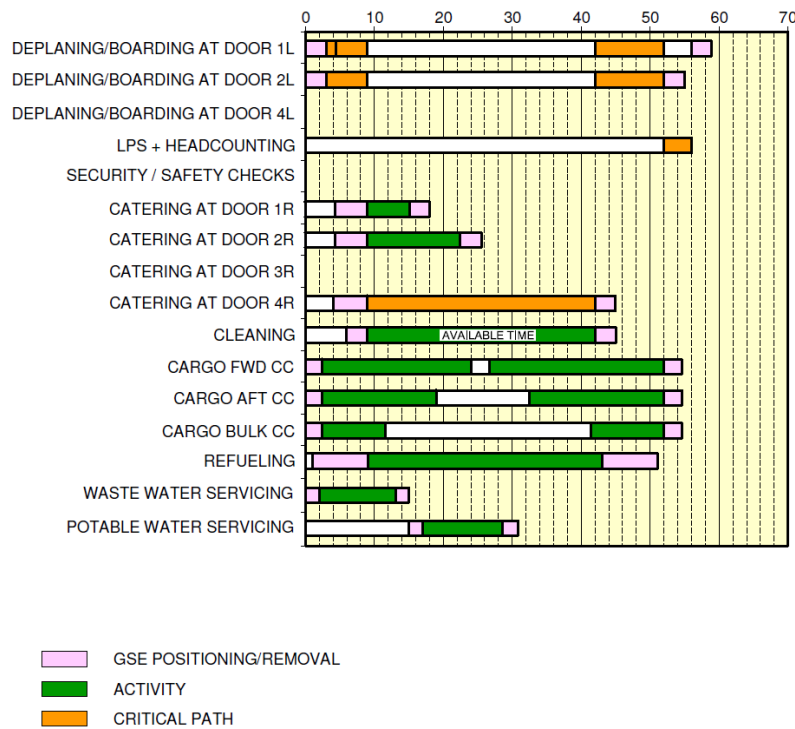


Figure 3.2: Gantt chart of A330 Airbus processes [11]

On this basis, the processes (and sub-processes) selected were the most likely to have an influence on the turnaround duration, i.e. to be on the critical path (see definition in Section 2.1.4). They are :

- Boarding and debordering of passengers.

Those processes are only considered done via bridges in this model, bridges being structures making a direct link between plane doors and terminals. Those bridges are fixed to the stands and therefore do not need to be considered as agents since they are always present and can therefore be considered solidary to the stand. The (de)boarding processes via stairs, i.e. people debarking on the tarmac and going to the terminals either on foot or in buses, are not taken into consideration due to the lack of information about it⁴. The model has been built in such a way that its modularity permits to consider stairs in a simple way if the data are available. The processes are composed of successive subprocesses. For instance, the debordering (often) consists in the equipment positioning (bridge or stairs) followed by the doors opening and finally the people embarkation. Similar successions of events can be found for the boarding process. Nevertheless, they are always successive events and can therefore be considered as one global process, i.e. the debordering process or the boarding process.

- Fueling of the aircraft.

Refilling the fuel tank of the aircraft is also a succession of subprocesses: the plug in of the equipment, the tank filling itself and the plug off of the equipment. Once again the succession makes it possible to consider it as one single process, the fueling. To be performed, it needs the presence of a fueling truck and its crew, the fueling truck moving from stand to stand to be part of different turnarounds. Fueling trucks are therefore the first mobile agent type.

- Catering of the aircraft.

This process is different from the other since it can be divided into sub-processes occurring simultaneously. To be accurate, catering is done via up to 3 doors (often less) by one or more catering crews (workforce and catering truck). An example of a plane with those doors is represented in Appendix on Figure B.1. For planes with small catering quantities, the catering can be performed by only one crew which go from a door to another. However, when big quantities are needed, several catering crews are needed, and they can therefore act in parallel at the different doors. The model takes into account up to 3 simultaneous catering crews on a plane. If there is only one crew which go from one door to another, it will only consider one catering process (with one crew from door to door performing each catering consecutively). If several crews are needed, the model simply considers simultaneous catering processes. Catering trucks are therefore a mobile agent type, going from stand to stand, and up to 3 catering trucks are sometimes required for a single turnaround⁵.

⁴Consider them would probably consist in creating stairs and busses agents, to compute new travel times, to know the boarding type (bridge or stairs), etc...

⁵From the literature, no aircraft needs more than 3 simultaneous crews, but if it is needed, the model can easily be modified in that way

- Cleaning of the aircraft.

Just like for the fueling process, the cleaning process only requires one crew (workforce and cleaning truck) to be performed. This process is sometimes skipped during some turnarounds. The cleaning trucks represent the third type of mobile agents.

- The unloading/loading of the aircraft.

This process has the specificity that, for some aircraft types, it must be performed by two types of crews, since those planes have two types of things to unload: containers and luggage gathered in the bunkers. The first type is (un)loaded by cargo loaders and transported by ULD trains, while the second one is transported by bulk trains and (un)loaded via conveyor belts⁶. However, since those devices always work in pairs (bulk train/conveyor belt and ULD train/cargo loader), only one of the equipment can be considered to represent both of them (a behaviour modification of one of the two has an influence on the whole pair). Therefore, the model considers two new types of mobile agents: the so called bulk trains and ULD trains. Also, the unloading of the containers can be done simultaneously on two doors. Therefore, two ULD trains can be needed for a loading/unloading. Considering both processes (loading and unloading), some aircrafts may need four ULD trains and two bulk trains in order to perform their whole turnaround. Once again, the doors and different equipment are represented in Appendix on Figure B.1.

Other processes have not been taken into consideration for two main reasons. The first one is that some of them (crew changes, water servicing, ...) are never on the critical path and therefore have no influence on the off-block time of the aircraft. The second one is that some extra processes are also performed really exceptionally (maintenance, de-icing, ...) and information about them was missing. The added value of modeling such processes has been judged insignificant in this work, but if this paradigm would come to change, a lot of processes could be modeled easily based on what already exists (a lot of situations have already been imagined).

In brief, the model takes into consideration seven different processes: deboarding, boarding, unloading, loading, fueling, catering and cleaning. They will be performed with the help of five types of mobile agents : ULD trains, bulk trains, fueling trucks, catering trucks and cleaning trucks. It should also be remembered that the stands are considered as fixed agents.

3.2.2 Processes duration

In order to make the model realistic, it has to be run with random durations. Indeed, in real life, the turnarounds duration are not deterministic. The randomness is represented by the random processes durations (fueling, boarding, ...). Since all the processes are performed by humans and not robots, it induces some uncertainty. For example, if everyone wants to deboard hastily and not properly, deboarding can last longer than if it is performed in a good way. Another example can be the duration of loading and unloading, which depend on the physical condition of the crew, on the weight of the luggage and

⁶The details of such equipment can be found in [11]

other undetermined factors. Processes' durations are modelled with random variables and drawn from specific time distributions. They are drawn at each simulation of the model.

To do a perfect job, real data would have been needed in order to fit some time distributions properly. However, such data has not been available (see explanations in the Introduction). Thus, reasonable and smart choices had to be made. They will be described later on. However, it is important to notice that the model is completely independent from these distributions and that if new data are available, they can easily be put through the model.

For now, Beta distributions have been chosen to model the random variables, the processes durations. The choice is mainly based on the shape of the distribution. Indeed, with the right parameters, the low values of the distributions are really clustered, contrarily to the highest values that are really spread (see the black curve on Figure 3.3). Actually, a right skewed probability density function is needed because what aircraft manufacturers give in their aircraft characteristics documents are approximately minimum turnarounds. This means that if the duration is drawn under the mean, it is not too small compared to the mean. However, if the duration is sampled above the mean, it can be huge. This assumption is realistic even if it is not based on real data. For example, the fueling process cannot be too short compared to what manufacturers announce for obvious operational reasons. However, due to a random problem, the fueling time can be a lot longer.

The random variables of the model are determined as linear transformations of a random variable X following a Beta distribution between 0 and 1 with parameters α and β . With the shape being chosen, parameters have to be determined too in order to have realistic choices. Since the announced time duration given by the aircraft manufacturers were the only data available, it has been decided to determine everything from them. Those data are considered as the mean of each distribution. They can be found in aircraft characteristics documents (see [11], [12] and [13]) and Section 4.1.2.2.

The Beta distribution is traditionally used to model continuous random variables whose range is between 0 and 1. Its probability density function is the following (see [14]):

$$f(x; \alpha; \beta) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1-x)^{\beta-1} \quad (3.1)$$

where $0 \leq x \leq 1$, $\alpha, \beta > 0$ are shape parameters and $B(\alpha, \beta)$ is the Beta function defined as

$$B(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha + \beta)} \quad (3.2)$$

where $\Gamma(y) = \int_{t=0}^{\infty} t^{y-1} e^{-t} dt$.

The shape of the distribution depends on its parameters. To be realistic, the probability density function needs to be unimodal (see the black and purple curves on Figure 3.3). The characteristics of such distributions is that both α and β are strictly greater than 1 and $\alpha < \beta$.

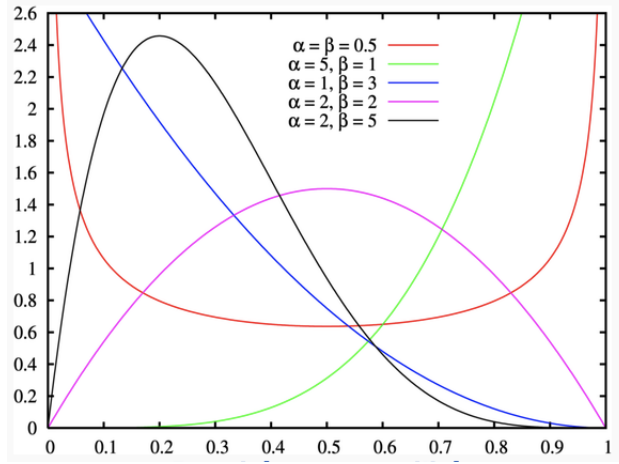


Figure 3.3: Probability density function of a Beta distribution depending on its parameters [15]

The expectation of the Beta distribution is $E[X] = \frac{\alpha}{\alpha+\beta}$ and its variance is $Var[X] = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$. These two characteristics are helpful to determine α and β for every random variable. Indeed, with the method of moments, by setting the mean and variance respectively to μ and σ^2 , the solutions for α and β are :

$$\alpha = \mu \left[\frac{\mu(1-\mu)}{\sigma^2} - 1 \right] \quad (3.3)$$

$$\beta = (1-\mu) \left[\frac{\mu(1-\mu)}{\sigma^2} - 1 \right] \quad (3.4)$$

With these results, if the mean and the variance of each random variable are fixed with reasonable choices, the parameters of their probability density functions can be found. As mentioned just above, the random durations are modeled as linear transformations of random variables following a Beta distribution. Thus, for every random variable T_i representing a process duration,

$$T_i = c_i + d_i X_i \quad \text{where} \quad X_i \sim Beta(\alpha_i, \beta_i) \quad (3.5)$$

$$E[T_i] = c_i + d_i E[X_i] \quad (3.6)$$

$$Var[T_i] = d_i^2 \cdot Var[X_i] \quad (3.7)$$

with c_i and d_i the parameters of the linear combination. Since $0 \leq x_i \leq 1$, the random sample drawn from the rescaled distribution respects $c_i \leq t_i \leq c_i + d_i$.

Since no real data is available, the parameters of the linear combination and the variance of the random variables representing processes duration have been defined for now as

$$c_i = m_i \cdot \mu_{T_i} \quad (3.8)$$

$$d_i = n_i \cdot \mu_{T_i} \quad (3.9)$$

$$\sigma_{T_i}^2 = p_i \cdot \mu_{T_i}^2 \quad (3.10)$$

with m_i , n_i and p_i some scaling parameters of the model, $\mu_{T_i} = E[T_i]$ and $\sigma_{T_i}^2 = Var[T_i]$. They determine the range of the random variable and its spread across this range. The linear combination parameters c_i and d_i are in seconds, that is why they are proportional to the mean contrarily to the variance that is proportional to the squared mean.

With this information, the characteristics of X_i only depend on the scaling parameters of T_i :

$$\mu_{X_i} = \frac{1 - m_i}{n_i} \quad (3.11)$$

$$\sigma_{X_i}^2 = \frac{p_i}{n_i} \quad (3.12)$$

Thus, for every random variable T_i with mean μ_{T_i} found in the aircraft characteristics documents available on the aircraft manufacturers websites, the Beta distribution parameters α_i and β_i can be computed from the mean and variances according to equations 3.3 and 3.4. It is important to notice that the chosen parameters need to lead to α and β parameters greater than 1 to get a unimodal probability density function shape. In practice, this means avoiding to have a too big variance because this would lead to distributions like the red or the blue ones on Figure 3.3. When both α and β have been computed, the probability density function of T_i is all known.

In conclusion, it is always possible to derive good distribution parameters with reasonable choices. However, the model could give more realistic outputs if distribution reflecting perfectly the reality were used, which was not possible due to the issues explained in Chapter 1.

3.2.3 Input

The definition of the inputs of the model are really important since they represent the scope of possibilities that can be passed through the model. They are every element that can change the values that will be obtained in output, i.e. an estimation of the time at which each turnaround ends (see Section 3.3).

The first big types of input concern the characteristics of the environment, they have been discussed in Section 3.1.1. They are :

- The scheduling of plane arrivals and departures. It includes scheduled in-block and off-block times (SIBT and SOBT), stand assignments and aircraft types.
- The number of stands in the airport.
- The number of mobile agents available in the airport, i.e. the number of fueling trucks, catering trucks, cleaning trucks, ULD trains and bulk trains.
- The travel times from stand to stand for each mobile agent. This distance, expressed in time unit, includes each agent stopping at the facilities in order to charge/discharge itself. For instance, for fueling trucks, this is the travel time to (and from) the fuel depot added to the refilling time. Since bulk and ULD trains can be used for both loading and unloading, the travel time depends on which process it does at each

stand. If the travel time is the time for the agent to go from stand x to stand y , there are indeed 4 possibilities :

- Train unloads stand x , loads stand y . At the terminal, it has to discharge what it has unloaded from stand x and to charge what it will load at stand y .
 - Train loads stand x , unloads stand y . Since it is empty after the loading of stand x and it has to arrive empty for the unloading of stand y , the train does not have to pass by the terminal on its way from stand x to stand y .
 - Train loads stand x , loads stand y . It arrives empty from stand x at the terminal but has to charge what it will load to stand y .
 - Train unloads stand x , unloads stand y . It has to discharge what it has unloaded from stand x at the terminal but can go empty to stand y .
- The distributions of the in-block time delays in order to sample the actual in-block time (compared to the scheduled one).
 - The agents scheduling method. Its type describes how the processes are allocated to the different agents. Currently, three types of methods are implemented : the first one is about using as few agents as possible among the ones available, the second one about allocating a similar number of actions to each agent in order for them to do approximately the same amount of work during the same time period and the third one considers allocating action to the agent which would be able to be present the sooner (detailed in Section 3.2.4.1). Also, the scheduling includes time margins before (tmb) and after (tma) the scheduled processes. They define the time window the agent needs to dedicate to the action in their schedule. If the action of scheduled time length l is supposed to start at a time t , the agent schedule indicates that it must be at the stand from time $t - tmb$ to time $t + l + tma$.
 - Information about time buffers. It indicates if the turnaround scheduling must be done using time buffers or not (see Section 2.1.2). The size of those time buffers can also be modified.
 - Starting time of loading and boarding. Sometimes, there is a long time between the scheduled in-block and off-block times. People who have to board are therefore not present at the stand after the end of the deboarding process, neither is their luggage. It is therefore important to consider the beginning of the boarding/loading process not only as something which must happen after the deboarding/unloading but also as something that must not start too early in relation to the time of departure of the plane.

As already mentioned, the aircraft types are inputs of the model. The model needs to know every aircraft type given as input. Knowing an aircraft type means knowing its different characteristics :

- Process duration estimations: they are deterministic durations used to plan the schedule of each process. Such an input can be represented in a Gantt chart like the one in Figure 3.2. The processes are the ones described in Section 3.2.1. Also, for the processes divided into sub-processes which can occur simultaneously, the

estimated time duration must be provided for all the sub-processes (for example, if there are three simultaneous catering processes at three different doors, the aircraft type must define the estimated duration of those three). Typical estimations of the duration can be the mean of the distribution or any other representative value. Processes which don't occur simply see their duration set to 0.

- Process duration distributions : for each process duration estimation, there is a distribution (and vice versa). They are used to simulate what could happen in reality. Ideally, they are the true distribution. However, since this model had to be tested without access to any real data about the processes, the model can also tolerate only means as input and can compute the distributions by itself (see Section 3.2.2).
- The authorization for the processes to be performed with passengers on board. As explained in Section 2.1.1, most of the time fueling cannot be performed if passengers are on board. However, some aircraft types allow fueling with passengers on board, this authorization can be integrated as input. Next to the ones for fueling, this model can also provide authorization for cleaning and catering to be performed with passengers on board.
- Other possible characteristics from the general ones : some global characteristics can easily be specified for only some aircraft types, like the buffers information or the starting times for loading and boarding.

Those inputs can represent a lot of different flights. Indeed, not only the aircraft model can change, but also the airlines. Two aircraft of a similar model and a similar airline can also be represented by two different aircraft types if, for example, some processes are not carried out at each turnaround, or if they have other different characteristics depending on the flight. In fact, each of the aforementioned characteristics can be modified in order to describe a new aircraft type.

Finally, some performance inputs also exist. To mention them briefly, the time step of the universal clock can be determined, as well as the beginning and end time of the model (to simulate only a part of the turnaround put in input). Some inputs concerning the computation of the output can also be chosen (see Section 3.3). It is also possible to decide to print every turnaround information at each time step or not.

3.2.4 Model description

After having declared the basis of the model in Section 3.1, the process choices have been described in Section 3.2.1. Next to that, all the inputs have been defined in Section 3.2.3. Therefore, it is now possible to describe precisely how the model works. In Figure 3.4, it can be observed that it is divided into three main blocks :

1. The inputs and the agents are set up and created as explained in the previous sections. The block is detailed in Section 3.2.4.1.
2. The inputs and agents are passed through a block that simulates each turnaround, as well as the actions and interactions of each agent, based on the universal clock concept explained in Section 3.1.4. It makes it possible to obtain a

duration for each turnaround. This block is repeated several times, each block realisation being a simulation necessary to the Montecarlo method (explained in Section 3.3). The block is detailed in Section 3.2.4.2.

3. The computation of the output, i.e. the confidence intervals over the off-block time obtained from the Montecarlo method results. The block is detailed in Section 3.3.

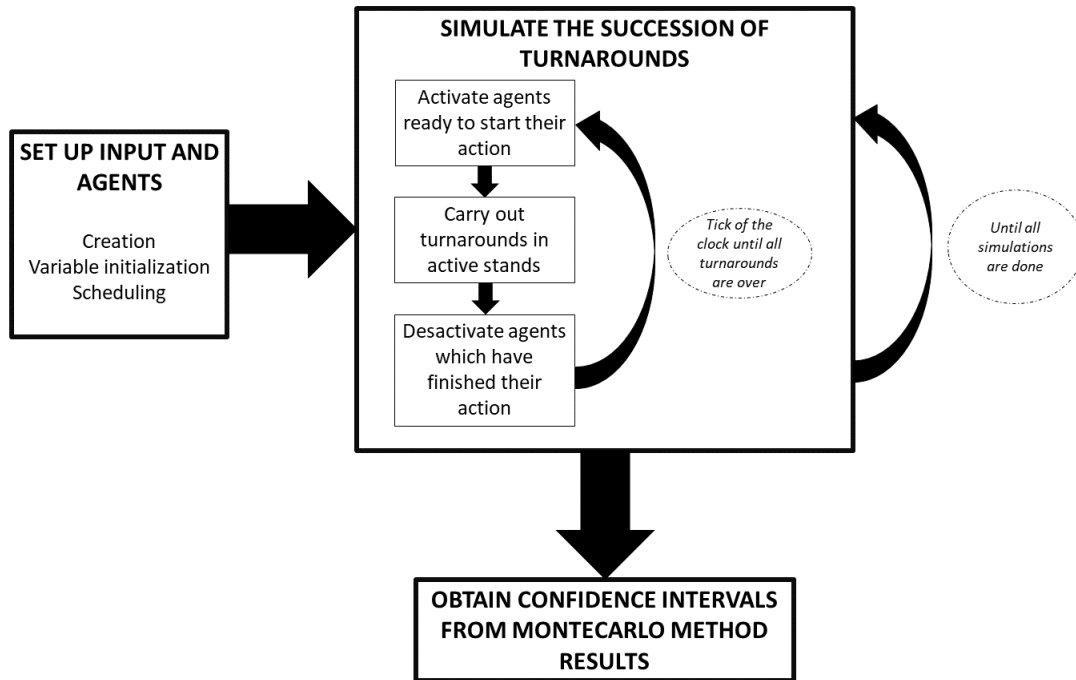


Figure 3.4: Block scheme of the model

3.2.4.1 Inputs and agents setting up

Inputs setting up

In this block, all the inputs from Section 3.2.3 are set up. It includes global inputs such as the number of agents, the schedule (time, stand and aircraft type), the travel times, ... But also the different aircraft type characteristics (processes durations, authorizations, ...). It can be noted that aircraft type characteristics can be memorized by the model since they are assigned to an identifier. It induces that input using an aircraft type already used with the model doesn't have to characterized it again. The implementation variables are also set up (time step for the clock, number of realizations of the second block, ...).

Agents creation

Once the inputs are set up, the agents can be created. Since their number has already been set up, the number of agents to create is therefore known. The stands and the different mobile agents (trucks and trains) are created.

Agents setting up and scheduling

Now that they have been created, each agent needs its schedule to be created. For stands, it is just determining from the general schedule the scheduled beginning and end time of each of their turnarounds, as well as the turnarounds indices and the corresponding aircraft types. It can be noted that, as previously mentioned, the stands agents have all the information about turnarounds, i.e. the different aircraft types characteristics (process durations, authorizations, ...). For now, those are just declared variables. During the realization of each turnaround, they will take the values related to the characteristics of the corresponding aircraft type from the input .

For mobile agents, their schedule contains the moments at which they are needed, the stands where they have to act, the different travel times between the stands where they operate, the corresponding turnaround indices and the actions they have to perform. For example, the bulk train has to know if it is a loading or an unloading process, and the catering truck needs to know at which door to perform the catering if it operates on an aircraft type allowing simultaneous catering sub-processes.

Computing the time at which the agents are needed for realizing their actions is not trivial. It must take into consideration the starting time of the turnaround, but also the fact that some actions must wait until the end of others in order to be performed. The summary of the conditions over the other actions for an action to start can be found in Table 3.1. The actions marked with asterisk must be over only if the fueling/catering/cleaning are not allowed with passengers on board, respectively. In this table, it can be read, for instance, that fueling/catering/cleaning must wait until the end of deboarding before starting if it does not allow passengers in the aircraft while being performed. It also indicates that the boarding must always wait until the end of deboarding, as well as the end of the different processes which do not allow passengers on board while being performed. Unloading and deboarding may start at the beginning of the turnaround.

Process	Fueling/Catering/Cleaning	Loading	Boarding
Actions that have to be over	Deboarding*	Unloading	Deboarding Fueling* Catering* Cleaning*

Table 3.1: Process start conditions over the other actions

The scheduling process needs to be independent from time distributions since it is not supposed to read the future. Thus, the scheduling process will use the means of time distributions with time margins around it in order to predict what is going to work most of the time but the scheduling knows nothing about the shape of the time distributions or their variance.

For scheduling, the agents take into consideration the time margins given in the input. These security times have been defined in Section 3.2.3. With the time estimation of the processes related to the corresponding aircraft type, they are used to schedule the actions of the agents. The first thing to do is to define the minimum beginning time, i.e. the minimum time at which an action can start in the theoretical case where the turnaround is only consists in this action. Deboarding, unloading, catering, cleaning and fueling can

be performed as soon as the turnaround begins. However, this is not the case for loading and boarding since they must wait for the stuffs/passengers to be present (especially for aircraft staying a long time at the stand). For those processes, the following definition holds :

$$\begin{aligned}
\text{minimum beginning time} &= \text{turnaround scheduled off-block time} \\
&\quad - \text{process estimated duration} \\
&\quad - (\text{process estimated duration} \\
&\quad \quad \times \text{process beginning security factor})
\end{aligned} \tag{3.13}$$

with the action beginning security factors given as inputs.

It is now possible to determine the scheduled beginning time of each action :

$$\begin{aligned}
\text{end time of previous processes} &= \text{turnaround scheduled start time} \\
&\quad + \text{previous processes estimated duration} \\
\text{process beginning time} &= \max(\text{end time of previous processes}, \\
&\quad \text{minimum beginning time})
\end{aligned} \tag{3.14}$$

and therefore the scheduled time window the actions can be determined for each agent:

$$\begin{aligned}
\text{needed time at the stand} &= \text{process beginning time} \\
&\quad - \text{before margin time} \\
\text{scheduled process end time} &= \text{action beginning time} \\
&\quad + \text{process estimated duration} \\
&\quad + \text{after margin time}
\end{aligned} \tag{3.15}$$

The actions being scheduled, they need to be assigned to the different agents, as well as their characteristics (stand, turnaround index, action type, start and end scheduled times, ...). The assignment method, also called scheduling method in this thesis, can be determined in the input. Currently, three methods are implemented :

- The smaller index method

The first one uses the indices of the agents. The action is assigned to the agent, which can be present (according to its schedule⁷) at the needed time at the stand, with the smallest index, the actions being assigned in chronological order in terms of needed time at the stand. Therefore, it minimizes the number of agents used within a feasible schedule. If no agent is available, the action is assigned to the agent that can arrive the sooner at the stand (as in the third method below). It will therefore probably induce a delay for the next action. This is the default method used in every application in this thesis.

⁷it means its previous action finished soon enough to allow it to effectuate the travel between the stands.

- The homogeneous method

The second one tries to spread the number of actions equitably among the different agents, also using their indices. After being sorted chronologically, the actions are spread among agents according to their indices. It means actions which have an index in the sorted list of the form $i + (k \times \text{number of agents})$, with $k \in \mathbb{N}$, are assigned to agent with index i .

- The sooner available method

The last implemented method assigns the action to the agent that is most likely to be the first one present at the stand, i.e. the one that has the smallest sum of the scheduled end of its previous action and its estimated travel time between the two stands.

Those methods, as well as their pros and cons, are fully described in Section 4.2.2.2.

3.2.4.2 Turnaround simulation

Once the agents and inputs are set up, the inputs can be passed through the core of the model simulating every turnaround, the actions of agents and the interactions between them under the influence of the universal clock. The way this universal clock has been modeled is represented in Algorithm 1. Although inputs can be given in minutes and outputs are also in this measure unit, the clock works with time steps in seconds in order to avoid rounding errors as much as possible. The setting up of the clock is simple : the time is set to 0. Also, every agent (stands and mobile ones) starts as inactive, since no turnaround is performed at the beginning. At each tick of the clock, each agent considers the state of the environment, as well as what is happening in its neighbourhood, in order to determine what it has to do according to its rules of behaviour. The clock stops once every scheduled turnaround has been performed.

Stands behaviour in the clock

Each stand checks three conditions successively at each tick of the clock and acts according to the following rules of behaviour :

1. If the stand is inactive, i.e. it's not performing any turnaround, and it still has at least one turnaround to perform, it checks if its next scheduled turnaround is ready to take place. This is the case if the corresponding plane has arrived at the stand, the arrival time being the sum of the scheduled arrival time and the delay (drawn from the distribution given as input, it can be either positive or negative). If the arrival time of the plane is reached by the clock, the stand is then set active. The turnaround characteristics are therefore given to the stand according to the aircraft type (processes durations drawn from distribution, processes to perform, authorization for the processes, ...), and it is ready to perform the different processes.
2. If the stand is active, then it performs its turnaround according to the time reached by the clock and the mobile agents. This step is fully described in Algorithm 2 and in the section "Performing a turnaround step" just below.

Algorithm 1: ABM clock in turnarounds modeling

```
all agents inactive
time  $\leftarrow$  0
while all turnarounds are not over do
  % STANDS PART
  for each stand do
    if inactive and it is time to start its next turnaround then
      | become active
    end
    if active then
      | perform turnaround          %function of time and other agents
                                   see Algorithm 2
    end
    if its current turnaround is over then
      | become inactive
    end
  end

  % MOBILE AGENTS PART
  for each mobile agent type do
    for each occurrence of the agent type do
      if inactive and at stand and it's time to start its next turnaround then
        | become active
      end
      if inactive and not at the next stand then
        | go to the next stand
      end
      if active then
        | act according to the stand (turnaround) state
        if action over then
          | become inactive
        end
      end
    end
  end

  time  $\leftarrow$  time + time_step
end
```

3. If the stand is active and has just finished its turnaround in the previous condition, then it is set inactive.

Mobile agents behaviour in the clock

Like stand agents, each mobile agent also checks three conditions successively at each tick of the clock and acts according to the following rules of behaviour :

1. If the mobile agent is inactive, i.e. it is not performing any action, and if it still has at least one action to perform, then it checks if it is currently at the stand corresponding to its next action, i.e. it has already traveled from the previous stand. If it is the case, it verifies that its next scheduled action is ready to happen. If the clock has reached the scheduled time, then the agent is set active.
2. If the mobile agent is inactive, still has at least one action to perform and is not at the stand corresponding to its next action, then it travels from its current stand to the next. It means that it is likely to wait a significant amount of time at the next gate if the two actions are separated by a long break. This modeling choice has been made because of a lack of information about what the agents do when they are not at a stand performing a process. The implementation of the travels has been done in such a way that it is easy to make the agent wait elsewhere, according to the assumptions made. From a modeling point of view, travelling is simply decreasing the travel time left by the time step.
3. If the mobile agent is active, then it will be used at the stand to perform its action. However, from a modeling point of view (contrarily to real conditions), as previously explained, the stands carry out the different actions and only give information to the agent that only needs to be present. If the stand informs the agent that its action is over, then the agent is set inactive.

Performing a turnaround step

As previously mentioned, at each tick of the clock, the active stands perform their turnaround. Performing a turnaround is performing its different processes according to different parameters and conditions, i.e. the characteristics of the turnaround processes, the time reached by the clock and the different mobile agents in the neighbourhood of the stand. From a modeling point of view, performing an action is simply decreasing the time left to finish the action by the time step (as a reminder, the initial duration of the actions are drawn from the distributions given by the aircraft type).

It has been seen that each action must respect some conditions to be performed. Those conditions are represented in Algorithm 2 and some of them have already been discussed in Section 3.2.4.1. Those other rules of behaviour are :

- Some actions must wait the end of others to be performed. Those conditions have already been seen and explained Table 3.1.
- Of course, if an action is done, it is not performed anymore.

- The loading and boarding actions must wait for their minimum beginning time to be reached. This minimum has already been defined in Equation 3.13.
- The action which needs a mobile agent to be performed (all except boarding/deboarding) can only be performed if the corresponding agent is present. For processes which are divided into simultaneous sub-processes, the sub-processes which have their agent present can be performed even if the other agents are not present for the other sub-processes. For example, if there are initially two simultaneous loading processes, one of containers and the other of luggage, but that the ULD train is delayed, the luggage loading can be performed if its bulk train is present. The loading of containers will be performed once its ULD train has arrived.

At the end of each process or sub-process, the stand sends the information to the agent responsible for it that the action is done. If all the processes are done, then the turnaround is declared over.

Dynamic buffer management

This model also takes into consideration dynamic time buffers (defined in Section 2.1.2). As previously mentioned, the input determines if the model must take dynamic buffers into consideration or not. If it is the case, their length is proportional to the length of the action they are attached to, the proportionality coefficient being. Time buffers are deterministic time scheduled periods connected to actions. In the scheduling of a turnaround, the time buffer starts at the end of the scheduled action. As long as the end of a time buffer is not reached, the processes which must wait for the end of the action related to the buffer to be performed cannot start.

To simplify, the time buffers have not been introduced in the model before. However, they have an impact on what has already been seen :

- For the scheduling, in Equation 3.13, 3.14 and 3.15, each estimated process duration (i.e. its scheduled duration) is in fact the sum of the estimated process duration and the buffer coming after it.
- In the realization of turnaround step, when processes have to wait for the end of others, they in fact must wait for their end and for the clock to have reached the end of the respective time buffers.

The use of time buffers and their pros and cons are detailed in Section 4.2.2.1.

Algorithm 2: Perform one step of a turnaround

```
if unloading not done then
  | unload (if the unloaders are at stand)
end
if unloading done
  and minimum beginning loading time is reached
  and loading not done then
  | load (if the loaders are at stand)
end
if deboarding not done then
  | deboard
end
if (deboarding done or fueling authorized with passengers)
  and fueling not done then
  | fuel (if the fueling truck is at stand)
end
if (deboarding done or catering authorized with passengers)
  and catering not done then
  | perform catering (if the catering trucks are at stand)
end
if (deboarding done or cleaning authorized with passengers)
  and cleaning not done then
  | perform cleaning (if the cleaning truck is at stand)
end
if deboarding done
  and (fueling done or fueling authorized with passengers)
  and (catering done or catering authorized with passengers)
  and (cleaning done or cleaning authorized with passengers)
  and minimum beginning boarding time is reached
  and boarding not done then
  | board
end
if all processes are done then
  | declare turnaround over
end
```

3.2.5 Model limits

Like every other ones, this model has some limits. However, it has been built in such a way that most of them can be corrected reasonably easily with small modifications. Indeed, lot of new processes, variables, inputs or functionalities can be applied to the model with simple updates. There are some other limits. More often, it is possible to overcome them but they have not been broken because the added value that exceeding them bring has not been judged sufficient. Here is a non exhaustive list of them :

- For now, the model can only simulate turnarounds that are done entirely at the same stand. In reality, it can happen that a plane which has a long break between its landing and the following take-off only makes the first part of its turnaround at the in-block stand, and completes it later at another stand. For now, those eventualities (which are not frequent as explained in Section 4.1)) are not allowed by the model. However, a way of breaking this limit is to transfer information about turnarounds from stand to stand. It would involve to create a new interaction type. In reality, it is also possible that a plane which has a long break between landing and next take-off does its full turnaround at the same stand, but that it is moved elsewhere during the break in order to allow another planes to perform their turnaround at the same stand. However, the model does not allow plane to leave the stand before the end of their turnaround. A way to overcome this limit would be to allow stand to stock information about multiple turnarounds simultaneously, and to deactivate/reactivate plane even if their turnaround is not over.
- For now, process time distributions are fixed for each aircraft type, i.e. they are not dependent on other factor than the aircraft type. In reality, they depend on other factors. For example, boarding duration depend on the number of passengers while loading duration is not independent from the load amount (currently, the model uses mean values to represent those factor). A simple way to take those new factors into account would be to transform the time distributions with a well chosen linear combination depending on those new factors.
- The input aircrafts schedule is fixed (scheduled in and off-block times, stand assignment, ...) and cannot be optimized by the model since this objective is beyond the scope of this thesis. A bad input would obviously lead to bad results independently from the model. Aircrafts schedule methods could be added to the model if needed.
- Once the agents assignment and scheduling have been done using the chosen method, they are never adapted. Those attributes are therefore not dynamic and cannot be adapted to the real time situation, i.e. if new information about the aircrafts scheduled off-block times arrives or if an agent encounters some problems, non of the agents adapt its schedule according to the events. The only way to adapt the situation is to change the input and relaunch the model. Once again, such live adaptations were beyond the scope of this thesis.

3.2.6 Model implementation

This section is a comment about the implementation. The model is implemented in *Netlogo* (see Section 2.2.3). It is object-oriented and makes it possible to define specific objects : agents. The syntax is really specific to the language but is easy to understand for readers. The Netlogo library does not contain many classical functions, that's why some of them have been built for the model to work (quick sort, matrix operations, list element-wise operations, ...). They can be useful for further development.

The model and functions are all in a global implementation accessible on Github [2]. A **README** is also available in order to use the script, and the script itself is fully commented. The software *Netlogo* needs to be downloaded and installed from [16]. The accessible implementation is applied on the life-size use case (see Section 4.1). The input is already included in the code.

The interface is made to contain a lot of visualizations to change parameters easily (see Figures A.1 and A.2 in the Appendix). It makes it possible, amongst others, to print or not to print what happens at each tick of the clock in order to visualize the behaviour of the model.

Also, as often mentioned, the model has been built in a modular approach in order to make it possible to modify its assumptions easily. The recommended method to add any new modification to the model is to first do it on a simplified version of it with a small input and less processes and then to verify it on the full model. Such a simplified version can be found on [17].

3.3 Output computation

Now that the model is built and fed with inputs, it has to bring outputs. The power of the model is its simulation and it is useful for different purposes.

Two of them are presented in this section. First, it can be used to derive mean off-block times of each turnaround to evaluate the impact of a strategy or another in different use cases, and especially to evaluate if a specific strategy is more likely to create delays compared to another. Thus, a method to compute the confidence interval on the mean off-block time is needed. It will use the Montecarlo method ([18]) and the Central Limit Theorem ([19]). Secondly, operational workers need a confidence interval on the actual off-block time to have less uncertainty on their schedules. Hopefully, it would be smaller than the presently available ones (15 minutes confidence intervals, see page 2). These confidence intervals would, for example, answer the simple following question:

What time window (as small as possible) can be guaranteed to include the actual off-block time of turnaround n°12 with 95% probability?

Thus, a method to compute these confidence intervals is needed too. It is based on the Montecarlo method and on approximations.

To sum up, on the one hand, the confidence intervals on the off-block times means will be used to evaluate delays on different strategies and situations. On the other hand, the confidence intervals on the actual off-block times will be directly used to predict the uncertainty.

3.3.1 Confidence intervals on the mean off-block time

The method to compute the confidence intervals on the mean off-block time for each turnaround will be described in this section. Using the Montecarlo method, with a large number of simulations, there will be a large set of different off-block times for each aircraft turnaround. Indeed, every simulation is different and unique because of the randomness of the process' durations. Thanks to this set of off-block times, the confidence intervals will be computable.

3.3.1.1 Mathematical formulation

In order to find some confidence intervals on the mean of a random variable, the Central Limit Theorem has to be applied and the hypotheses have to be valid.

Theorem 3.3.1 (Central Limit Theorem [19]) *Let $Y_1, Y_2, \dots, Y_n$ be independent and identically distributed random variables with*

$$E(Y_j) = \mu \quad \text{and} \quad V(Y_j) = \sigma^2 < \infty \quad (3.16)$$

Define

$$U_n = \frac{\sum_{j=1}^n Y_j - n\mu}{\sigma\sqrt{n}} = \frac{\bar{Y} - \mu}{\sigma/\sqrt{n}} \quad \text{where} \quad \bar{Y} = \frac{1}{n} \sum_{j=1}^n Y_j \quad (3.17)$$

Then the distribution function U_n converges to the standard normal distribution function as $n \rightarrow \infty$. That is,

$$\lim_{n \rightarrow \infty} P(U_n \leq u) = \int_{-\infty}^u \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt \quad \text{for all } u \quad (3.18)$$

In the inputs of the model are the time distributions of the processes on each turnaround, depending on the aircraft type. Those inputs are used in every simulation to draw randomly numerical values of the processes durations. Thus, with n different simulations, the realizations of each time distribution are drawn independently n times with the same distributions. Thus, the n sets of processes random durations are independent and identically distributed.

Then, for each simulation, the model acts as a huge block that takes all the durations and transforms them into several outputs: the different off-block times of each aircraft. Those outputs Y^i , for $i \in \{1, \dots, q\}$ and with q the number of turnarounds to perform throughout the day, are defined from midnight in seconds. For simulation $j \in \{1, \dots, n\}$, the agent-based model gives outputs $\{Y_j^1, Y_j^2, \dots, Y_j^q\}$. Gathering all the outputs for one of the turnaround $i \in \{1, \dots, q\}$, $Y_1^i, Y_2^i, \dots, Y_n^i$ are outputs of the same model that has used independent and identically distributed random processes durations. Plus, they are corresponding to the same turnaround. Thus, they are independent (a simulation has no impact on another) and identically distributed outputs. That is true for each turnaround $i \in \{1, \dots, q\}$.

For each $i \in \{1, \dots, q\}$, $E(Y_j^i) = \mu_i$ and $V(Y_j^i) = \sigma_i^2 < \infty$. Define

$$U_n^i = \frac{\sum_{j=1}^n Y_j^i - n\mu_i}{\sigma_i\sqrt{n}} = \frac{\bar{Y}^i - \mu_i}{\sigma_i/\sqrt{n}} \quad \text{where} \quad \bar{Y}^i = \frac{1}{n} \sum_{j=1}^n Y_j^i \quad (3.19)$$

Then, by the Central Limit Theorem (see Theorem 3.3.1), the distribution function of U_n^i converges to the standard normal distribution as $n \rightarrow \infty$ and this for all i . Since σ_i^2 is not available, it is approached with s_i^2 , the sampled variance. Thus, the confidence interval for μ_i is given by

$$CI = [\bar{Y}^i \pm \frac{z_c s_i}{\sqrt{n}}] \quad \text{with} \quad P[-z_c \leq Z \leq z_c] = 1 - \alpha \quad (3.20)$$

The parameter α is the significance level and defines the confidence level $1 - \alpha$. It is the confidence that is put in the interval. For example, if $\alpha = 0.05$, then the confidence interval is built with 95% confidence: on n simulations, the mean off-block time of each aircraft has 95% chance to rely on the confidence interval that has been computed for this specific aircraft. As n increases, the confidence interval gets narrower. Its length is inversely proportional to $\sqrt{n}$. Since the mean off-block time of each turnaround is wanted to be approached very accurately, the confidence interval must be narrow. Thus, for the applications, a very large number of simulations would be required to make the interval length go to zero.

3.3.1.2 Procedure

In practice, the Montecarlo procedure is done as shown in the Algorithm 3. First, the setup is done, the distribution parameters are computed and the schedule is calculated for all the simulations since it will be the same for each. Then, the typical day for which predictions are wanted is simulated n times. In these simulations, all the off-block times are stored for each turnaround at each iteration. Finally, for each turnaround, the confidence interval is computed with confidence level $1 - \alpha$ according to Formula 3.20. This implementation uses the model as a black box. Indeed, the agent-based model is only a tool to simulate the different turnarounds that have to be performed.

Algorithm 3: Mean off-block times confidence intervals procedure

```

 $n \leftarrow$  number of simulations
Setup all the aircraft and input data
Compute all the distribution parameters
Calculate the needed schedule
for  $i = 1 : n$  do
    Initialize the model and the schedule
    Perform one day (Randomness in processes durations)
    Store every off-block time
end
for each turnaround do
    Calculate the mean off-block time
    Calculate the standard deviation on the off-block time
    Compute the confidence interval on the mean off-block time with confidence
        level  $1 - \alpha$ 
end

```

After such a procedure, each turnaround can be characterized as follows :

The mean off-block time (if the day was simulated an infinite number of times) of turnaround i is ensured to be between h_1 and h_2 with a level confidence $((1 - \alpha) \cdot 100)$ %.

This kind of result is mainly used to analyze the impact of different strategies on the delay they occur.

3.3.1.3 Computational characteristics

A lot of simulations have to be done in order to have reliable confidence intervals. That induces a lot of computations for the hardware. Indeed, the time needed for one simulation is directly proportional to the number of turnarounds to perform. For example, in a life-size airport application (see Section 4.1), there are hundreds of turnarounds to perform at each iteration. However, two main solutions have been found to cope with that issue.

First, the time step can be increased: if x seconds are added at each tick of the model instead of 1, it simply reduces the simulation time by this factor x . The drawback is that it can induce rounding errors and approximations of a few seconds from time to time. It therefore can't be increased too much. Secondly, at the initialization, nothing changes

from one simulation to the other apart from the random draws of the processes durations. Thus, everything is stored and used several times. These computational characteristics are also used in the next method to compute the actual off-block times confidence intervals.

3.3.2 Confidence intervals on the actual off-block time

This second method is used to evaluate the uncertainty on the off-block time of each turnaround. Indeed, as mentioned just before, operational workers need a confidence interval to use in practice so it has to take into account the randomness of the off-block time and not only its mean. The goal of this section is to describe the used procedure.

Usually, to mathematically compute confidence intervals, the probability density function of the random variable to be bounded has to be known. In practice, the agent-based model uses a lot of different rules and transformations of the input random variables to compute the off-block times. For these blocks, no simple analytic expression is available. So even if all input distributions are available, it is not practically possible to derive the distribution of the off-block times theoretically. Thus, the observed probability density function for each turnaround off-block time is used.

Different methods can build a confidence interval on an observed distribution. In this case, as a reminder, the smallest confidence interval is needed because operational workers want to decrease the uncertainty on the off-block time. Also, by choosing the smallest one, exceptional values are rejected from it and it better reflects reality. The used procedure is an approximation, based on observations and is not proven by tangible mathematical results on exact probability density functions. It is described in Algorithm 4. The beginning is the same as in the previous section to compute the confidence intervals on the means : simulations are performed. Then, for each turnaround, all the possible confidence intervals containing $((1 - \alpha) \cdot 100)\%$ of the values are computed and their lengths are stored. Finally, the smallest (in seconds) confidence interval is chosen.

Computational characteristics, presented in Section 3.3.1.3 just above are still used. Taking into account that simulations tend to reflect reality, the computed confidence intervals on the actual off-block times can be reliable if the number of simulations is big enough. If they are reliable, they can be used by operational agents to better predict the turnaround durations. Results on this type of output will be described in Section 4.1 on the life-size airport application.

Such a method can give narrow or wide confidence intervals depending on α , the significance level chosen. After having discussed with an expert in airport operations, a value of $\alpha = 0.05$ has been chosen to get confidence intervals with the model. However, such a value rejects most of the outliers and does not reflect the very uncommon cases. In economics, for example, they usually work with significance level $\alpha = 0.005$ to compute their Value at Risk [17]. The methods used in this field reflect better the whole range of values their output can take. However, this is not in the scope of this thesis.

Algorithm 4: Actual off-block time confidence intervals procedure

```
 $n \leftarrow$  number of simulations
Setup all the aircraft and input data
Compute all the distribution parameters
Calculate the needed schedule
for  $i = 1 : n$  do
    Initialize the model and the schedule
    Perform one day
    Store every off-block time
end
for each turnaround do
    OBT  $\leftarrow$  Sorted vector containing the realizations of the off-block time in
        ascending order
    CI size  $\leftarrow$  round( $(1 - \alpha) * n$ )
     $\Delta \leftarrow$  vector containing all the possible confidence interval duration lengths
        (initialized with zeros)
    for  $i = 0 : \text{round}(\alpha * n)$  do
        |  $\Delta(i) = \text{OBT}(i + \text{CI size}) - \text{OBT}(i)$ 
    end
     $x \leftarrow$  index(min  $\Delta$ )
    lower bound  $\leftarrow$  OBT( $x$ )
    upper bound  $\leftarrow$  OBT( $x + \text{CI size}$ )
end
```

3.4 Demonstration of ABM power

In Section 2.2.2, the agent-based model has been introduced as a powerful tool to model and better understand interactions between agents. Other models that already exist are aircraft-centric (see Section 2.2.2). The agent-based model is helpful since it offers an airport-centric point of view. It means that it is able to simulate the interactions across the boundaries of the different stands between the agents. For example, it is known that for most of the aircraft types, fueling cannot be performed during deboarding. If deboarding lasts a lot longer than scheduled, it delays the fueling. But if the fueling truck needs to go to another stand afterwards, it will delay the fueling on this other stand too. This kind of interaction, such as the ones explained in Section 3.1.3, cannot be implemented in time-based or event-based models that composed the state-of-the-art before the implementation of the agent-based model.

In order to show the power of the model, it will be run on a simple example that contains 2 consecutive turnarounds on different stands and a few agents. The input is available in Table 3.2⁸. To make the example more interesting, the number of agents has been very restricted to see how their unavailability impacts the schedule. Their respective numbers are available in Table 3.3. No delays at the in-block time have been taken into account at this point.

⁸see Section 4.1 for the description of different aircraft types

Turnaround n°	1	2
Scheduled in-block time⁹	10:00	10:30
Scheduled off-block time	11:15	12:00
Stand n°	1	2
Aircraft type	A320	A320

Table 3.2: Example input

Agent type	Number
Fueling trucks	1
Catering trucks	1
Cleaning trucks	1
ULD trains	4
Bulk trains	2

Table 3.3: Number of agents for the example

For the selected aircraft type, the fueling, catering and cleaning agents have to wait for deboarding to finish before beginning their processes. Also, the scheduling assignment strategy is the default *smaller index* method explained in Section 3.2.4.1. The Figure 3.5 shows the scheduled airport-centric Gantt chart since it is not centered around one single turnaround but around the several agents that compose the system. The Figure 3.6 shows the two aircraft-centric Gantt charts: one for each stand since there is only one turnaround per stand in this example.

The consecutive scheduled actions of the different agents are available on Figure 3.5. The different properties of the scheduling strategy can be observed:

- There are time margins before and after each process during which agents are not supposed to do anything to cope with small delays (observation **I.** on Figure 3.5)
- The minimum number of agents to avoid any delay is used: ULD train 8 and 9 are used just once since the trains 6 and 7 are available for the last loading.
- The travel times are correctly taken into consideration.
 - Before fueling, the travel time is medium because the tank of the truck only has to be refilled.
 - Before a loading, the ULD train or the bulk train has to drop the luggage or containers it has taken at the last unloading and to load the luggage or containers for the next flight before coming to the next stand (observation **II.** on Figure 3.5).
 - Before cleaning, the truck needs to put the waste into the garbage.
 - Before catering, the truck also needs to put the waste into the garbage and to refill the trolleys with new products.

⁹**Notation:** *hh:mm* represents a time in the day

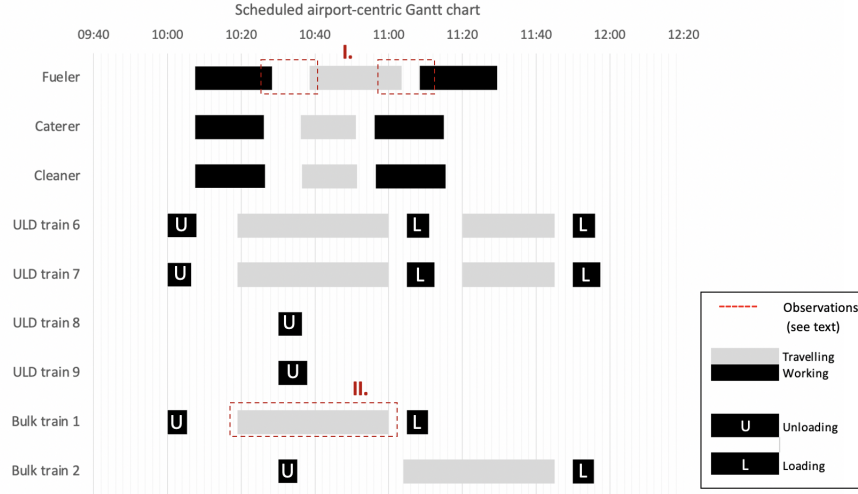


Figure 3.5: Scheduled airport-centric Gantt chart

The consecutive scheduled processes performed on the two stands are available on Figure 3.6. The scheduling respects the common sense:

- The interactions between the processes are respected. For example, fueling, catering and cleaning processes wait for deboarding to be finished. Also, unloading and loading are independent from other processes (but loading starts after the end of the unloading).
- Boarding and loading are scheduled with respect to the scheduled off-block time (observation **III.** on Figure 3.6).

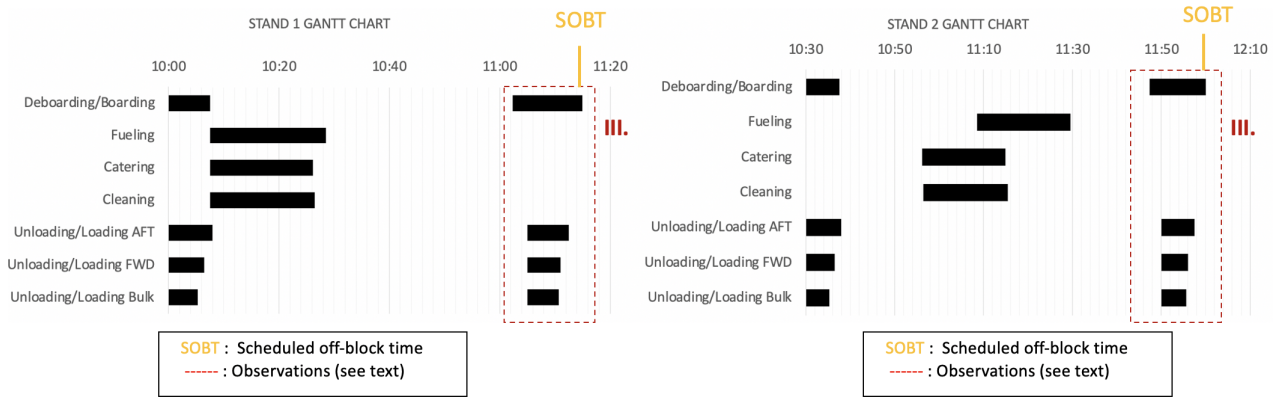


Figure 3.6: Scheduled aircraft-centric Gantt charts

After having done the schedule, one realisation of the day has been simulated. It is only one of the possible realisations since, as a reminder, the process's durations are drawn randomly according to the input distributions. However, the goal here is only to show the power of the agent-based modeling, not to observe the true processes durations. The results of the actual realisation are shown on Figures 3.7 and 3.8. A few comments can be made in order to show the power of the model:

- In reality, the time margins around the agents' actions are not used if they don't have to be used. Indeed, the agents begin their journey to the next stand directly after having finished their process (observation **I.** on Figure 3.7).
- Since the fueling on stand n°1 has lasted a lot longer than scheduled (45 minutes instead of 21), the time margin after the process has not been able to dampen the delay. Thus, fueling operation on the stand n°2 has been delayed too. It started at 11:20 instead of 11:08 as scheduled (observation **II.** on Figure 3.7).
- Catering and cleaning on stand n°1 have been performed in a reasonable time so catering and cleaning on stand n°2 could begin as scheduled at 10:56 (observation **III.** on Figure 3.7).
- The second fueling was very long as well (35 minutes instead of 21 minutes scheduled). Thus, boarding had to be delayed and the off-block time had been delayed as well (observation **IV.** on Figure 3.8).
- The loading of the first position on stand n°1 has lasted a lot longer than scheduled. Thus, it has delayed the off-block time.
- As it can be seen in Figure 3.8, all the aircraft-centric interactions and rules are respected by the agent-based model (for example fueling after deboarding).

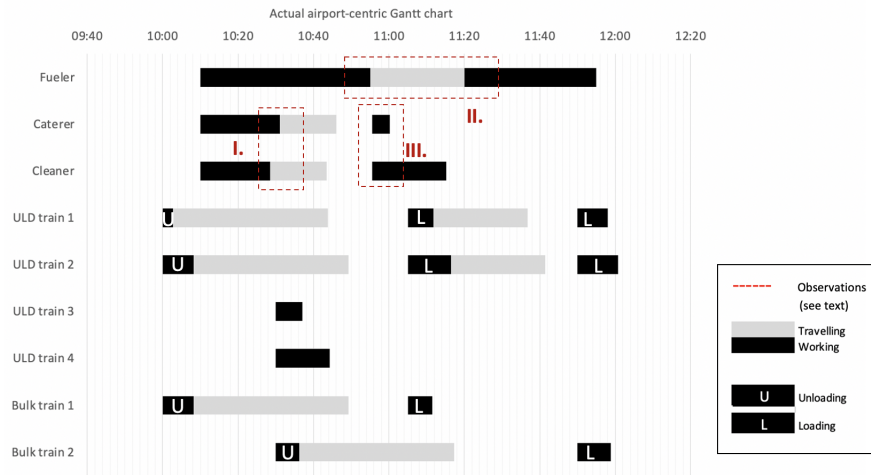


Figure 3.7: Actual airport-centric Gantt chart

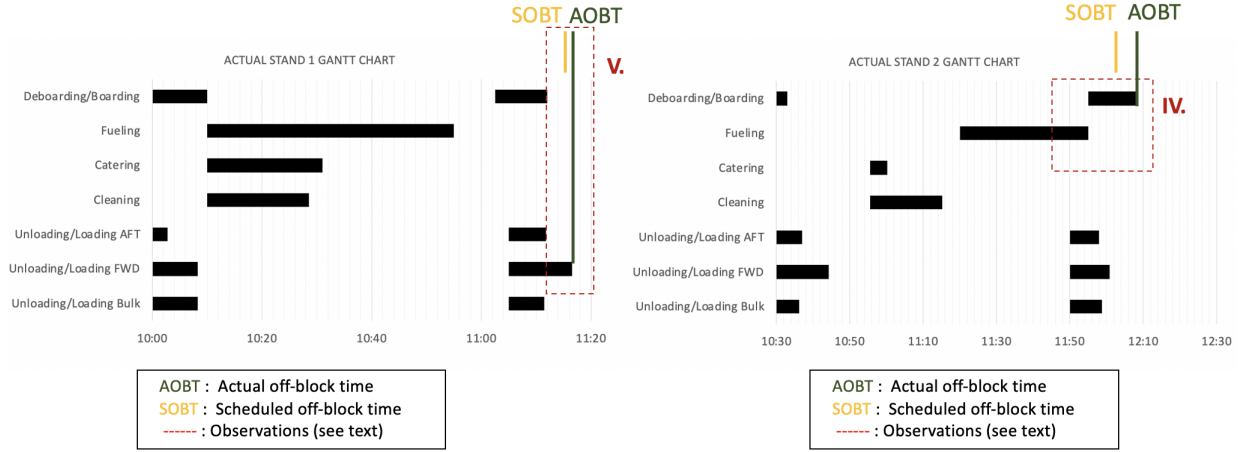


Figure 3.8: Actual aircraft-centric Gantt charts

All these observations could be done on a larger example. If a limited number of agents is kept, then it can induce a snowball effect. For example, the boarding of the 2 turnarounds just above had to be delayed. Thus, the off-block time had been delayed too. If this delay is too long, the next turnarounds on these stands could be delayed too. Thus, the fueling, catering and cleaning agents that have to work on these turnarounds have a delayed schedule too. If they have a delayed schedule, that can induce delays on their next turnarounds, etc. It is the snowball effect. In practice, buffers are used to cope with that issue. Two consecutive turnarounds on the same stand are separated by a time margin. However, if unexpected events induce too big delays, the snowball effect can be really dangerous for adherence to the schedule.

In conclusion, agent-based modeling, an amazing tool, helps to simulate properly the interactions between the agents on an airport scale. The simple rules introduced in event-based and time-based modeling could not have been able to simulate properly all the observations that have been done just above.

Chapter 4

Model applications

4.1 Life-size airport application

In order to validate the model on some data, a life-size use case has been considered. The idea is to simulate turnarounds on a European airport¹ for which a dataset, containing information from a busy day on hundreds of aircrafts movements (take-offs or landings), was given.

The objective is to simulate a few hours of this day with the model. Thanks to hundreds of simulations, a confidence interval on the off-block time can be computed. As a reminder, one of the objectives of the thesis is to reduce the confidence interval on the off-block time that can be given to airport agents. Currently, they work with -5min and $+10\text{min}$ margins around the scheduled in-block time. Thus, the aim is to reduce this confidence interval thanks to the *Montecarlo* method.

This section will first describe the dataset that was given. Then, due to the lack of real data about the processes durations, the investigation through aircraft manufacturers document has been described. Finally, the results of the simulations are presented and commented.

4.1.1 Given dataset

The dataset includes about 800 arrival/departure pairs that can be found on Github [2]. They are organized as on Figure 4.1². For a few records, some attributes were missing. Since the dataset was big enough, it has been filtered and only complete records have been kept.

¹The airport name is not mentioned for confidentiality reasons

²This example is fake due to confidentiality terms. The original dataset that has been used for the thesis has been sent to the readers by email and is not available on Github.

Registration	Aircraft type	Callsign In	Origin AP ICAO	Origin AP IATA	SIBT	AIBT	Stand ID In
CFLSW	B737	KL1720	ZGGG	HKG	09/08/2022 14:10:00	09/08/2022 14:13:09	E09
Turnaround ID		Callsign Out	Destination AP ICAO	Destination AP IATA	SOBT	AOBT	Stand ID Out
201807090004		OR473	ESGG	PVG	09/08/2022 14:55:00	09/08/2022 15:07:14	E09

Figure 4.1: Arrival/departure pair example

The model actually needs the following data :

- the aircraft type
- the scheduled in-block time (SIBT)
- the actual in-block time (AIBT)
- the scheduled off-block time (SOBT)
- the actual off-block time (AOBT)
- the *stand ID in*
- the *stand ID out*

All other data present in the record are not used and thus not defined in this thesis. Every used data is defined just below.

Aircraft type

The aircraft type is essential for the analysis. Indeed, depending on the aircraft, the process durations are quite different. These durations are available in the airplane characteristics documents available on the different aircraft manufacturers websites. Since there are 55 different aircraft types in the dataset, a selection has been performed to decrease the time devoted to data research. Thus, a frequency analysis has been performed on the dataset. The results are displayed on Figure 4.2. The size of the square illustrates the frequency magnitude. With only the 11 mainly used aircraft types, 80% of the data was reached. This assumption has been done because the added value of using more of them has been considered insignificant. Their list is available on Table 4.1. Other types have been associated with the most frequent one: the B738 (*Boeing 737-800*). It has also been assumed that airlines do the same type of turnarounds if they have the same aircraft type at their disposal. However, this can be wrong. For example, some low cost and high standing airlines both use *Boeing 737*. However, low cost airlines are known for performing several turnarounds during the day and sometimes omitting some processes like the full cleaning of the aircraft. High standing airlines won't do that. It can be introduced in the model by differentiating the aircraft types with the airlines.

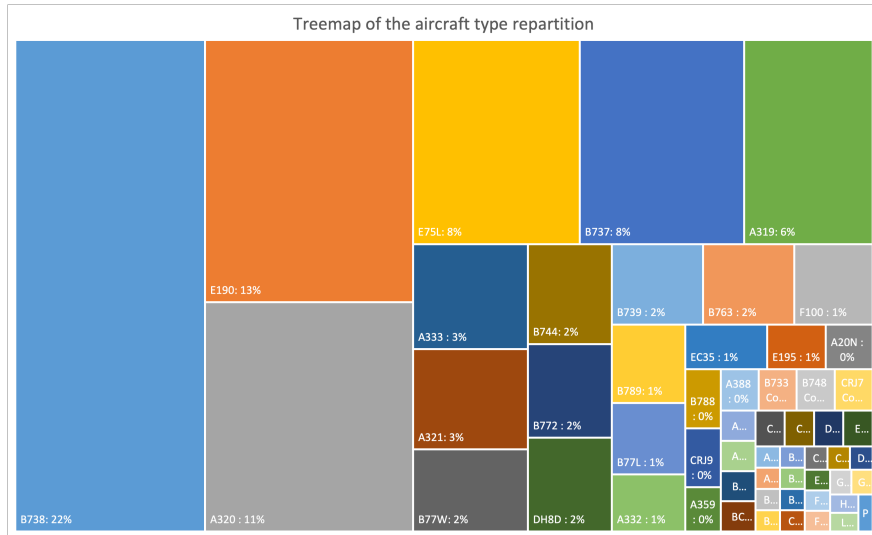


Figure 4.2: Treemap of the aircraft repartition

Manufacturer	<i>Airbus</i>	<i>Boeing</i>	<i>Embraer</i>
Aircraft types	A320	B738	E190
	A319	B737	E75L
	A333	B77W	
	A321	B744	
		B772	

Table 4.1: Main aircraft types of the dataset

SIBT and SOBT

The scheduled in-block time (SIBT) corresponds to the time the aircraft is supposed to arrive at the stand just after landing. On the other hand, the scheduled off-block time (SOBT) corresponds to the time the aircraft is supposed to leave the stand just before the take-off. They are essential for the planification and the allocation of resources.

Stand ID in and stand ID out

The stand ID in and out respectively correspond to the stand at which the aircraft arrives just after landing at the in-block time and the stand the aircraft leaves just before take-off. These two data of the aircraft arrival/departure pair are used for the scheduling and are also used to define the travel time of the different agents between the stands. Sometimes, the aircraft moves from a stand to another during the day. However, it is really uncommon. Indeed, on the whole dataset, only 26 landing/take offs pairs (3.82%) have different stands at the in-block time and at the off-block time. Thus, the model implements the assumption that the stand ID in is the same as the stand ID out. In fact, records with different in-block and off-block stands have been deleted. This issue comes from one of the model limits explained in Section 3.2.5.

AIBT and AOBT

The actual in-block time (AIBT) and the actual off-block time (AOBT) correspond respectively to the time the aircraft actually arrived at the stand just after landing and the time the aircraft actually left the stand just before take-off. However, the model can't use these actual in-block and off-block times because it is used to simulate a day that will happen in the future. Thus, the AIBT and AOBT have only been used to measure the delays at the in-block time aircrafts use to have (to be able to sample a delay with a reasonable mean and standard deviation). The delay has been implemented in the model and can be defined different than zero in the input.

4.1.2 Further research made

To use the model, more data was needed and had to be created/found among the ones existing. They are divided in two parts :

- The travel time between stands
- The processes durations

4.1.2.1 Travel time between stands

Agents have to move from a stand to another. It has been taken into consideration for the modeling. The travel times are inputs of the model. They can change from an airport to another. The input is a matrix $M = [m_{ij}]$ with m_{ij} the travel time between stand i and stand j . This matrix is computed externally. For this application, several assumptions have been made:

- Only the 5 mainly used aprons³ have been taken into consideration. Other distances are an average of the inter-distances between the 5 main aprons.
- The distance between two stands has been computed as the sum of:
 - the distance between their two aprons and
 - the distances from the two stands to the middle of their apron. These distances are drawn from a uniform probability density function between 0 and 500 meters (the approximate size of an apron).
- $dist(S_i, S_j) = dist(S_j, S_i)$ where S_i and S_j are some stands. The input matrix is symmetric but it can be changed if further details on the different routes are available.
- All agents have the same travel speed: 30 km/h. It seems to be a reasonable assumption since they try to minimize the speed difference between agents to ease traffic flow.

³An apron is a place where several stands are located. It is the letter A in the stand $A56$ for example.

- Agents make a stop on the way between two stands to perform different actions. Because of lack of information, it has been considered that agents always find facilities (terminal, fuel depot, ...) on their way between two stands and that they stop there for a specific amount of time. Their durations and descriptions are available in Table 4.2. They are parameters and can be changed if further details are available. Special stops have been introduced for loaders. Indeed, after a loading operation, no stop has to be performed since the loader is empty. However, after the unloading process, the truck needs to drop all the luggage or the containers. Before a loading operation, the truck needs to contain the luggage but not before an unloading. The Table 4.3 contains the input data that has been used for a truck that performs a loading/unloading operation on stand S_i then on stand S_j . The assumption that agents can make their stop on their way to the next stand is a strong assumption. It has been done because of a lack of data. Indeed, it is not possible to know where the fueling agent has to go to refill its tank for example. However, if the data is provided, then the travel time could be computed as

$$t(S_i \rightarrow S_j) = t(S_i \rightarrow \text{stop place}) + t(\text{stop}) + t(\text{stop place} \rightarrow S_j) \quad (4.1)$$

Agent	Fueling trucks	Cleaning trucks
Description	Refueling of the truck	Throw the waste
Duration [min]	20	10
Agent	Catering trucks	ULD trains & bulk trains
Description	Empty the truck and refill it	Unload/load the luggage/containers
Duration [min]	10	see Table 4.3

Table 4.2: Descriptions and durations of agents stops

Process on stand S_i	Process on stand S_j	Stop duration
Loading	Unloading	0
Loading	Loading	20
Unloading	Unlading	20
Unloading	Loading	40

Table 4.3: Special stops durations for ULD trains & bulk trains going from S_i to S_j

4.1.2.2 Processes durations

As mentioned in Section 3.2.3, the model needs some data concerning the processes durations to compute the parameters of the different time distributions. Since no access to real data has been given, the distributions can't be fitted. Thus, as an assumption, the durations given by the aircraft manufacturers have been used as means of the time distributions (see Section 3.2.2). The standard deviation has been chosen to have a reasonable⁴ variance. For the use case, all the distributions have the same variance. However, it can be easily changed in the input.

⁴The term "reasonable" is difficult to define because of the lack of data. A distribution with a realistic shape has been found with a trial-and-error methodology.

The aircraft characteristics and process durations are found on the aircraft manufacturers websites ([11], [12] and [13]). The needed data is always found in the fifth chapter (*Terminal Servicing*) of the document. The use case supposes a full servicing turnaround on a stand (with a bridge but no stairs). An Excel sheet has been filled with the data of those documents. It is accessible on [2] with other results and data. Then, computations have been done to get the raw timings for each process. Most of the time the research and time computations were similar even with different manufacturers. The process time t is computed as below for each process. It includes elements for each process like :

- Deboarding/boarding
 - boarding and deboarding rates (in passengers/minute)
 - passengers capacity⁵
 - establishment durations : bridges positioning/removal and doors opening/closing durations

Then, deboarding and boarding times are computed with

$$t = \text{establishment duration} + \frac{\text{number of passengers}}{\text{rate}} \quad (4.2)$$

- Unloading/loading
 - luggage load and number of containers per compartment. The containers (which are considered fully loaded at each turnaround) are loaded on two different compartments on the aircraft: the FWD compartment at the front and the AFT compartment at the tail.
 - luggage (in kg/minutes) and containers (in containers/minute) loading/unloading rates
 - establishment durations : cargo loaders/conveyor belts positioning/removal and doors opening/closing durations

Then, the unloading and loading times are computed with

$$t = \text{establishment duration} + \frac{\text{luggage load}}{\text{luggage rate}} \quad (4.3)$$

or

$$t = \text{equipment time} + \frac{\text{number of containers}}{\text{containers rate}} \quad (4.4)$$

- Fueling
 - fuel tank capacity (the whole tank is fueled at each turnaround)
 - fueling time
 - equipment : dispenser positioning/removal and connection/disconnection times

⁵To make the simulations realistic, aircrafts have been considered to contain only 73% of their passengers capacity because it is the average load rate in Europe, as it has been suggested by an expert in airport operations.

The total fueling is computed as

$$t = \text{fueling time} + \text{equipment time} \quad (4.5)$$

- Catering
 - number of trolleys per door (all of them are considered)
 - loading and unloading rates of the trolleys
 - equipment : connection positioning/removal and opening/closing doors times

The work is divided at the different doors. It is either done in parallel with several catering agents or sequentially with one catering agent. The timings are computed as

$$t = \frac{\text{number of trolleys}}{\text{rate}} + \text{equipment time} \quad (4.6)$$

An example of the *Airbus A320neo* data can be found in the appendix at Figures B.3, B.4 and B.5. The results of the data research for *Airbus* aircrafts can be found on Figures B.6, B.7 and B.8 in the Appendix. All the extended results are available in the Excel sheet *Acft data* on Github [2].

Also, a minimum *Full Servicing Turn Round Time Chart* is always given. It is a Gantt chart that shows if processes can be performed in parallel or if they have to be performed sequentially (see example on Figure 4.3).

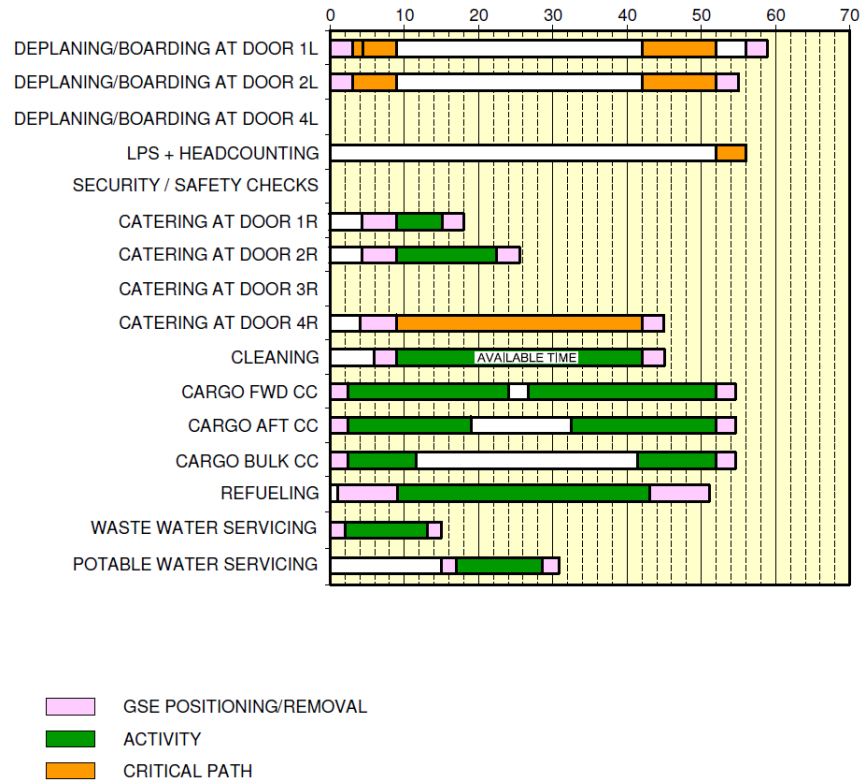


Figure 4.3: Full servicing time chart of an Airbus A319neo

4.1.3 Other input

The model also needs different inputs (see Section 3.2.3) about the environment and about the aircrafts:

- The number of stands in the airport: 156 (computed from the real schedule)
- The number of mobile agents available in the airport: 80% of the number of agents that would be needed to induce no delay on minimum turnarounds. This assumption has been done to keep a good compromise between the use of different equipment and the schedule accordance (very busy day).
 - Fueling trucks: 39
 - Catering trucks: 45
 - Cleaning trucks: 34
 - ULD trains: 129
 - Bulk trains: 19
- Delays at the in-block time: 0. In this application, delays have a huge impact on the confidence intervals length and means because of the scheduling that does not take the possible delays into account. Plus, measuring their distribution on more data would be preferred because it seems that on this specific day, the in-block times have been a lot delayed (positive mean of the delays).
- Scheduling method: the *smallest index* one (using the less possible agents among the ones available).
- Time margins for agents: 5 minutes before and 10 minutes after the scheduled processes (see explanation on page 27)
- Buffers: not used in this application except when absolutely needed because of the number of agents available.
- Loading and boarding beginning coefficients (see explanations on page 31): 1/3 and 0.
- For the use case, the fueling, catering and cleaning have been considered impossible to proceed while passengers are on board.

Three more parameters have to be specified:

- Time step of the universal clock: 15 sec.
- Number of simulations: 1000.
- Significance level $\alpha = 0.05$

4.1.4 Results

With such inputs, the simulations can be performed to get the 95% confidence intervals. They have been performed on turnarounds that have a scheduled in-block time between 13:00 and 20:00. There are 273 different turnarounds during this period. The extended results are available on Github [2]. A sample of the results of turnarounds with an in-block time between 13:00 and 13:30 are available at Figure 4.4. Only the confidence interval on the actual off-block time is shown. Here, it is the uncertainty that is wanted to be highlighted. As a reminder, operational stakeholders want to minimize the uncertainty on the actual off-block time for logistic and economic reasons.

SIBT	SOBT	ACTUAL OBT			MEAN OBT	Delay
		LOWER BOUND	UPPER BOUND	CI LENGTH		
13:00	13:35	13:33	13:37	4'30"	13:35	0'01"
13:10	14:20	14:17	14:22	4'30"	14:20	0'08"
13:10	15:20	15:15	15:25	10'30"	15:20	0'41"
13:10	14:00	13:55	14:05	10'15"	14:00	0'30"
13:10	14:35	14:30	14:40	10'15"	14:35	0'30"
13:15	14:00	13:57	14:02	4'30"	14:00	0'02"
13:20	14:05	14:00	14:13	12'15"	14:06	1'35"
13:20	14:05	14:02	14:10	8'00"	14:05	0'36"
13:20	13:50	13:53	14:08	14'30"	14:00	10'30"
13:20	13:55	13:57	14:12	15'15"	14:04	9'46"
13:20	14:05	14:00	14:12	12'15"	14:06	1'34"
13:20	15:55	15:50	16:00	10'15"	15:55	0'32"
13:20	15:50	15:45	15:55	10'15"	15:50	0'30"
13:25	14:25	14:20	14:30	9'45"	14:25	0'27"
13:25	14:00	14:02	14:17	15'30"	14:09	9'43"
13:25	14:25	14:23	14:30	6'15"	14:26	1'48"
13:30	15:50	15:45	15:55	10'00"	15:50	0'29"
13:30	14:05	14:07	14:22	15'00"	14:14	9'41"
13:30	14:20	14:18	14:22	4'30"	14:20	0'12"
13:30	14:25	14:20	14:30	9'45"	14:25	0'32"
...	...	...	...	...	...	...
Means :				11'12"		03:33

 Mentioned in the text

Figure 4.4: Sample of the extended results for the airport application

As a reminder, for now, airport operational agents work with 15 minutes confidence intervals (5 minutes before the scheduled off-block time and 10 minutes after). Here, the mean length of the 95% confidence interval on the actual off-block time is 11 minutes and 12 seconds⁶. It is under the 15 minutes confidence interval airport operational agents work with. Also, some of the confidence intervals are a lot shorter and some are longer. For example, the first turnaround of Figure 4.4 has a confidence interval of length 4'30", contrarily to the tenth one that has a confidence interval of length 15'15". Thus, even if the results seem satisfying, they need to be clarified.

It seems logical that the final output of a transformation of random events is really dependent on these random events' means and variances. The means of these random

⁶**Notation:** *hh:mm* represents a time in the day and *mm'ss"* represents an amount of minutes and seconds

events mainly impact the mean off-block times but the variances induce smaller or larger confidence intervals. Scaling and variance parameters about the random variables have been introduced in Section 3.2.2. In all the use cases, the same values of parameters are used for each process. As a reminder, they need to define a Beta distribution with a unimodal probability density function. The typical parameters that have been used are the following :

$$m_i = 0.4 \quad (4.7)$$

$$n_i = 1.8 \quad (4.8)$$

$$p_i = 0.15 \quad (4.9)$$

That gives standardized Beta distributions with mean 0.32 and variance 0.0155 (see Section 3.2.2 for more details). The plot of the probability density function is available on Figure 4.5. The means, the variances, and the distributions are reasonable choices but could be improved. Indeed, they would have to be refined with some operational data about the processes durations which, as a recall, were not available in the frame of this thesis. This Beta distribution is used, afterwards, to build each process duration probability density function according to its mean duration (see Section 3.2.2). As a reminder, if T is the random variable representing a process duration, it is computed with a linear combination of a Beta random variable: $T = c + dX$ where $X \sim Beta(\alpha, \beta)$, with a probability density function shown on Figure 4.5.

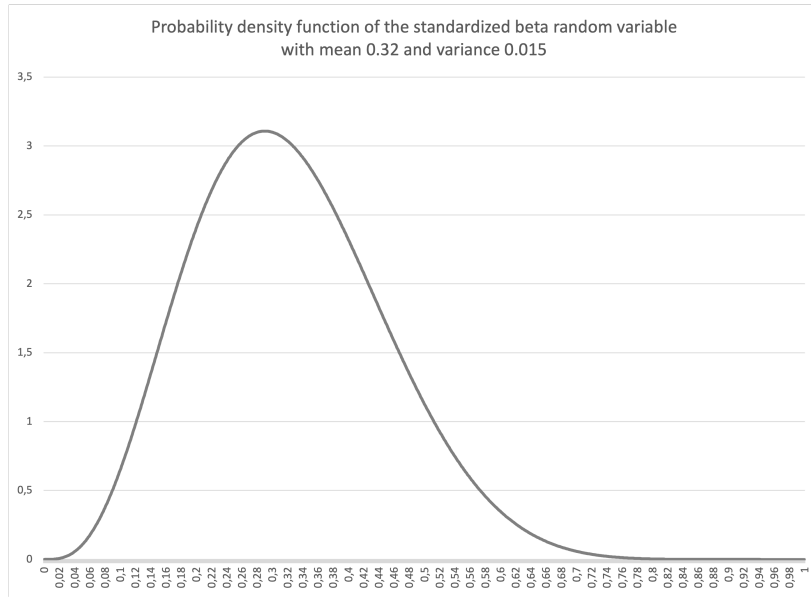


Figure 4.5: Probability density function of the Beta standard distribution used for the use case

Another point of comparison is the distance between the sample mean off-block time and the scheduled off-block time, defined as the mean delay. It can give information about the delays which are susceptible to occur. The sample mean off-block time can be used as a good approximation of the mean off-block time. Indeed, results (not in the table, available on Github [2]) show that the confidence interval length on the mean off-block time is always smaller than the minute. Since operational agents work with minuted schedules, it is a good approximation.

The delay is most of the time a bit positive (mean of 3 minutes and 33 seconds). This means that the model predicts that the off-block times have to be delayed and that it is most of the time impossible to respect the schedule. This result is a consequence of the assumptions that have been made and can be explained by different ways. First, the agents scheduling strategy is surely different than the one used in practice or inefficient. This can induce some delays in some scenarios where important agents (for instance ULD or bulk trains) have to work on different stands successively with almost no time breaks (snowball effect, see page 47). Secondly, the number of agents has been limited. Only 80% of the needed agents for a perfect scheduling⁷ are available in the input. With the snowball effect, this limited number of agents can induce some delay since it induces a more charged schedule for each of them. Next, as a reminder, aircraft types that are not in the 11 mainly used types are considered as a *Boeing 737-800* that can have longer processes to perform than the unknown aircraft types. Also, the assumption that data available in the aircraft characteristics documents are means of the time distributions can be incorrect. Finally, in reality, sometimes, processes can be performed in parallel (for example the fueling with secured fuel pipes or with fire brigades during the deboarding or boarding processes). There could be a lot of other explanations because the hypotheses can always be discussed. However, most of them can be changed in the model if it is needed.

To conclude, the main objective was to reduce the confidence interval length and has been reached in average. These exciting results are promising but have should be put in perspective with the fact that for some turnarounds, this confidence interval is bigger than 15 minutes. Maybe this new result can give new insights into the handling of operations. Indeed, since the agent-based model can give narrow confidence intervals on certain turnarounds and bigger ones on others, a new way of imagining how the schedule can be interpreted can be derived. Operational agents would be certain to have a precise schedule on some turnarounds but would need to have more flexibility on others.

The results are still satisfying, encouraging and realistic because on airport-centric point of view, there is a real added value compared to what existed before. However, they would be even more trustful if airport agents had worked in collaboration on the thesis. Indeed, a lot of assumptions have been done on airport operations and aircraft data, even if they have been discussed with an expert.

⁷A scheduling is said "perfect" when the processes are scheduled according to the minimum turnaround Gantt chart.

4.2 Other use cases

In order to demonstrate the usefulness of the model, different use cases have been considered. These applications show the power of the model and its ability to fit life-size examples. First, an illustration of how the information that the model provides can be used is presented. After that, it will be shown how it is possible to compare different strategies, namely the choices about the number of agents, the scheduling method and the use of dynamic time buffers.

This list of applications is non exhaustive. The way the model is used depends on the objectives to reach. Therefore, a lot of other possibilities can be envisaged. The versatility of the model offers a lot of opportunities and small updates of it would make it possible to discover even more possibilities, from recovering from unexpected events to establishing dynamic strategies, evolving according to what happens in real time.

The presented applications offer simple examples. If not mentioned otherwise, the travel time from stand to stand has been fixed on 60 seconds, the scheduling method is the *first index* one and the aircrafts considered are A320 Airbus, for which the characteristics have been described in Section 4.1. Every other input which is not explicitly mentioned is exactly the same as the ones used in the large-scale application of Section 4.1.

4.2.1 Delays

The agent-based model presented in this thesis is able to give a lot of information about how the turnarounds are performed. Using this information, it is often possible to observe the origin of a bad or good behaviour of some strategy. As mentioned, the model simulates every process of the selected turnarounds. Therefore, each agent's actions start and end times can be observed. With such information, it is possible to know what actions are susceptible to be delayed, and the effect of those delays on other actions. It can be useful to determine if some agent or action schedule is responsible for the global delays of several turnarounds off-block times. In fact, it makes it possible to detect the source of the delay in order to adapt the inputs accordingly.

In order to illustrate this kind of analysis, a simple example has been made. It considers five turnarounds widespread on two stands, with 2 fueling, cleaning and catering trucks and 3 ULD and bulk trains. Based on the Montecarlo method detailed Section 3.3.1 and the *smallest index* scheduling method explained in Section 3.2.4.1, for this simple example, the 95% confidence interval on the mean off-block time based on 1000 model simulations has a shorter length than 30 seconds for each turnaround. It is therefore relevant to round these intervals to the closest minute to study the mean delay. As it can be observed in Table 4.4, the mean off-block time is significantly greater than the scheduled off-block time for the three last turnarounds.

Stand n°	SIBT ⁸	SOBT ⁹	Rounded mean OBT ¹⁰
1	10:00	10:54	10:54
2	10:45	11:36	11:36
1	11:30	12:24	12:46
2	12:00	12:51	13:05
1	13:00	13:36	13:52

Table 4.4: Data for the analysis of the delays with 3 ULD trains ¹¹

The problem can come from different factors: the scheduling method, a lack of agents, a bad turnaround schedule, ... It is relevant to determine where the delay comes from in order to find a better strategy. In order to do that, observing the delays on the action start is relevant. As mentioned, the model is able to store the difference between the scheduled and actual start of each action of an agent (as well as the difference between its scheduled and actual end). Since the index of the turnaround and the stand on which it operates are also known, it is possible to create, for each agent, a table of the form shown Figure 4.6. This one represents the delays at the start of each ULD train actions for this example. The delays are computed as the mean delays over 1000 simulations of the 5 turnarounds. The results for other agents can be seen in the Appendix on Figures C.1 and C.2, but do not present any local delay¹².

ULD train 1				ULD train 2			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
0	1	1	Unloading 2	0	1	1	Unloading 1
0	1	1	Loading 2	0	1	1	Loading 1
0	2	2	Loading 2	960	2	2	Unloading 1
870	1	3	Unloading 1	210	1	3	Unloading 2
780	1	3	Loading 1	450	2	4	Unloading 1
1080	2	4	Loading 1	540	2	4	Loading 2
300	1	5	Unloading 2	810	1	5	Unloading 1

ULD train 3			
Delay [sec]	Stand	TA	Process
0	2	2	Unloading 2
0	2	3	Loading 1
0	2	2	Unloading 2
1500	1	4	Loading 2
150	1	2	Unloading 2
1230	1	3	Loading 1

Figure 4.6: Detailed start delays for 3 ULD trains

In order to find the source of the off-block time delays, it is relevant to look at the

⁸scheduled in-block time

⁹scheduled off-block time

¹⁰based the 95% confidence interval of the mean off-block time

¹¹**Notation** : *hh:mm* represents a time in the day

¹²On Figure C.1 and C.2, the slightly negative delays are due to floor rounding errors of the different distributions.

first significantly delayed action. Indeed, other delays can simply be the consequence of previous ones (snowball effect), but it is sure that the first delay is not induced by any other previous one. By looking at the tables, ULD trains are the only agents to have some actions with a significant delayed start. Therefore, they are part of the problem. The first delay appears when the ULD train 2 performs the unloading of turnaround n°2. The source of this delay is easily found in the table since it can be observed that its previous action was loading turnaround n°1. By checking the input concerning the scheduled start of the loading and unloading for such an aircraft type, the loading of turnaround n°1 should start at 10:44 and the unloading of turnaround n°2 at 10:55 to respect the turnarounds schedules. ULD train 2 can therefore not be present on time for the second action since in its own schedule, the unloading of turnaround n°2 will be scheduled to let him the time to carry out the loading of turnaround n°1, the travel between the two stands and to take into consideration the after time window margin (see Section 3.2.4.1).

One source of the delay is therefore the fact that ULD train 2 has to carry out two actions almost simultaneously at two different stands. Some solution to deal with this issue can be considered. Since the mean delay for the unloading start of the second turnaround is 16 minutes (see Figure 4.6), decreasing the after time window margin is not sufficient (they are only 10 minutes long). ULD train 3 already performs simultaneously the other part of the unloading of the second turnaround. Therefore, it is not available to help. ULD train 1 has performed the other part of the loading of turnaround 1 simultaneously, starting therefore also at 10:54. Therefore none of the three ULD trains is available on time to carry out the unloading ULD train 2 has to do on the second turnaround. Thus, no schedule method should help to avoid this delay. The solution has to be found elsewhere.

One of these solutions is to add a ULD train. Turnarounds n°3 and n°4 are now likely to finish on time but turnaround 5 is still susceptible to end later than scheduled, as it can be seen on Table 4.5.

Stand n°	SIBT ¹³	SOBT ¹⁴	Rounded mean OBT ¹⁵
1	10:00	10:54	10:54
2	10:45	11:36	11:36
1	11:30	12:24	12:24
2	12:00	12:51	12:54
1	13:00	13:36	13:44

Table 4.5: Data for the analysis of the delays with 4 ULD trains

However, by looking at the data, the mean delay at the start¹⁶ of each action of the five turnarounds are now negligible. These delays can be shown on Figure C.3 in Appendix. This means the delay of turnaround five does not come from any action. By observing Table 4.5, the last turnaround must be performed in 36 minutes while the succession deboarding - fueling - boarding for such an aircraft type is scheduled on a larger duration. Therefore, this delay is due to a poor initial schedule.

This example is one among many, but it allows to illustrate some information that can

¹³scheduled in-block time

¹⁴scheduled off-block time

¹⁵based the 95% confidence interval of the mean off-block time

¹⁶Still computed over 1000 simulations

be extracted from the model simulations and how they can be used. Simply by looking at the delay at the start of each action, it is obvious that the predicted off-block times delays do not come neither from the scheduling method nor from the time window margin. In fact, simply by observing the information given by the model, it is possible to draw a conclusion on a lot of issues or good behaviours sources.

4.2.2 Strategies

As a reminder, one of the main goals of the thesis is to evaluate strategies in order to compare them between each other. Such a comparison makes it possible to evaluate the pros and cons of a strategy with respect to another, and to chose the best one according to the objectives that have to be reached. These objectives often consist in finding the best compromise between economic profit, accurate predictions about the off-block times and minimal delays. Since such objectives are not part of the thesis, this section only shows how it is possible to compare strategies between each other. Optimizing the strategies according to defined objectives is subject to further research, as explained in Section 6.

The three next use cases aim to compare the choices concerning the number of agents, the scheduling method and the use of dynamic buffers. A lot of other strategies can be compared by modifying the different inputs of the model. For instance, it is possible to compare the best schedule of turnaround or to evaluate the impact of a change of the time distribution of a process (due, for example, to a new boarding methodology). Also, by updating the model, a lot of new horizons can be explored, from real time strategy updates to the impact of the creation of new agent types.

4.2.2.1 Buffers

Dynamic buffers are time buffers used to avoid the snowball effect on further actions if a process lasts more time than scheduled. They have been defined in Section 2.1.2. As a reminder, the time buffers are related to the different actions. A process which must wait for the end of an action to be performed, must also wait for the time buffer connected to the action to be over. It makes it possible to avoid delaying the process if the previous action is delayed.

An example of the time buffers usefulness can be seen on Figure 4.7. It studies the effect of a delayed fueling process on the deboarding process (considering boarding must wait until the end of fueling to be performed). Without a buffer, the start of deboarding is delayed by a time period equal to the fueling delay. Predicting the moment at which deboarding will start will therefore largely depend on the duration of fueling. However, if a time buffer is used in the scheduling, the delay must be greater than the buffer length to have an impact on the start of the boarding process. The fueling duration has therefore a smaller impact on the boarding start time if buffers are used (no impact at all if the delay is smaller than the buffer length). It means that the boarding end time is more easily predicted, since it will depend much less on the fueling time than without a buffer.

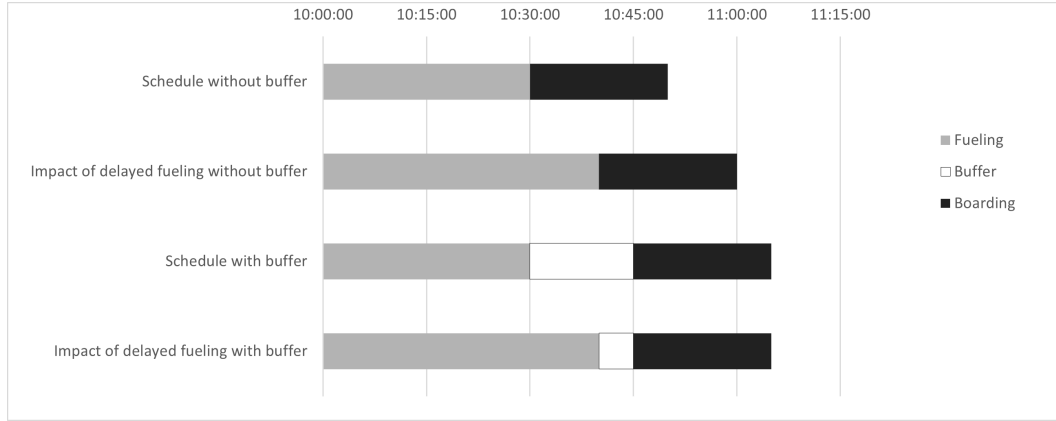


Figure 4.7: Time buffer utility example on a Gantt chart

However, as it is shown, if the delay is shorter than the buffer length, there is a time lap (between the end of the fueling and the end of its buffer/start of boarding) when the people could board but do not (since they must wait for the end of the time buffer). The total duration of both processes is therefore longer than without a buffer, since there is a period of inactivity.

The main idea while using time buffers is therefore to find the best compromise between increasing the predictability of the turnaround duration and avoiding extending them to much. Such a compromise depends on economical aspects and subjective objectives. However, the model presented enables one to assess the accuracy gain in prediction compared to the increase in turnarounds length while using buffers.

To illustrate that power, the model has been implemented, with and without buffer, on a simple example of 5 successive turnarounds. To avoid any bias, each turnaround is operated on a different stand, and the number of agents has been chosen not to have an impact on delays. When buffers are applied, they are applied to each process. The size of the buffers is equal to half the scheduled process duration they are attached to. On Figure 4.6, the scheduled in-block time can be observed (scheduled start of the turnaround, which corresponds to the actual start in this example without delay), such as the confidence intervals over the actual off-block time (actual end time of the turnaround), computed as explained in Section 3.3. The size of the confidence intervals are also shown, as well as the minimum turnaround duration.

	Turnaround n°	1	2	3	4	5
	SIBT ¹⁷	10:00	10:45	11:30	12:00	13:00
Without buffer	AOBT CI lb ¹⁸	10:36	11:21	12:06	12:36	13:36
	AOBT CI ub ¹⁹	10:52	11:37	12:22	12:52	13:52
With buffer	AOBT CI lb	10:50	11:35	12:20	12:50	13:50
	AOBT CI ub	11:00	11:46	12:30	13:01	14:01
Whithout buffer	AOBT CI size ²⁰	16'30"	16'00"	16'15"	16'00"	16'15"
	Turnaround duration	44'15"	44'00"	44'08"	44'07"	44'08"
With buffer	AOBT CI size	10'30"	10'45"	10'15"	10'45"	10'30"
	Turnaround duration	55'00"	55'52"	55'30"	55'30"	55'15"

Table 4.6: Example output with and without buffer²¹

It can be noted that, without a buffer, the confidence interval size is in average 53.3% bigger than with one, while the turnaround duration decreases by 20.4%. According to the objectives, the strategy can be defined as acceptable or not.

In the example, the buffer proportionality factor is either 0 (no buffer) or $\frac{1}{2}$ for buffers with a size equal to half the scheduled duration of the attached process. To go further, it is possible to find the best strategy by optimizing the proportionality factor according to the objectives of prediction accuracy and turnaround durations. Such an optimization problem is beyond the scope of this thesis. It is also possible to attach buffers only to the processes the more susceptible to lead to uncertainty. Once again, it is possible to create an optimization problem giving the best strategy according to the objectives.

4.2.2.2 Scheduling

As already mentioned in Section 3.2.4.1, different methods can be used in order to assign the actions to the different agents. According to those assignment strategies, some advantages or disadvantages can appear, depending on the situation.

On the one hand, an assignment with scheduled actions really close in time for agents is susceptible to have a negative impact on the turnarounds durations. Indeed, if an agent has two successive actions too close to each other, it will not be able to start the second one on time, the second action will therefore be delayed until the end of the first (and after that, the agent also has to travel from stand to stand). Such a delay can have a really bad snowball effect, as seen in Section 3.4.

On the other hand, spacing the actions in the agent schedule often leads to the use of more agents. However, each agent has a cost (workforce, equipment acquisition and maintenance, ...). Therefore, the less you use, the cheaper it is.

Depending on the situation and on the objectives, the best method to choose can vary a lot. That is where the model comes into play. It enables to simulate different scheduling assignment methods. In this section, three different methods will be compared to show what is possible. With real objectives and constraints, it would be possible to determine which one is the optimized one according to the goals, but this is not in the scope of this thesis (see Section 6).

Up to now, three methods have been implemented in the model. However, each of them implies the sorting of the actions chronologically (compared to the time the agent is needed at the gate to perform the action). This section will describe the methods as well as their theoretical pros and cons. The methods, as described in Section 3.2.4.1 are :

¹⁷scheduled in-block time

¹⁸lower bound of the 95% confidence interval on the actual of block time

¹⁹upper bound of the 95% confidence interval of the actual on block time

²⁰length of the 95% confidence interval on the actual of block time

²¹**Notation:** *hh:mm* represents a time in the day and *mm'ss"* represents an amount of minutes and seconds

1. The smaller index method

In this method, the actions (taken in the chronological order) are assigned firstly to agents that should be able to be present at the stand according to their schedule, i.e. that have their previous action which finished soon enough to allow them to effectuate the travel between the two stands and being on time when the action needs it. Among the agents respecting these conditions, the action is assigned to the one with the smaller index.

If no agent has a fitted schedule, then the action is assigned to the one that can be there sooner (as in the third method). In that case, the action is not scheduled at the optimal moment but with a delay due to the overbooked schedule of its agent.

Such a method makes it possible to concentrate the different actions on a small part of the agents, allowing one to get rid of the ones for whom no action had been assigned. The strategy could also be to get rid of the ones for whom a small amount of actions have been assigned and to reassign those actions to other very busy agents. Also, if an agent has a problem, it can switch its schedule with an agent who has less scheduled actions in order to avoid too many problems (before considering any other rescheduling).

However, such a strategy concentrates the actions for agents with a small index, in consequence they have a lot of actions to perform, sometimes very consecutively, which means that delays are theoretically more likely to happen.

2. The homogeneous method

Contrarily to the first method, this one tends to spread the actions homogeneously among the agents. In order to do that, the actions (in chronological order) are assigned to successive agents, meaning the first action is assigned to the agent with index number 1, the second to the one with index number, and so on. Once an action is assigned to the agent with the last index, the next action is assigned to the first agent and we come back to the ordered assignment. Mathematically, the x^{th} action to be assigned, with $x = i + (k \times \text{number of agents})$ and $k \in \mathbb{N}$, is assigned to the agent with index i .

This method allows an homogeneous allocation of the actions, which means that the charge over the schedules is spread more evenly and that delays are less likely to occur.

However, the number of action per agent differs by at most one, meaning the failure of one agent must induce more difficulties than with the first method. Also, getting rid of an agent means rescheduling all those actions, which can be numerous.

3. The sooner available method

This method is objective is to chose agents who are likely to be the first at the stand, according to their previous schedule. The actions, still assigned in chronological order, are assigned to the agent that can be most rapidly at the stand. It means that the sum of the end time of its previous action and its travel time to the stand is the smallest compared to all other agents (if there are several agents with this property, one is chosen randomly among them).

This method makes it possible to have a spaced schedule and seems therefore useful to avoid delays due to the scheduling. However, recovering from agent failure seems really complicated with such a method since all the schedules are already optimized.

These three methods have been compared on different examples but only one is presented. The context in which they have been tried out are the following:

- Life-size application (see Section 4.1) arrival/departure pairs with an in-block time between 2pm and 8pm.
- 0 minute before and after margins around the processes (see page 27 for explanations about these margins) to really see the impact of the methods of scheduling
- The number of agents has been limited to the number of agents needed to respect the schedule with the smaller index method.
- Other non specified inputs are the same as in the life-size application.

The average results over all the turnarounds are available in Table 4.7. They are quite interesting. Indeed, a difference about the delays and the confidence interval lengths have been observed between the three different methods.

Method name	Average CI ²² length	Average delay
Smaller index	12'02"	3'11"
Homogeneous	11'19"	3'21"
Sooner available	10'25"	2'30"

Table 4.7: Results of the simulations : comparison between the three methods²³

The results show that the two last methods lead to a decrease of the uncertainty on the off-block times of the turnarounds, even if this improvement is limited. It is a consequence of the more homogeneous task allocation amongst all the agents and their less charged schedule. The last one is even better because it really takes into account the availability of the agents and their travel times. The last method avoids, most of the time, the snowball effect because consecutive tasks are spaced in time. That is why it leads to a higher predictability. Plus, there is an improvement in the average delays for the last method too. It is also a consequence of the fact that most of the time, it avoids the snowball effect.

However, even if the differences are not insignificant, they are not tremendous. It is due to the fact that with realistic examples, the three methods are only different on a limited number of turnarounds. They would be a lot different with very specific borderline cases.

Still, this use case shows the power of the model because of its broad area of applications. Different insights can be discovered through the use of the model, like the difference between some strategies. Operational stakeholders know the economical parameters and other constraints they have to respect. Thus, with the model, they could found the balance they are looking for and derive new reassignment methods in case of a disturbance.

²²confidence interval on the actual off-block time

²³**Notation:** *mm'ss*" represents an amount of minutes and seconds

4.2.2.3 Number of agents

This use case goal is to determine what are the consequences of an increase or a decrease in the staffing. Deciders have two main objectives when they chose how many agents to hire or to use on a specific day. On the first hand, they want to respect the schedule and have a good reliability on the off-block times. On the other hand, they surely want to limit the costs because they have no infinite resources. This use case shows how the agent-based model can be used to help deciders answer their questions.

The *smaller index* scheduling method (see page 31) can be implemented with any potential number of agents. As a reminder, the agent who can be there for the process at the needed with the smallest index is chosen. If no agent can be present, the process will simply be delayed until one agent is available to perform the action. Thus, there is a maximum number of agents above which the presence of additional agents is not useful (unless some agents are just there for security but it is not taken into account here). This number has been determined to make sure there are no delays in the sequence of processes.

However, in practice, this scheduling method really requests a lot of agents to avoid any delays in the process. To assess the impact of the number of agents on the off-block time, simulations have been performed in different conditions, by decreasing the number of agents. The inputs about the aircrafts and the global environment are the same as in the life-size use case (see Section 4.1). The invariant input about the schedule considers the SIBT²⁴, the SOBT²⁵, the stand n° and the aircraft type. They can be seen on Table 4.8.

SIBT	SOBT	Stand n°
10:00	10:45	1
10:15	11:00	2
10:30	11:30	3
10:45	11:30	4
10:54	11:39	5
11:00	11:45	6
11:06	11:51	1
11:15	12:00	2
11:30	12:15	3
12:00	12:45	4

Table 4.8: Input for the analysis of the number of agents impact

This use case can be divided into two parts:

- Impact of decreasing the number of fueling, catering and cleaning trucks while keeping the number of ULD trains and bulk trains constant
- Impact of decreasing the number of ULD trains and bulk trains while keeping the number of fueling, catering and cleaning trucks constant

²⁴SIBT: scheduled in-block time

²⁵SOBT: scheduled off-block time

Indeed, observing a minimum turnaround Gantt chart on Figure 4.8, loading and unloading are completely independent of deboarding, fueling, catering, cleaning and boarding. In the minimum turnaround, the maximum duration between fueling, catering and cleaning will directly determine the start of boarding and thus maybe the off-block time. The off-block time is determined by the latest end between boarding and loading, the first one being influenced by the actions of the fueling, catering and cleaning trucks, the second one by the ones of ULD and bulk trains.

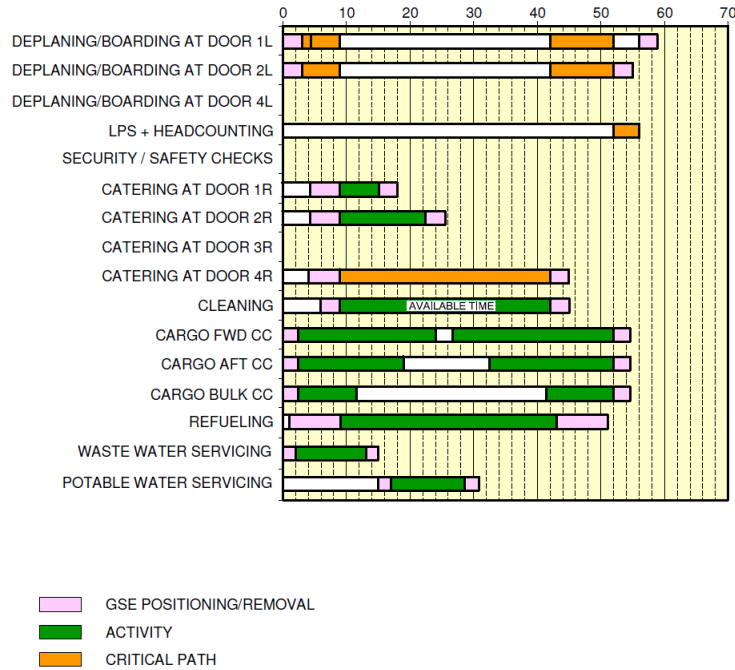


Figure 4.8: A330 minimum turnaround Gantt chart

For the input introduced in Table 4.8, it has been computed that the airport needs a number of mobile agents summarized in Table 4.9 for the schedule to respect the expected beginning of each process on each turnaround.

Agent type	Number
Fueling truck	5
Catering truck	5
Cleaning truck	5
ULD trains	18
Bulk trains	9

Table 4.9: Number of agents needed

As mentioned just above, the analysis has been divided into two parts, one decreasing the number of fueling, catering and cleaning trucks, the other decreasing the number of ULD and bulk trains. To compute confidence intervals on the mean off-block time, a number of $n = 1000$ simulations have been performed for every test, with a time step of 15 seconds.

Decreasing the number of fueling, catering and cleaning trucks

This first analysis has been performed in 5 different settings. In all of them, the number of ULD trains and bulk trains are respectively 18 and 9. The results are available on Figure 4.9.

It seems that the decrease in this type of agents has a negative impact both on delays and the confidence intervals lengths. Indeed, the confidence interval size increases linearly while the delay seems to increase exponentially. First, the increase in delays is quite easy to understand. Since there are less agents, the off-block times will be delayed mostly for the last turnarounds because agents accumulate delays compared to the minimum turnaround schedules. Thus, in the end, it results in delays in the boarding and then on the off-block times because of a snowball effect. Secondly, the confidence intervals lengths increase is a bit harder to explain. Most of the time, when there are enough fueling, catering and cleaning agents, the off-block time is only dependant of the boarding and loading duration. Indeed, the schedule makes the fueling, catering and cleaning begin early enough to not impact the boarding beginning. However, when the number of agents is decreased, the scheduling delays the beginning of their tasks since they have to go from one stand on another consecutively. Thus, the off-block time does not depend only on the boarding duration, but also on these last three processes durations. Since all these durations are random, they induce some uncertainty.

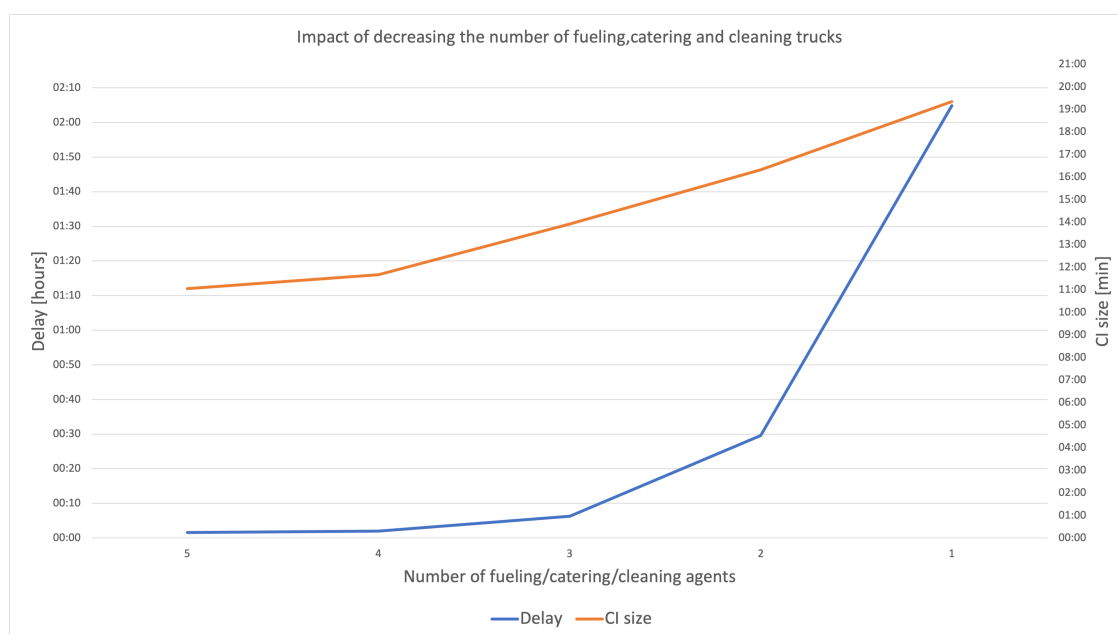


Figure 4.9: Mean delays and mean confidence interval lengths in terms of the number of fueling, catering and cleaning trucks

Decreasing the number of ULD and bulk trains

This analysis has been performed in different settings. In all of them, there are 5 fueling, catering and cleaning trucks. The results are available on Figure 4.10.

In this case, it seems that the decrease in this type of agents has a negative impact on delays but a positive one on confidence interval lengths. The delays are exponentially

increased since. If there are less agents, they have a delayed schedule compared to the minimum turnaround schedule. Since loading is the last process (even if it can be done in parallel with boarding), its delay has negative consequences the off-block time. Confidence interval lengths are shorter because if there are less loading agents (ULD and bulk trains), this process always induces a delay. Indeed, in the minimum turnaround it is scheduled from the scheduled off-block time (the end of the turnaround). As a consequence, the uncertainty only comes from this process and all others have no impact on the off-block time. Thus, if the uncertainty comes only from the loading process, it will be smaller than if it could also come from the boarding. Finally, it is important to note that the decrease in confidence interval length is connected to very high delays and are thus, not very realistic. The confidence intervals lengths are almost constant for reasonable delays.

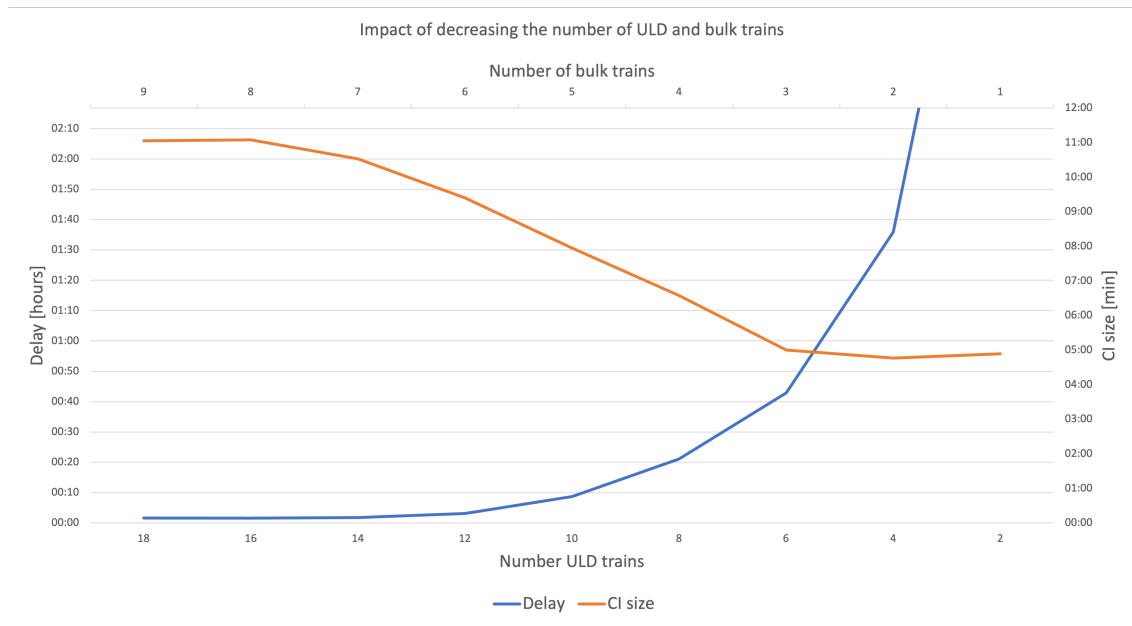


Figure 4.10: Mean delays and mean confidence interval lengths in terms of the number of ULD and bulk trains

In conclusion, these 2 analysis give insights into an efficient management of the airport. The idea is to find the best compromise between the agents' cost and their impact on the turnaround durations and their predictability. Increasing the number of fueling, catering and cleaning agents can only be profitable in terms of logistics. However, for economical reasons, they are limited. Increasing the number of bulk and ULD trains is profitable for the turnaround duration but has an insignificant impact on the confidence interval lengths for reasonable delays. The solution to this problem depends on many economical parameters and assumptions but this use case proves that the model can be useful as a tool for decision-making.

Chapter 5

Conclusion

In order for the different stakeholders of the airport economy to take the best decisions collaboratively, they need to have a tool allowing them to estimate as accurately as possible the moment the different aircrafts will finish their turnaround. Since such estimations predict, in a particular confidence interval, the off-block times of the aircrafts, it makes it possible to assess when the aircraft will be able to take-off, which is a precious piece of information in order to allocate the aircrafts the smallest and most accurate possible take-off time window, i.e. the time duration during which the runway is reserved for the plane to take off. Indeed, since those time windows prevent other aircraft from accessing the runway, they have a significant cost, but not respecting them is even more costly since it induces effects on the time windows of the other aircrafts. Also, if the stakeholders can predict the end of each turnaround based on the airport/turnarounds characteristics (schedule, resources allocation, stands location, ...), they will be able to determine what is the best strategy to adopt in order to maximize their economic benefits. Those benefits can vary from the optimized resources allocations to the best possible schedule to avoid delays.

The objective of this thesis was to provide such a tool using agent-based modeling as an airport-centric modeling method. Compared to the aircraft-centric modeling existing methods (time and events based), it involves the fact that the different turnaround durations, besides being dependent on what happens while the corresponding aircraft is at the stand, are also dependent on previous actions of the different agents performing the different processes. What happens on a turnaround, or to an agent, can have an impact on a lot of other turnarounds due to a snowball effect. Taking these impacts into consideration, including the interactions between the different agents and turnarounds, is the main added value agent-based modeling brings compared to the tools that were available before the development of this thesis.

Therefore, this thesis was about creating such a model and showing how useful it could be. To start with, it was necessary to determine the context in which the model is built. It was done in Chapter 2. It includes some descriptions of the airport world such as the difference between minimum, scheduled and actual turnaround, but also the notions of dynamic buffer and critical path. Also, the main different processes constituent the aircraft turnarounds were introduced, i.e. the deboarding/boarding, cleaning, catering, fueling and unloading/loading processes.

Next to those airport notions, the concept of agent-based modeling was presented. This type of model simulates the interactions that occur between agents in a given environment. It is based on a universal clock so that at each of its tick, agents act in their environment according to different rules of behaviour based on their own state and the state of the other agents, mainly the ones located in their neighbourhood. It is important to observe how low-scale behaviour rules impact the high-scale environment. A good tool to implement an agent-based model is Netlogo, a programming language also introduced in the state-of-the-art chapter.

In Chapter 3, the theoretical basis was used to describe the model that has been built. First, it was presented from the agent-based modeling point of view in Section 3.1. It has introduced the fact that six agent types would interact in an environment consisting in the different stands of the airport, the travel distance between them and the different facilities useful for the different processes (fuel depot for fueling, terminal for loading/unloading, ...). The agent types are divided into two groups : the mobile agents¹ representing the crews responsible for the different turnaround processes, and a fixed agent type, the stand. At each tick of the universal clock, the agents act according to the other agents in their neighbourhood, i.e. stands perform processes if the corresponding agents are present and agents come to the stand if no other one is already doing the task. It was also shown that the different properties of the agent-based modeling hold for the explained model approach.

Using this framework, Section 3.2 has described the model itself. It has started with the explanations of the choices of process which had be implemented, i.e. the catering, cleaning, fueling, unloading/loading and deboarding/boarding. After that, since no data was available for this thesis, the way Beta distributions are used to determine the processes durations distributions was presented.

With all that information, it was possible to describe the inputs that are passed through the model in Section 3.2.3. They are divided into three types : characteristics of the environment, characteristics of each aircraft type and performance inputs.

Those inputs pass through the model described in Section 3.2. It first consists in setting up these inputs, creating the agents, setting them up and creating their schedule thanks to the chosen scheduling method. Once all this is done, it passes through a block that simulates the actions and interactions of the agents at each tick of the clock. At each tick, both stands and mobile agents have different behaviours depending on the time reached by the clock, their own state and the state of the agents situated in their neighbourhood. Those behaviours were fully described in Section 3.2.4.2. The way the implementation is done using Netlogo was also described in this section.

With the inputs and the model fully described, the way of computing the outputs could be determined. It was fully done in Section 3.3. The outputs are there to help operational stakeholders have insights about the delay a strategy can create and get reliable confidence intervals on each aircraft off-block time. First, the chapter has described how the Central Limit theorem and the Montecarlo method are used to derive confidence intervals on the mean off-block time of each aircraft. Using this confidence interval on the mean, the mean delays can be computed. Secondly, another method based on observations has been detailed. It gives the confidence intervals on the actual off-block times. Even if it is not

¹fueling, catering and cleaning trucks, ULD and bulk trains

strictly mathematical, it works as a heuristic, is convincing and can give reliable results given that the model is realistic and that enough simulations are performed.

Since the details of how inputs are passed through the model, and how outputs are computed from them, were explained, the usefulness of the model could be demonstrated. First, it was done by illustrating the agent-based modeling power on such a situation. Practical examples have shown that its airport-centric point of view leads to a good simulation of the interactions between agents that was not done before, and takes into consideration the possible snowball effect that can occur if an agent is delayed. In Section 3.4, an example with only two stands, two turnarounds to perform and a limited number of agents has provided interesting insights into what state-of-the-art models would have missed compared to what agent-based modeling is focused on.

The model was applied on a life-size application in order to validate it on some data. After creating inputs from partial data of a full airport day, it has been possible to predict the confidence interval of the actual off-block time for each of the turnarounds of the day. It has mostly led to smaller confidence intervals than the 15 minutes operational stakeholders work with. Thus, the results are satisfying even if some intervals are bigger and that the results have to be put in perspective with all the assumptions about the airport and aircrafts that have been done.

In Section 4.2, different use cases results were presented to show the usefulness of the model. It permits to compare different strategies in order to determine which one is the best. It was shown that the model makes it possible to :

- Assess the impact of the number of agents. Decreasing it increases the delays and also has an effect on the accuracy of the prediction, depending on what agent type is decreased.
- Quantify the pros and cons of dynamic buffers, i.e. the compromise between short confidence interval length and small delays.
- Find the best scheduling method for a given input by comparing their impact on the off-block times.

It was also shown that the model can provide information about each action, making it possible to observe the different local delays and defining of the bad or good behaviour of a strategy.

Finally, the model can be really more useful if further research is performed, in particular research about the use of the model in optimization problems including the model output and economical objectives or constraints. The details can be found in Section 3.2.5 and Chapter 6.

Therefore, this master thesis has provided a significant tool allowing to simulate successive aircraft turnarounds in an airport. By taking into consideration the interactions between agents and the snowball effect that a delayed agent can produce on the airport-scale, it has offered a new perspective, innovative and unpublished, in the prediction of aircraft off-block times. Indeed, agent-based modeling makes it possible to simulate behaviours which were never taken into consideration in the preexisting model. Such an added value should make possible, with actual data, to increase the accuracy of the

off-block times predictions. On the one hand, it permits to create optimized time windows for the aircraft to take off. On the other hand, it is useful for the stakeholders of the airport economy to find better strategies by evaluating more accurately their impact on the off-block time and the confidence interval on it. This thesis aims to be the foundation of further work in order to accomplish the different objectives mentioned earlier. This is not the end. This is just the beginning.

Chapter 6

Further research and recommendations

This thesis has shown the different properties of the model built, from the theory hidden behind to the different applications it can be used for, including the description of the different blocks of the model itself. However, further research could increase the model quality, but also makes it possible to use it to achieve new objectives.

First of all, it is obvious that the use of data would permit to compute the real distribution of processes and the true input of the model, and therefore to obtain more realistic results. With such data, the model could be used to predict the different off-block times realistically and would be useful in practice. The use of true data would permit quantify the real advantages of the agent-based model compared to the existing time-based and event-based ones.

Besides, as mentioned in Section 4.1, with the varying confidence interval lengths on the turnarounds, it is possible to identify the turnarounds that are a lot uncertain. Thus, a new way of handling these turnarounds schedules can be derived.

Moreover, all the model limits detailed in Section 3.2.5 can be broken. It just needs some more development as explained in the section itself.

Finally, the biggest improvement that could be done to this thesis would be to use it in different optimization problems. Indeed, by including some economic constraints or objectives, it would be possible to use the model in order to find the best possible strategies. Indeed, by evaluating the cost of delays and the benefits of an accurate off-block times prediction, it could be possible to :

- Determine what is the optimized number of specific agents by identifying the costs of each agent.
- Determine what is the best buffer strategy.
- Determine what is the best scheduling method.
- ...

Of course, this list is non exhaustive. The main thing to have in mind is that the capacity of the model to predict the off-block times of the turnarounds can be used in optimization problems in order to help the different stakeholders of the airport economy to take the best decisions collaboratively.

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Appendix A

Netlogo interface

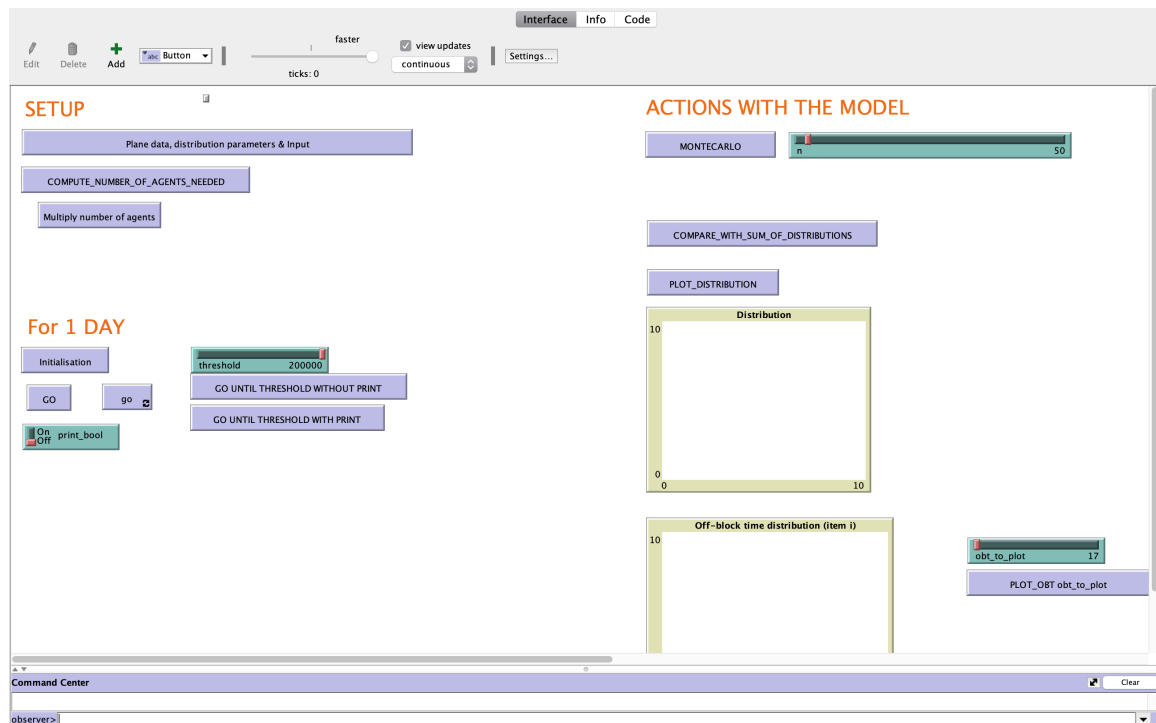


Figure A.1: Netlogo interface - 1

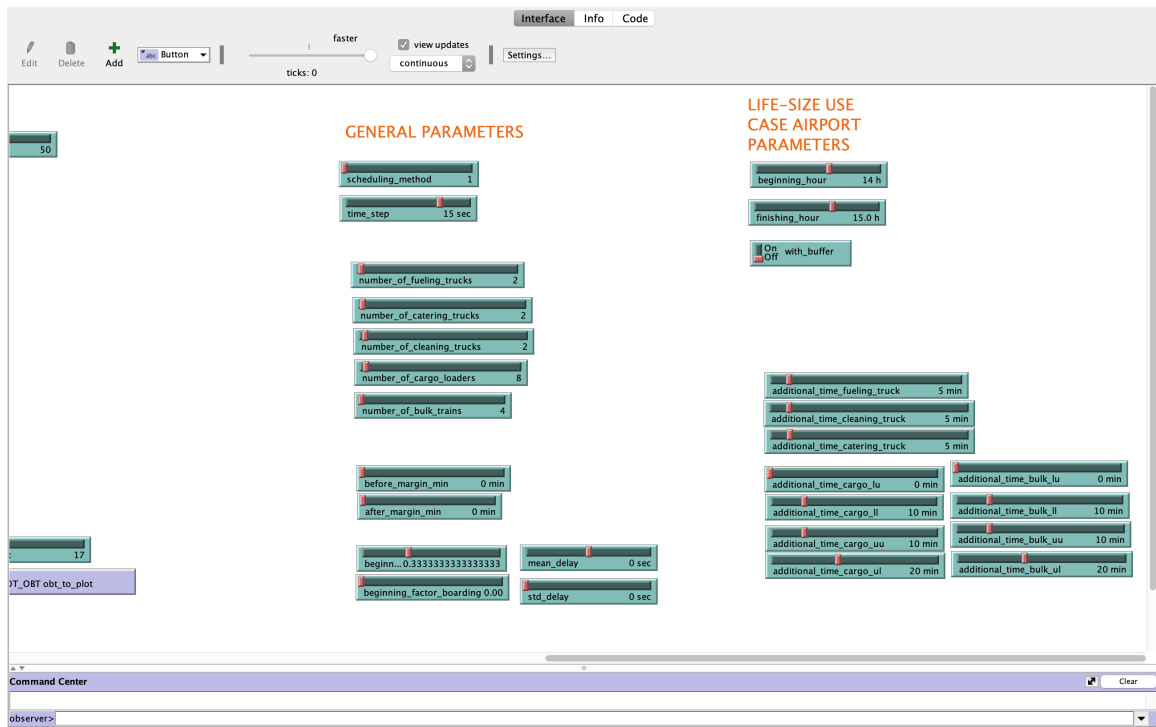


Figure A.2: Netlogo interface - 2

Appendix B

Aircrafts and data

B.1 Representation of an A330 Airbus in its environment

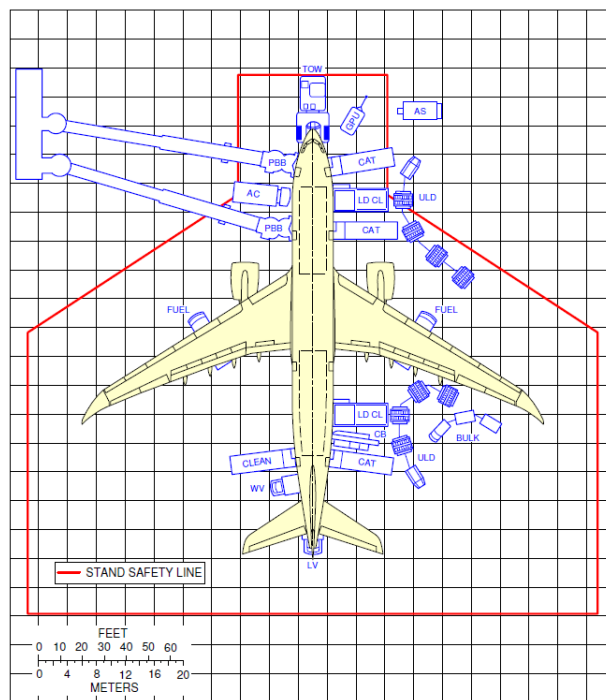


Figure B.1: Representation of an A330 Airbus in its environment. See legend on Figure B.2

. From [11].

Ground Support Equipment	
AC	AIR CONDITIONING UNIT
AS	AIR START UNIT
BULK	BULK TRAIN
CAT	CATERING TRUCK
CB	CONVEYOR BELT
CLEAN	CLEANING TRUCK
FUEL	FUEL HYDRANT DISPENSER or TANKER
GPU	GROUND POWER UNIT
LD CL	LOWER DECK CARGO LOADER
LV	LAVATORY VEHICLE
MD CL (A330-200F only)	MAIN DECK CARGO LOADER
PBB	PASSENGER BOARDING BRIDGE
PS	PASSENGER STAIRS
TOW	TOW TRACTOR
ULD	ULD TRAIN
WV	POTABLE WATER VEHICLE

Figure B.2: Legend of Figure B.1 from [11]

B.2 Example of the *Airbus* manufacturer characteristics documents for the A320



AIRCRAFT CHARACTERISTICS - AIRPORT AND MAINTENANCE PLANNING

5-2-0 Terminal Operations - Full Servicing Turn Round Time Chart

****ON A/C A320-200 A320neo**

Terminal Operations - Full Servicing Turn Round Time

1. This section provides a typical turn round time chart showing the typical time for ramp activities during aircraft turn round.
Actual times may vary due to each operator's specific practices, resources, equipment and operating conditions.
2. Assumptions used for full servicing turn round time chart
 - A. PASSENGER HANDLING
150 pax: 12 F/C + 138 Y/C.
All passengers deplane and board the aircraft.
1 Passenger Boarding Bridge (PBB) used at door 1L.
Equipment positioning + opening door = +2 min.
Closing door + equipment removal = +1.5 min.
No Passenger with Reduced Mobility (PRM) on board.

Deplaning:
 - 150 pax at door 1L
 - Deplaning rate = 20 pax/min per door
 - Priority deplaning for premium passengers.
Boarding:
 - 150 pax at door 1L
 - Boarding rate = 12 pax/min per door
 - Last Pax Seating allowance (LPS) + headcounting = +2 min.
 - B. CARGO
2 cargo loaders + 1 belt loader.
Opening door + equipment positioning = +2 min.
Equipment removal + closing door = +1.5 min.

100% cargo exchange (baggage only):
 - FWD cargo compartment: 3 containers
 - AFT cargo compartment: 4 containers
 - Bulk compartment: 500 kg (1 102 lb).
Container unloading/loading times:
 - Unloading = 1.5 min/container
 - Loading = 1.5 min/container.
Bulk unloading/loading times:

5-2-0

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Figure B.3: Characteristics document for the A320 - 1 (page 200) from [11]



AIRCRAFT CHARACTERISTICS - AIRPORT AND MAINTENANCE PLANNING

- Unloading = 150 kg/min (331 lb/min)
- Loading = 120 kg/min (265 lb/min).
- C. REFUELING
 - Uplifted quantity: 20 000 l (5 283 US gal) at 50 psig (3.45 bars-rel), one hose (right wing).
 - Truck positioning/removal + connection/disconnection times = +2.5 min.
 - No refuel with pax on board
- D. CLEANING
 - Cleaning is performed in available time.
- E. CATERING
 - 1 catering truck for servicing galleys sequentially at doors 1R and 4R.
 - Equipment positioning + opening door = +2 min.
 - Closing door + equipment removal = +1.5 min.
 - Time to drive from one door to the other = +2 min.
- Full Size Trolley Equivalent (FSTE) to unload and load: 11 FSTE
 - 4 FSTE at door 1R
 - 7 FSTE at door 4R.
 - Time for trolley exchange = 1.2 min per FSTE.
- F. GROUND HANDLING/GENERAL SERVICING
 - Start of operations:
 - Bridges/stairs: $t_0 = 0$
 - Other equipment: $t = t_0$
 - Ground Power Unit (GPU): up to 90 kVA.
 - Air conditioning: one hose.
 - Toilet servicing: draining + rinsing.
 - Potable water servicing: 100% uplift, 200 l (53 US gal).

5-2-0

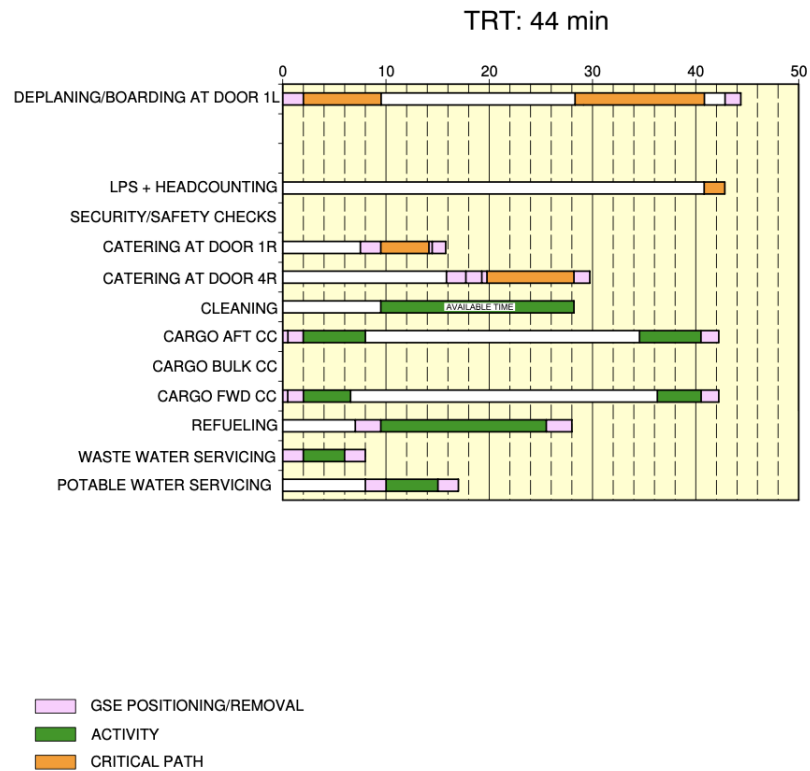
Page 2
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Figure B.4: Characteristics document for the A320 - 2 (page 201) from [11]



AIRCRAFT CHARACTERISTICS - AIRPORT AND MAINTENANCE PLANNING

**ON A/C A320-200 A320neo



N_AC_050200_1_0060101_01_04

Full Servicing Turn Round Time Chart
FIGURE-5-2-0-991-006-A01

5-2-0

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Figure B.5: Characteristics document for the A320 - 3 (page 202) from [11]

B.3 Example of the Airbus data research results

Builder	Aircraft type	MAX_N(PAX)	Deboarding		Boarding			
			Infos	Numbers	Infos	Numbers		
AIRBUS	A321	202	1 bridge	Deplaning rate [PAX/min]	20	1 bridge	Boarding rate [PAX/min]	12
		147		Equipment positioning + Opening door [min]	2		Equipment removing + closing door [min]	1,5
							LPS allowance + headcounting [min]	2
				Actual deplaning time [min]	9,35		Actual boarding time [min]	15,8
	A320	150	1 bridge	Deplaning rate	20	1 bridge	Boarding rate [PAX/min]	12
		110		Equipment positioning + opening door	2		Equipment removing + closing door [min]	1,5
							LPS allowance + headcounting [min]	2
				Actual deplaning time [min]	7,5		Actual boarding time [min]	12,7
	A319	124	1 bridge	Deplaning rate	20	1 bridge	Boarding rate [PAX/min]	12
		91		Equipment positioning + Opening door	2		Equipment removing + closing door [min]	1,5
							LPS allowance + headcounting [min]	2
				Actual deplaning time [min]	6,55		Actual boarding time [min]	11,1
A330-300 =A333	300	1 bridge	Deplaning rate	25	1 bridge	Boarding rate [PAX/min]	15	
	219		Equipment positioning + Opening door	2		Equipment removing + closing door [min]	1,5	
						LPS allowance + headcounting [min]	4	
			Actual deplaning time [min]	10,8		Actual boarding time [min]	20,1	

Figure B.6: Airbus data - 1 from [11]

Builder	Aircraft type	Unloading		Loading				
		Infos	Numbers	Infos	Numbers			
AIRBUS	A321	2 cargo loaders + 1 belt loader. Max 500 kg bulk FWD : 5 & AFT : 5 = max 10 containers	Opening door + equipment positioning [min]	2 2 cargo loaders + 1 belt loader.	Equipment removal + closing door [min]	1,5		
			Bulk unloading [kg/ min]	150 Max 500 kg bulk	Bulk unloading [kg/ min]	120		
			Containers unloading [min/container]	1,5 FWD : 5 & AFT : 5 = max 10 containers	Containers unloading [min/container]	1,5		
			Bulk load	500	Bulk load	500		
			Bulk time	5,33	Bulk time	5,67		
			n_containers FWD	5	n_containers FWD	5		
			Containers FWD time [min]	9,5	Containers FWD time [min]	9		
			n_containers AFT	5	n_containers AFT	5		
			Containers AFT time [min]	9,5	Containers AFT time [min]	9		
			A320	2 cargo loaders + 1 belt loader. Max 500 kg bulk FWD : 3 & AFT : 4 = 7 containers	Opening door + equipment positioning [min]	2 2 cargo loaders + 1 belt loader.	Equipment removal + closing door [min]	1,5
					Bulk unloading [kg/ min]	150 Max 500 kg bulk	Bulk unloading [kg/ min]	120
					Containers unloading [min/container]	1,5 FWD : 3 & AFT : 4 = 7 containers	Containers unloading [min/container]	1,5
	Bulk load	500			Bulk load	500		
	Bulk time	5,33			Bulk time	5,67		
	n_containers FWD	3			n_containers FWD	3		
	Containers FWD time [min]	6,5			Containers FWD time [min]	6		
	n_containers AFT	4			n_containers AFT	4		
	Containers AFT time [min]	8			Containers AFT time [min]	7,5		
	A319	2 cargo loaders + 1 belt loader. Max 500 kg bulk FWD : 2 & AFT : 2 = 4 containers			Opening door + equipment positioning [min]	2 2 cargo loaders + 1 belt loader.	Equipment removal + closing door [min]	1,5
					Bulk unloading [kg/ min]	150 Max 500 kg bulk	Bulk unloading [kg/ min]	120
					Containers unloading [min/container]	1,5 FWD : 2 & AFT : 2 = 4 containers	Containers unloading [min/container]	1,5
			Bulk load	500	Bulk load	500		
			Bulk time	5,33	Bulk time	5,67		
			n_containers FWD	2	n_containers FWD	2		
			Containers FWD time [min]	5	Containers FWD time [min]	4,5		
			n_containers AFT	2	n_containers AFT	2		
			Containers AFT time [min]	5	Containers AFT time [min]	4,5		
			A330-300 =A333	2 cargo loaders + 1 belt loader. Max 1000 kg bulk FWD : 18 & AFT : 14 = 32 containers	Opening door + equipment positioning [min]	2,5 2 cargo loaders + 1 belt loader.	Equipment removal + closing door [min]	2,5
					Bulk unloading [kg/ min]	110 Max 1000 kg bulk	Bulk unloading [kg/ min]	95
					Containers unloading [min/container]	1,2 FWD : 18 & AFT : 14 = 32 containers	Containers loading [min/container]	1,4
	Bulk load	500			Bulk load	500		
	Bulk time	7,05			Bulk time	7,76		
	n_containers FWD	18			n_containers FWD	18		
	Containers FWD time [min]	24,1			Containers FWD time [min]	27,7		
	n_containers AFT	14			n_containers AFT	14		
	Containers AFT time [min]	19,3			Containers AFT time [min]	22,1		

Figure B.7: Airbus data - 2 from [11]

Builder	Aircraft type	Fuelling		Cleaning	Catering			
		Infos	Numbers		Infos	Numbers		
AIRBUS	A321	20000L	Dispenser positioning + connection times [min]	2,5	Performed in available time	1 catering truck and 2 doors	Equipment positioning + opening door [mi	2
			Dispenser removal + disconnection times [min]	2,5	Time [min]	19 11 FSTE in total (4 and 7)	Closing door + equipment removal [min]	1,5
			Fueling time (from the GC)[min]	16			Time to go from a door to the other [min]	2
			Whole fueling [min]	21			Time rate for trolley exchange [min/FSTE]	1,2
							Number of FSTE	11
							Max time for trolley exchange	13,2
							Total sequential time (catering_1)	18,7
	A320	20000L	Dispenser positioning + connection times [min]	2,5	Performed in available time	1 catering truck and 2 doors	Equipment positioning + opening door [mi	2
			Dispenser removal + disconnection times [min]	2,5	Time [min]	19 11 FSTE in total (4 and 7)	Closing door + equipment removal [min]	1,5
			Fueling time (from the GC)[min]	16			Time to go from a door to the other [min]	2
			Whole fueling [min]	21			Time rate for trolley exchange [min/FSTE]	1,2
							Number of FSTE	11
							Max time for trolley exchange	13,2
							Total sequential time (catering_1)	18,7
	A319	20000L	Dispenser positioning + connection times [min]	2,5	Performed in available time	1 catering truck and 2 doors	Equipment positioning + opening door [mi	2
			Dispenser removal + disconnection times [min]	2,5	Time [min]	15 8 FSTE in total (4 and 4)	Closing door + equipment removal [min]	1,5
			Fueling time (from the GC)[min]	16			Time to go from a door to the other [min]	2
			Whole fueling [min]	21			Time rate for trolley exchange [min/FSTE]	1,2
							Number of FSTE	8
							Max time for trolley exchange	9,6
							Total sequential time (catering_1)	15,1
	A330-300 -A333	90000L	Hydrant positioning + connection [min]	8	Performed in available time	3 catering trucks servicing galleys SIMULTANEOUSLY	Equipment positioning + opening door [mi	5
			Disconnection + hydrant removal [min]	8	Time [min]	15 at doors 1R, 2R and 4R	Equipment removal + closing door [min]	3
			Fueling time (from the GC)[min]	34		35 FSTE in total (4, 9 & 22)	Number of FSTE	35
			Whole fueling [min]	50			Time rate for trolley exchange [min/FSTE]	1,5
							Max time for trolley exchange	33
							n_FSTE 1st door	4
							n_FSTE 2nd door	9
							n_FSTE 3rd door	22
							1st door catering (catering_1) [min]	14
							2nd door catering (catering_2) [min]	21,5
							3rd door catering (catering_3) [min]	41
			ATTENTION : Refuelling with PAX on board ALLOWED					

Figure B.8: Airbus data - 3 from [11]

Appendix C

Delay use case results

Delays observation on example

Cleaning truck 1				Cleaning truck 2			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
-3.1	1	1	Cleaning	-1	2	4	Cleaning
-5.5	2	2	Cleaning				
-1	1	3	Cleaning				
-2.9	1	5	Cleaning				

Fueling truck 1				Fueling truck 2			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
-3.1	1	1	Fueling	-1	2	4	Fueling
-5.5	2	2	Fueling				
-1	1	3	Fueling				
-2.9	1	5	Fueling				

Catering truck 1				Catering truck 2			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
-3.1	1	1	Catering 1	-1	2	4	Catering 1
-5.5	2	2	Catering 1				
-1	1	3	Catering 1				
-2.9	1	5	Catering 1				

Figure C.1: Detailed start delays for actions of example of Section 4.2.1 with 3 ULD trains.

ULD train 1				ULD train 2				ULD train 3			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
0	1	1	Unloading 2	0	1	1	Unloading 1	0	2	2	Unloading 2
0	1	1	Loading 2	0	1	1	Loading 1	0	2	3	Loading 1
0	2	2	Loading 2	960	2	2	Unloading 1	0	2	2	Unloading 2
870	1	3	Unloading 1	210	1	3	Unloading 2	1500	1	4	Loading 2
780	1	3	Loading 1	450	2	4	Unloading 1	150	1	2	Unloading 2
1080	2	4	Loading 1	540	2	4	Loading 2	1230	1	3	Loading 1
300	1	5	Unloading 2	810	1	5	Unloading 1				

Bulk train 1				Bulk train 2				Bulk train 3			
Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process	Delay [sec]	Stand	TA	Process
0	1	1	Unloading	0	2	2	Unloading	0	2	4	Loading
0	1	1	Loading	0	1	3	Unloading				
0	2	2	Loading	0	1	3	Loading				
0	2	4	Unloading	0	1	5	Loading				
0	1	5	Unloading								

Figure C.2: Detailed start delays for actions of example of Section 4.2.1 with 3 ULD trains.

```
(fueling_truck 5): [-17.57952286282306]
(fueling_truck 4): [-20.994035785288244]
observer> ask turtles [show mean_delay_in]
(cleaning_truck 8): [-20.994035785288272 -4.711729622266402 -8.961232604373757 -14.015904572564612]
(catering_truck 7): [-17.57952286282306]
(fueling_truck 4): [-20.994035785288272 -4.666998011928429 -8.752485089463221 -14.015904572564612]
(bulk_train 14): [0 0 0 0 0]
(uld_train 12): [0 0 0 0]
(stand 3): []
(fueling_truck 5): [-17.57952286282306]
(stand 1): []
(bulk_train 16): [0]
(bulk_train 15): [0 0 0 0]
(stand 0): []
(uld_train 10): [0 0 0 0 0 0]
(uld_train 13): [0 0 0 0]
(catering_truck 6): [-20.994035785288272 -4.711729622266402 -8.961232604373757 -14.015904572564612]
(stand 2): []
(uld_train 11): [0 0 0 0 0 0]
(cleaning_truck 9): [-17.57952286282306]
```

Figure C.3: Detailed start delays (in seconds, in action chronological order) for actions with 4 ULD trains of example of Section 4.2.1

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