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Ground handling management modelling and visual interface conceptual design

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ABSTRACT

The airports are the air traffic infrastructures where the landing, taking-off and stopovers of aircraft happen so as to proceed to the passengers' boarding/deboarding, and luggage and cargo loading/unloading. For these operations to result successful the participation of a great number of people and equipment is necessary. Many of those operations are encompassed within the ground handling process.

Most certainly the passengers are not quite aware of the very many services that they benefit directly or indirectly from when they are at an airport. The ground handling includes different essential services for the air transport. From how well it works we could get an idea of the quality of the service that is provided to the users. Any error leads to disastrous consequences for all the air transport actors: passengers, airport, airlines, and, of course, the companies providing ground handling services.

Those errors must be avoided at all costs. Nevertheless, it is not only important for that reason, but also because many airports are starting to be congested and enlarging them does not seem like a feasible option currently. Increasing the efficiency in the operations is another way to increase the capacity. To that end, it has been found that the ground handling operations is a critical factor. It is vital to ensure that both, material and human resources, are used in such manner that they give optimal performance, always allowing a certain margin of flexibility in order to be able to adapt to possible unexpected situations.

However, this is easier said that done. The ground handling is one of the most complex airport processes. Ground handling is the collective name given to all the activities around the aircraft while it is grounded. Many different actors, stakeholders, are involved in the process. What is more, they have different interests which makes the turnaround still more difficult.

The present work belongs to the field of Operations Research and deals with the management of resources in the airport apron, more precisely those from the ground handling activities. This is done by means of modelling, using Petri nets as the main tool, and then through the introduction of a visual interface for the managers. All of this is developed in the framework of the Airport Collaborative Decision Making (ACDM) proposed by EUROCONTROL (an international organisation which helps its member states to achieve safe, efficient and environmentally-friendly air traffic operations across the European region), which emphasizes the need to take decisions jointly by all the stakeholders in order to maximize the capacity and efficiency of the airports.

The Petri net model helps understanding how the activity develops. It makes quite automatized the communication between operator and manager, resulting in saving a significant amount of time. We can find the different states of a ground handling vehicle along its operation represented in the above mentioned net. On the other hand, the visual interface for the manager is just a very simple way to represent the information obtained through the Petri net.

ACKNOWLEDGEMENTS

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Beatriz Arias Alonso

Chapter 1

WORK OVERVIEW

1.1 INTRODUCTION

1.1.1 MOTIVATION AND OBJECTIVES

The main motivation of this work is to provide with a thorough explanation of how the ground handling management should be done in order to improve airport performance. This work arises from Ms. Salma Fitouri-Trabelsi PhD thesis [3] and is necessarily a complement to the work developed by her in the past years under the supervision of Prof. Mora-Camino.

Improving airport performance is a key goal in the current air transportation industry. The main reason is that the number of passenger and cargo movements have increased dramatically over the past few decades. As a result, many of the existing infrastructures have become saturated. The trivial solution to this problem would be to expand those infrastructures so as to adapt to the current situation. However, this is an extremely costly solution. What is more, it will often not be feasible since not every airport counts on enough space to do so.

For many years the ground handling activities have been unnoticed when trying to optimize airport performance. Nevertheless, at some point researchers started to realize that many of the delays at airports were caused by poor ground handling management and operation. These delays translate in higher operational costs and, of course, in the above mentioned saturation of the infrastructures. We can easily conclude that improving the ground handling management is fundamental for airport performance improvement and not at a high cost.

Since the ground handling encompasses many different activities performed also by different actors, the aim of minimizing the waste time before and in between them should be a priority if we are searching for optimal airport operation. The previously mentioned minimization is done by making the communication processes among those actors more automatic which results in shorter processing times.

The problem is simplified by considering an only task carried out by an only company at a time. This is an obvious simplification of the problem since habitually there is more than just one company involved in the many ground handling activities that need to be performed. The actual problem would be a lot more complex to face. In order to deal with the resulting simplified problem, after doing a detailed literature study, I decided to develop my work based on a tool called Petri Nets. Along my thesis I propose a Petri Net which I consider as a good start to solving the problem that arises from the real (not simplified) situation at the airports nowadays.

Through the adopted Petri Net the different states and processes relevant to the communications are modelled. The underlying idea is that instead of voice communication among agents and fleet managers a more automatic and therefore efficient means of communication is possible.

1.1.2 OUTLINE

The work presented in this thesis is divided in four chapters, being **chapter 1** an overview of the work developed along the present project. **Chapter 2** is basically an introductory chapter so as to lay the foundations of my work. A literature study is presented focusing in the two main concepts that are being treated along the present work: the ground handling activities and the Petri Nets. This way we can get a general idea of the works developed previously that are related to the subject of this thesis. A historical summary is presented as well so as to give the reader perspective on how the aviation and the air transport have been developing, suffering enormous changes at an increasing pace along time. At the end of the chapter, the motivation for this work is put into context, explaining what the current situation is and how we have reached it.

In **chapter 3** an explanation of why it is important to accomplish the ground handling not introducing any kind of delay is provided. In aviation, more than in any other field, time is money. It is absolutely necessary to prevent more delays than those unforeseeable and not avoidable from happening. Since ground handling is an important source of delays this is not anything useless to be said. Detailed information is given about all the activities comprised under the concept of ground handling, explaining what each of them entails and their main particularities.

Chapter 4 is the real core of the present work. At the beginning, the ACDM concept is explained and the reason why with our work we are trying to follow the path recommended by it. Afterwards, we can find the reason why Petri Nets have been chosen in order to make a model within the ground handling system. Then the Petri Net model is presented and the validation of it is made, through two different methods. To conclude, we can find the visual interface that has been designed for the fleet managers and operators which is meant to be a very advantageous tool for the managers to visualize the situation of their fleet at any given moment and to give orders to the operators, and for the operators to inform the managers of their state at each moment and receive instantaneous instructions from them.

To add up, the conclusions and possibilities for further research are presented in **chapter 5**, setting different paths that could lead to beneficial future developments in the present matter.

Chapter 2

INTRODUCTION

2.1 LITERATURE REVIEW

2.1.1 GROUND HANDLING

Quite some research has been performed so as to make airport activity more efficient and inexpensive. Initially the research was not approached with the ground handling in the spotlight at all. Nevertheless, nowadays more and more articles can be found concerning airport performance approached from the improvement of the ground handling perspective. It is not hard to find publications about the application of the CDM method to the airports, as the great reference it is in the efficiency improvement process.

In the Master thesis entitled "Management of ground resources on an airport platform" [2] the author focuses in the management of the existing resources on an airport platform. A detailed conceptual model of the turnaround is developed, and through simplifications different scenarios are analysed. The author also proposes a mathematical formulation of the problem of minimizing delays while a set of aircraft are serviced by the ground handling operators. The problem can be regarded as a hybrid of the project scheduling problem and the vehicle routing problem. The entire work is framed in the Operations Research (OR) area, for that reason an OR technique is used to solve the aforementioned problem. The main aims of this work are the reduction of flight delays as well as cost reductions.

Dr. Fitouri-Trabelsi contributes with her PhD thesis dissertation [3] to the organization of the ground handling management, in the frame of the ACDM concept. She proposes a new hierarchical structure with a ground handling coordinator, who serves as interface among the ACDM partners and the different ground handling managers. She develops decision making processes based on heuristics at each level of the aforementioned organization, which are evaluated in nominal conditions but also when major disruptions are present.

In [4] the authors explain the importance of applying the Collaborative Decision Making (CDM) at the airports and the difficulties that arise from its implementation. They make emphasis in how beneficial the standardization is for its implementation. A standard of application prepared by EUROCONTROL is presented, and there is an explanation of why without it the Single European Sky project would not be viable.

EUROCONTROL provides with a manual [5] which intends to make easier the understanding of the impact that the application of ACDM should have on the air traffic, stress how essential it is that all the intervening agents embrace the conceptual change (for instance, on similar jobs, standard agreed methodologies to be applied with no deviations), show how to organize, manage and implement the necessary procedures to make ACDM fully operational. It clearly demonstrates how high the benefits of a relatively low investment are in the case of ACDM application.

In reference [6] the authors outline that the ground handling process is one of the most limiting factors when trying to adapt to a growing air traffic (expected to keep growing after the current economical crisis). In order to improve and always within the CDM context, an algorithm is proposed which determines the minimal resources that each provider needs to use. Equally it calculates a maximum value (for the resources) which allows the providers to choose according to their preferences and their business model. Besides, the approach to the problem provides the advantage of making the providers as autonomous as possible one from each other. Also, it simplifies the replanning and coordination in case of possible perturbations.

The management of the ground handling in a collaborative way is studied in [7], with the objective of minimizing the delays in the departing flights, as well as the operational cost of the service fleets. The novelty that is introduced is precisely the management of the different intervening fleets, which had not been considered before in the CDM approach specifically.

Reference [8] presents a study about the improvement of the ground handling process through what is called *critical path analysis*, concluding that the activities in which we should concentrate are those carried out in the cabin. The *critical path* is defined as the longest possible sequence of depending tasks that takes the longest to be accomplished. Proposals of specifications for a new ground handling concept both for the B737-800 and B747-400 Combi are made, reaching time savings of 42% and 38% successively. When shortening the critical path duration is achieved, other paths can become critical, so a new phase should be implemented. Apart from shortening the path, other goals are reached this way: reduction of pollutant particles emissions, safety enhancement (less people and vehicles involved in the process) and supply of flexibility in the service in such way that it is able to adapt to future aircraft.

In paper [9] the authors model hub airports by reducing their operations into blocks (which simulate a basic type of aircraft operation at the airport) and then develop a simulation language (SLAGOM) for such a model via MATLAB, which is useful in ground handling operations. The main aim is to attain more efficient scheduling, prediction of delays at operations and therefore the improvement of the airport efficiency.

The objective of the work presented in [10] is to improve the way that ground handling resources are allocated at airports even when disturbances are present. For that purpose the authors develop an updated decision support system by means of combining artificial intelligence techniques with visibility technologies. They propose a combined use of Multi-Agent Systems (MAS) along with Wireless Sensor Networks (WSN) to provide the required information.

Due to an obvious research gap in airport logistics, research to elaborate paper [11] was done by researchers and some of the main EU hub airports for one year, in order to develop a holistic performance measurement system (PMS) for benchmarking ground handling services. The developed PMS combines Balanced Scorecard-derived perspectives with process-oriented dimensions, adapting it to the context of logistics services.

The International Civil Aviation Organization (ICAO) means to increase situation awareness in airports via the Advanced Surface Movement, Guidance and Control System (A-SMGCS), which provides assistance to the airport stakeholders with the ground handling operations, reducing their workload. The A-SMGCS also enhances airport efficiency, which, thanks to it, is not affected by bad visibility conditions, traffic density or airport layout, for instance. In paper [12] an implementation of the A-SMGCS concept is presented: the A-Guidance. This system has the capability to cope with the management of ground handling traffic movements.

2.1.2 PETRI NETS

Petri Nets have already been used for the purpose of modelling ground handling management issues. However, there are not so many publications concerning this area as there are about ground handling management in general. Other similar multi-agent system problems have also been tackled by means of Petri net modelling and may serve as inspiration to be applied to the ground handling case.

References [13] and [14] both correspond to notes from courses in which the basics of Petri net modelling are explained. They serve as good sources of information, enabling us to learn how to use this type of modelling and to what extent it could be used.

In [15] a new model of the ground handling is introduced by means of using Petri nets, so as to understand and measure the effect that possible perturbations in the service would have on the airport operation in general due to propagation. The proposed model can also help to investigate the consequences in the airport operation when structural and/or operational changes are made. A specific type of Petri net was used for this purpose: a Hierarchical Stochastic Coloured Timed Petri Net, which is much more powerful that a simple Petri net.

Article [16] discusses the operation efficiency and the average delay of the air cargo handling system. For that purpose the authors build a stochastic Petri net and give the homogeneous Markov chain as well. The system bottlenecks are found and eventually some suggestions are given so as to improve the efficiency of the operations.

In paper [17] we can find the development and the application of simulation models for air cargo terminal operations, which are useful due to the complex and stochastic nature of terminal operations. Timed Colour Petri nets are the tool that the authors chose for the modeling. The model is validated running the model based on actual cargo retrieval schedules. The model is developed in modules and can thus be adapted easily to different situations by adding/removing modules.

The authors of reference [18] introduce the use of Petri net in order to model multi-agent systems. Those generic systems do of course resemble the ground handling system. To proceed with the modelling the authors first make an abstract architecture approach, where how agents behave with respect to changes in their environment is shown. This approach helps making the understanding of the problem more thorough. From the obtained architecture the Petri net model can be established very intuitively. Submodels for each agent can be made and then linked.

2.2 HISTORICAL SUMMARY

2.2.1 EVOLUTION OF THE AVIATION

For over two thousand years humans have had an obsession with accomplishing the mission of making different inventions (developed along the years) fly. As a matter of fact, in the Greek mythology there is already the Icarus and Daedalus story, for instance.

There is evidence of the existence of flying machines since very distant times, even though not very relevant progress was made until the invention of the **kite**, which emerged in China around the year 300 b.C. In the 6th century, also in China, experiments were made with flying kites, but the outcome of the experience was not very successful. The kite was not enough, of course, to put humans off trying to develop new ideas that would later allow men to fly.

Abbas Ibn Firnas, in the IX century, is said to have succeeded to fly by means of a very rudimentary **glider**. However, there is no documentary evidence of this event until the XVII century, which makes the veracity of the information quite uncertain. Eilmer of Malmesbury, Benedictine monk, managed to fly some 200 meters in the XI century according to the references given by another monk from his very same abbey some years later.

In the XV century, the most relevant humanistic figure must be mentioned: Leonardo da Vinci. His fascination for flight made him devote an important part of his life to the study of the birds flight and to the development of different machines which allowed the man somehow to fly (an example can be observed in figure 2.1). As a matter of fact he never succeeded in flying. Nevertheless, at a later stage it was empirically proved by means of physically constructing prototypes of some of his inventions, that flying would perfectly be possible with them.

Already in the XVIII century we find another big name in the history of aviation: the Montgolfier brothers. Despite having been proved that there was a Brazilian who

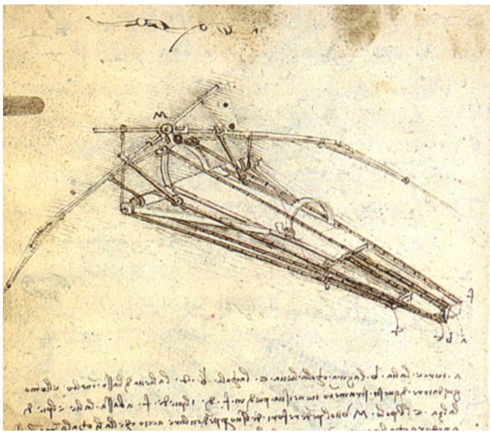


Figure 2.1: Ornithopter designed by Leonardo da Vinci

got ahead of them, they are considered the inventors of the **hot air balloon** (see figure 2.2). At first they would only embark animals, and after some trials they started boarding humans as well.

In 1848, William Henson and John Stringfellow accomplished, by means of an **unmanned vapour plane** model, the first flight in a heavier-than-air machine. In the XIX century as well, Sir George Cayley carried out a series of experiments and wrote a paper exposing for the first time the scientific principles of flight with a heavier-than-air object. What is more, he became the first adult pilot of a non-controllable aeroplane. For all the mentioned reasons he is considered by many as the father of aviation.

In 1899, the Wright brothers (Orville and Wilbur) started their struggle towards the development of a mechanism that would allow the control of their aircraft. These Americans together with the Brazilian Santos-Dumont compete for the honour of the first controlled flight in a heavier-than-air aircraft. As of today no agreement has been reached as to designate who achieved such in first place. The controversy is born basically out of the fact that the first flight of the Wright brothers, in 1903, counted on the help of rails and a catapult in order to take off. That is what makes some experts opt for the flight of the Brazilian in 1906, the first actually achieved without any help of external agents, and which was registered and published. In figure 2.3 the plane with which Santos-Dumont carried out his tremendous deed.

It is not until 1914 that the first commercial flight takes place, within Florida (USA) and with an only passenger. Before that, mail was already being transported by plane. 1916 is the year when Boeing starts its activity. Its bigger competitor, Airbus, was not born until 1970 on the other hand. In 1919 the first airlines of many to come were born: the Dutch KLM and Colombian Avianca. In that same year John William Alcock and Arthur Whitten Brown (British) successfully accomplished the first transatlantic flight, between Canada and Ireland.

Just after the end of World War II, in September 1945, the first flight with a turbine-propelled aircraft occurred. The turbines were manufactured by Rolls Royce. In 1947, Chuck Yeager with a Bell X-1 (figure 2.4) was the first man to break the sound barrier. Also before the 50s, the jet engines began to be used, which was a complete revolution since the flying hours decreased importantly. The

Figure 2.2: Depiction of the Montgolfier brothers' balloon

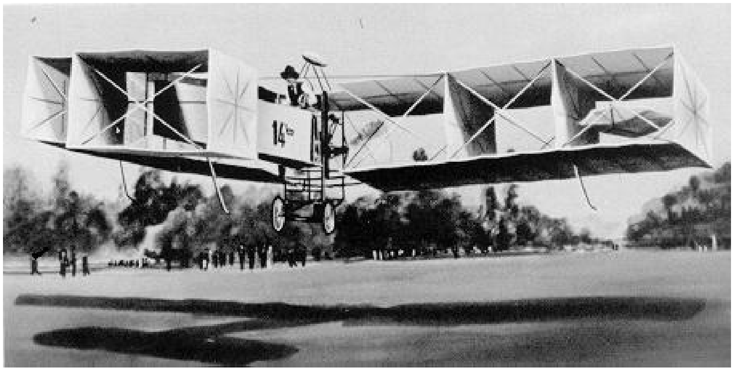


Figure 2.3: 14-bis, main protagonist of Santos-Dumont first flight

first commercial jet aircraft was the De Havilland D-106 Comet, which can be seen in figure 2.5. At the end of 1968, months before the Concorde, the Russian Tupolev Tu-144 became the first supersonic commercial plane.

The 11th September 2001 is a date not to forget. After the terrorist attacks that day in the USA and as a consequence of them, the number of air passengers dropped significantly and most airlines had to face very serious economical difficulties along the following years for that reason. The reaction was to try to enhance the security in the air transport through more thorough security measures at the airports all over the world.

2.2.2 EVOLUTION OF THE AIR TRANSPORT

The first attempt to start airlines was made by two Americans in the 19th century. However, it did not succeed due to different incidents. DELAG, German, was the

Figure 2.4: Yeager and the Bell X-1 with which he broke the sound barrier

Figure 2.5: De Havilland D-106 Comet, first commercial jet aircraft

world's first airline to use an aircraft in revenue service. It was founded in 1909 with the support of the German government. It operated Zeppelin rigid airships, dirigibles. As for the oldest non-dirigible airlines that still operate under their creation name KLM and Avianca have already been previously mentioned. Qantas and Czech Airlines could be added to those two.

Since a great deal of the air transport operations involve either American or European companies we are going to further elaborate on how those two markets have been developing since the beginning of the commercial aviation.

EUROPEAN AIR TRANSPORT DEVELOPMENT

Austria, Belgium, Finland, France, Germany, the Netherlands and the United Kingdom were the first countries within Europe to adopt air transport. Very many airlines appeared along the 20s in Europe. In the first European airlines great importance was given to the beauty of the interior of the plane and spacious surroundings, which translated into less aerodynamic efficiency and flying at lower speeds. Due to the lack of navigational aids and the very rudimentary instrumentation used by the time, accidents frequently occurred, and passengers became used to delays especially in the winter time as a result of the bad weather.

Most of the early born airlines counted on governments' assistance, and they grew bigger and bigger very quickly based on the needs of the nations to be better linked to colonial possessions overseas. This growth lasted until the loss of those colonies. KLM, for instance, found itself based on a small country with few possibilities of attracting passengers unless for transferring reasons. And that is basically how the hub-system concept originated, so as to facilitate easy transfers. Schiphol airport (Amsterdam) was one of the first to introduce this system.

It is necessary to point out that in the early 1990s deregulation of the EU airspace occurred, which resulted in a noticeable change in the structure of the industry. Low-cost carriers started to grow at the expense of traditional airlines (flag carriers). Another collateral effect was the privatization of many flag carriers. Also, more recently, these national carriers have suffered very badly as the price of the oil has been increasing along the past five years.

USA AIR TRANSPORT DEVELOPMENT

Like mentioned before the first commercial flight took place in Florida in 1914 and lasted 23 minutes. Tony Jannus conducted it with a a biplane flying boat.

In 1919 an operator called Chalk's International Airlines began to fly the route Miami-Bimini (Bahamas). They stopped flying in 2008, but until then they claimed to be the oldest continuously operating airline in the USA.

After World War I, in 1918, the Congress decided to support the United States Postal Service in their experiment with air mail service. They were provided with an army aircraft for the task. For many different reasons along the next few years the service provided was not as good as expected. However, the Postal Service managed to develop an air mail network and offered the routes through contracts to independent bidders. Some of the winners of those bids evolved into Delta Air Lines, American Airlines and United Airlines, for instance. This helps us imagine how relevant the air mail was for the development of the air transport in the USA.

In 1925 the Ford Motor Company began to construct their own all-metal aircraft, the Ford Trimotor, which can be observed in figure 2.6. It was the first successful American airliner (12 seats). Back in the days the main mean of transportation was the rail service. Air service was just regarded as a supplement to it, but from the development of the Ford Trimotor it started to be seen as something potentially profitable.

Simultaneously a group of men created Pan American World Airways, linking the USA both with Asia and Europe in their attempt to connect the USA with the rest of the world. Northwest Airways followed the same path, flying to Canada. Those were the two only airlines until the 1940s that flew internationally.

The 1930s we could say that meant a true revolution somehow for the air transport industry. The Boeing 247 (figure 2.7a) and Douglas DC-3 (figure 2.7b) were introduced in the market making the business profitable, even in adverse situations such as the Great Depression.

Figure 2.6: The first successful American airliner: the Ford Trimotor.

(a) Boeing 247 (b) DC-3

Figure 2.7: These aircraft revolutionized the air transport

After the end of World War II the USA government decided to set the standards and scope for the air industry. That is when the "open skies" position was taken, which still continues up to the current moment, even though there are some limitations. By that time as well the Boeing Stratocruiser, Lockheed Constellation and Douglas DC-6 emerged as air travel flagships, and boosted the airline industry. Many airlines were willing to make investments foreseeing an increasing demand of both, passenger and cargo air transport.

In the 1950s, after the invention of the jet engine, the first flagships equipped with such engines appeared. The De Havilland Comet, Boeing 707, Douglas DC-8 and Sud Aviation Caravelle are the most important representatives. The Lockheed L-188 Electra was the first large American turboprop airliner, introduced in 1958.

It was not until the 1970s that a new boost for the airlines happened, with the appearance of Boeing 747, McDonnell Douglas DC-10 and Lockheed L-1011, the first wide-body aircraft (jumbo jets).

Airline deregulation in the USA began in 1978 (first major market to do so), which lowered the federal control barriers for new airlines. It happened amidst an economical downturn. This deregulation caused new airlines to emerge, even though competing with the major airlines was not an easy task. In some cases some of these major airlines decided to implement a very aggressive strategy lowering prices in some routes under the actual operation price. That was something the new start-ups could never afford to do. This resulted in an important drop of the revenues and service quality. The average price of a domestic flight ticket has dropped by 40%, and the employee pay as well. We can conclude that the passenger was the winner in this situation.

Partly thanks to the deregulation the demand of air transport started to grow very significantly, reaching the point (in the 1980s) of almost 50% of the world air transport took place in the USA.

At the end of the century the low-cost carrier concept emerged. They represented a very serious threat to the traditional airlines. This also happened in Europe as already mentioned before. As a matter of fact, after the deregulation happened and along time the American flag carriers' status changed from profitable to depressed nowadays. For this reason many flag carriers' chief executive officers (CEOs) state that the deregulation was definitely a bad decision.

2.3 EVOLUTION UNTIL PRESENT SITUATION

2.3.1 CURRENT SITUATION

Air transport seems to be the most suitable option for medium and long distance journeys currently. From a certain critical distance travelling by air starts being more advantageous than doing so by earth. Within the medium distance, the high-speed trains are a tough competitor basically for two different reasons. First of all, the train tickets are usually keeping lower prices than the plane ones. And secondly, the train leaves the passengers in the city centre whilst the passengers flying to their destination still need to take some complementary means of transport in order to reach the city. Also, the ever-increasing high-speed network enables the connection of the main cities almost in every country nowadays. For journeys of thousands of kilometres the plane is undoubtedly the king.

The development of air transport has entailed an increasing in time demand, due to all kinds of trips, from business to family visits or vacation. This demand has been increasing as the development of air transport has allowed the prices of the tickets to drop, making them more affordable for everybody's pocket. To a considerable extent this has happened thanks to the irruption of the low-cost carriers in the market.

This growth in the air activity results in a congestion of both the air space and the airports. When designing an airport the possible evolution of its activities along the following decades is always borne in mind. If the activity increases in an excessive and unexpected manner then the already mentioned congestion problems could appear, which can already be noticed in a number of airports at present.

This congestion problem normally arises from the terminal size, but also from the apron, taxiways and runway, of course. In the present project we are focusing in how the airport operation could be improved, reducing that way the congestion as much as possible, through the improvement of the ground handling, which is known to be the second most important source of delays.

Airport capacity has become a bottleneck in the growth of air transport. Airport authorities keep trying to find a solution by proposing a more efficient use of the available resources, since an expansion would result too costly and, in addition to that, it is not feasible in many cases for a number of reasons. For a long time, research was focused in the improvement of the departures/arrivals management or the allocation of parking stands management, for instance. However, it was not until more recent times that the focus was set in the ground handling management.

The ground handling covers all the activities that are carried out around that plane from the moment it is parked in the apron until it leaves again. The ground handling optimisation is not a trivial problem due to the many actors involved which have different interests each, which do not necessarily correspond to the optimal situation for the airport operation. Anyhow, coordination among the different service suppliers must be achieved so that the plane is ready to take off at the scheduled time, bearing in mind the existing technical constraints owing to the available vehicles.

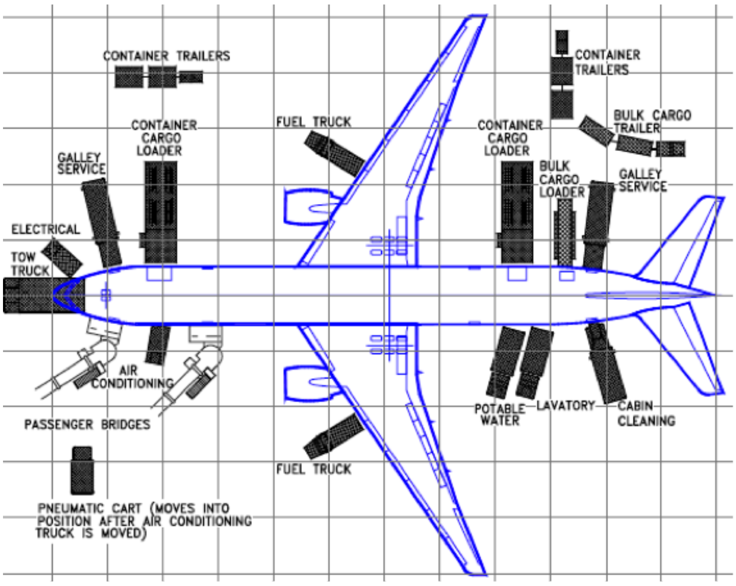


Figure 2.8: Example of ground handling operations on a B-777. Source: Boeing.

A not negligible part of the flight delays are generated while the plane is parked. this implies that if the ground handling is optimized these delays will be diminished. Not only that, but also the distance covered by the suppliers' vehicles will be reduced, and for that reason less fuel will be required. The optimization of the process results in money saving, which is after all one of the main interests, plus less polluting emissions, making the process more sustainable. We can conclude that in order to improve the efficiency in the air transport we need, unavoidably, to optimize the ground handling.

Along the first decades of commercial aviation there were only the so-called *flag airlines*, which were usually owned by the governments, at least partially. As the users' needs changed the market evolved in two directions:

1. creation of airlines alliances, groups of flag carriers trying to offer the client a *global* destination network;
2. appearance of low-cost carriers, creating a parallel market, structured and simple, in which *point-to-point* flights are offered as an alternative to the traditional airlines.

FLAG CARRIERS AND ALLIANCES

There are three main alliances: One World, Skyteam, and Star Alliance. Their aim is to grant global destination coverage efficiently, coordinating the operation of all the different members/allies of the group.

The alliances often count with a *hub*, which main purpose is to receive passengers to later redistribute them to their final destination. These *hubs* can be found within the **hub and spoke** system, originated in the 1950s in the USA. More precisely, Atlanta was the first hub. Delta Air Lines was the pioneer, in its effort to compete with Eastern Air Lines. The *hub and spoke* concept is antithesis of the point-to-point model.

Currently, being a *hub* of an alliance is a privilege, since that means covering a very wide range of international and transoceanic destinations. Each alliance counts with at least one hub per continent. These *hubs* are airports in which over 30% of the passengers are in transit.

One of the key principles of the alliances is to ensure flight connections in transfers of reasonable time lengths. For this purpose the alliances' normal operation can become considerably complex.

LOW-COST CARRIERS

The appearance and development of the low-cost carriers, on the other hand, happened due to the consolidation of the fifth freedom of the air, which eliminates the restrictions for the airliners of a certain country to operate flights with origin and destination in third countries.

Their business model is simple: maximizing the occupancy rate of the aircraft and optimizing the operational efficiency in order to reduce the costs to the minimum. This strategy's success can be seen through the productivity figures of the airlines. While a flag carrier may register an average productivity of 4.76%, the low-cost can reach an average of over 10%.

From a merely economical point of view, it is possible to succeed in maximizing the occupancy rates of the aircraft by means of very attractive promotional fares for potential clients. The prices are fixed months in advance of the flight date. As the demand increases, so does the ticket price. This is how, by knowing the clients' priorities, they maximize the unitary profit they make per flight.

As for the costs, in order to minimize them, the most important factor is to keep the planes flying as much time as possible, minimizing the operation times at the airports. To that end it is essential that the flights that the companies operate are short haul ones. That would make possible to do 7 or 8 flights per day and plane. The low-cost carriers tend to use regional airports, with a reduced number of operations and little or no congestion, which allows shortening the stopover time (the time the aircraft remains grounded).

A second way to reduce costs is attacking the basis of direct costs, like the employees salaries (lowering them), on-line sales, ticket printing (customers need to print their own ticket at home), on-board service (always pay services), fleet variety (homogenization for lower maintenance costs), etc.

Of course the irruption of the low-cost companies is of high importance to the ground handling operation. Actually, they could be one of the main reasons why the airports have run out of capacity along the past decade. It seems very likely that low-cost carriers will continue to grow in the next few years. We could wonder about the possible impact that their further development could have on airport infrastructures. In fact, independently of this hypothetical growth, flag carriers are not expected to disappear, so the airports will possibly need to face a trade-off process and to reach an intermediate solution in order to satisfy the needs of both kinds of airliners. Airports must be able to find an equilibrium point. What seems clear is that improving the ground handling operation would help reaching that equilibrium more easily.

Chapter 3

THE GROUND HANDLING PROCESS

3.1 INTRODUCTION

The air traffic growth is closely related to the growth of the international trade market. The development of the economy and the air traffic are very strongly linked. While the economical situation was positive (until 2009 approximately) passenger transport multiplied by seven along the four previous decades.

In this context of the air transport, flight delays is one of the most prominent problems. A delay in the departure of a flight can easily entail other delays and issues. Usually, a plane covering short/medium range routes does more than one journey every day, which means that if it suffers a delay when departing from anywhere this delay will propagate affecting the following flights. Problems with time slots at airports and ground handling resources allotted beforehand to the referred aircraft can arise from the described situation.

The main problem is that the activities that the ground handling comprises cannot be done whenever wished nor in whichever order is preferred, but some constraints are to be applied. This means that if delay occurs in certain activities, that will necessarily translate into general delay in the whole set of activities. These activities can be regarded as *critical*. Anyhow, important delays in non-critical activities could also mean in some cases delay as a whole.

The ground handling covers all the services that the aircraft requires from the moment it is parked at the apron (at a terminal gate or a remote position, it does not matter) until it abandons it. Passenger, baggage and cargo movements through the terminals as well as aircraft movements on the apron are therefore done by means of ground handling. Safety, timeliness and efficiency are the main objectives of ground handling management.

Safety : it is essential to take into account the safety in the management of the ground handling in order to prevent dangerous situations from happening or at least decreasing the probability of harm occurrence. Also, in the case that they do happen the goal is to minimize the severity of the harm caused, both to the passengers and the equipment and infrastructures. For that purpose it is of vital importance that each operator respects the safety rules at all times.

Timeliness : the consequences stemming from possible delays affect the airlines but also the passengers, who may miss their next flight in the case of being in transfer. The organisation and scheduling of the ground handling needs to be meticulously planed so as to avoid delays and/or to deal with eventual delays caused by any other component of the airport system.

Efficiency : since the timeliness and safety constraints need to be met, it is important that all the ground handling activities are performed efficiently.

These services can well be covered by the airline itself (or even by another airline), or they can be outsourced, therefore being an specialized supplier the one in charge of serving the aircraft. The airport can also be the one to arrange and perform the ground handling tasks.

Within the ground handling two different types of activities can be distinguished: activities in the airside and terminal activities. In our case we will focus in the activities that are developed in the airside, which is understood to be the area where activities related with the aircraft movement and the turnaround happen (which covers the loading/unloading of the aircraft and all the service activities).

The aircraft turnaround begins with the blocks on at the apron, once it is fully stopped, and finishes with the blocks off just before the push-back.

3.2 THE *GROUND HANDLING*: DEFINITION

The ground handling comprises all the different operations that are meant either to prepare an aircraft for a new (commercial) flight, or to conclude an arriving one.

Within the ground handling activities we can find: deboarding of crew and passengers, unloading of luggage and cargo, fueling, catering, cleaning, sanitation, (potable) water supply, boarding of crew and passengers, loading luggage and cargo. Optionally, de-icing and aircraft handling can be performed if necessary. All these activities are represented in figure 3.1. As a matter of fact, the diagram represented is just an example, since it may vary from airport to airport. For instance, in some airports the sanitation and watering may be done in parallel.

In figure 3.1 we can observe that boxes are filled with different colours. That is not a random choice, the choice is meaningful. The activities have been split in groups: luggage and cargo flow (brown), passenger and crew flow (orange), cabin flow (yellow), fuel flow (green), and aircraft technical operations (purple). Those groups are representative of the activities that need to be performed during the aircraft turnaround. There are also some blue boxes but they are not part of the

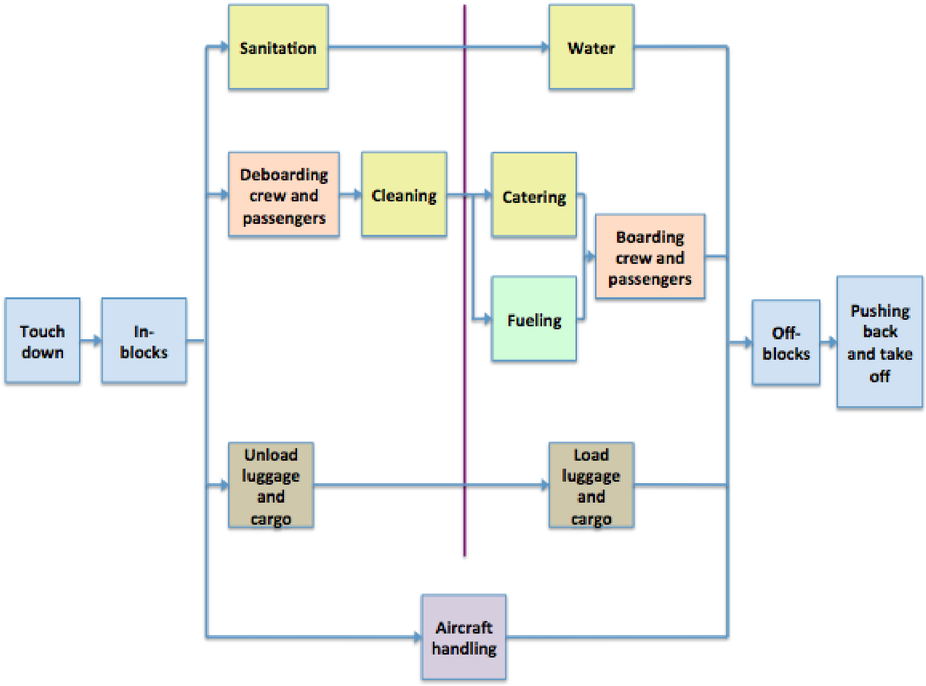


Figure 3.1: Example diagram of the ground handling activities.

ground handling. They are intended to represent what happens from the arrival of the aircraft until its departure.

The moment at which the ground handling activities are performed can be referred either to the arrival moment of the plane or to the departure. In figure 3.1 this can clearly be seen since depending on which of these references is applied the activities are placed at the left or at the right of the purple vertical line. The activities at the left are those which are scheduled according to the arrival time, while the ones at the right are scheduled taking the departure as the reference.

Between the two types of activities mentioned above (landing or taking-off as reference) there may be a gap, idle time, depending on how long the aircraft stays at the airport. If the stay is short enough all the activities can be performed consecutively, with no idle time in between. In that case, the diagram presented in figure 3.2 would not count with the space named *idle period*.

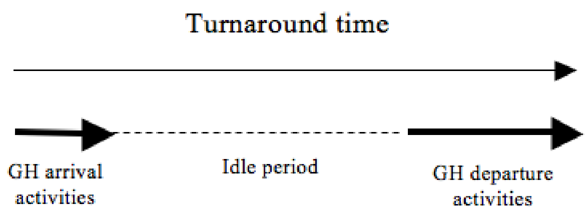


Figure 3.2: Sketch of how the turnaround time is organized.

The turnaround duration depends on different factors:

1. aircraft size: the bigger the aircraft the longer the turnaround. There is a minimum turnaround time (around 20 minutes) which is the time for the brakes to cool down
2. type of flight: short-haul flights commonly operate with very tight schedules, while long-haul ones tend to count with a wider time margin
3. number of passengers and amount of cargo
4. airline strategy: some airlines decide to leave idle time in between flights so as to be sure that they can meet their schedules.

Upon the arrival of the aircraft the first activities which must be performed are the deboarding of crew and passengers and the unloading of luggage, provided that they can be done in safe conditions. It is fundamental to guarantee that minimum delay is suffered by the passengers so that the risk of missing hypothetical connecting flights is minimized.

Once the deboarding and unloading has been performed, if there is need to free the parking stand for another aircraft to use it, assuming that the next departure scheduled is not very tight in time, the aircraft can be driven to a remote parking position.

The unloading/loading of cargo can be done more or less rapidly depending on how urgent it is and on the availability of resources to do so at the parking stand/remote parking position. The aircraft handling (maintenance) is provided by each airline, and can be done at the parking stand/remote parking position as well.

The cleaning and sanitation, which are usually scheduled taking the landing as a reference, can also be done at the parking stand/remote parking position. Those activities are often desired to be performed with as little delay as possible to get the aircraft clean the sooner the better but, in fact, they could in some cases take the take-off as a reference as well. It is a matter of finding the right moment so as to make it less costly and not to disrupt other activities.

As the time of departure approaches some other activities need to be done. If the aircraft is parked at a remote parking position it can be driven to a parking stand if necessary. Generally, fueling is done at the airline's request. Once fueling, luggage and cargo loading, and boarding are completed, the aircraft is completely prepared to leave the apron. The push back can be performed after the pilot is given clearance by the ATC tower to take-off.

The ground handling processes are characterized by the diversity of activities performed, as well as by the wide range or equipment and vehicles required for that purpose. Also, complexity is clearly a characteristic of the process, as different activities need to be accomplished in parallel and/or sequentially.

3.3 GROUND HANDLING OPERATIONS

3.3.1 BOARDING/DEBOARDING OF PASSENGERS

The boarding/embarking process consists on the entrance of the passengers to the plane and on them taking seats. The process is over once the doors are closed. The disembarking process is the exact opposite to the previously described. These operations are watched both by the crew and by the ground staff, and they are both carried out on the left side of the plane. They can be performed simultaneously with luggage loading/unloading since they do not need the same area around the aircraft (luggage operations commonly take place on the right side of the aircraft). In figure 3.3 we can observe how passengers are boarding the plane by means of an airstair by one side while the luggage loading operation takes place at the other side.

Figure 3.3: Boarding by airstairs.

Depending on the type of parking stand under use, these processes will be more or less complex. For instance, if the aircraft is parked in contact with the terminal façade an airbridge will be required in order to proceed to boarding/disembarking. On the contrary, if the parking stand is remote stairs would be needed (which can be carried within the plane if is a small one usually) so that the passengers can descend to the apron, and in certain cases also apron buses can be required in order to drive the passengers from/to the terminal to/from the plane.

When this operation is done by using of airstairs, one for the front door and another for the back door, the boarding/disembarking process is accelerated (provided that no apron bus is required; otherwise airbridges perform better) in relation to the case in which one only airbridge is used. However, the use of two airbridges would result still more advantageous.

The boarding/deboarding system depends on the airline policy (flag/low-cost carrier), but also on the available resources at a certain airport.

3.3.2 BAGGAGE LOADING/UNLOADING

Baggage loading/unloading refers to the pieces of luggage which are checked in. Hence, this does not include the hand luggage.

There are two different ways in which the luggage can be stowed. The different pieces of luggage can either be loaded/unloaded individually (one by one, in bulks), or (for the bigger aircraft) they can be stored in containers so that the loading/unloading process duration can be reduced when the number of pieces of luggage is high.

The checked-in luggage needs to be sorted, unless we are speaking of a point-to-point flight (low-cost, charter). In that case all the pieces of luggage have the same priority and destination so no sorting is required to be done. Otherwise the bags are labelled as transferring, high-prioritized, odd size, etc.

3.3.3 CLEANING

The airlines have the possibility to ask for different kinds of cleaning services, which go from the most basic (which consists in emptying the garbage and takes around five minutes) to a much more exhaustive cleaning, which can take up to forty minutes (emptying garbage, vacuuming, seat-pocket cleaning, etc.). This more exhaustive cleaning is only possible in the case of long duration stopovers. On the other hand, during the night-time (when there is more time available) is when the more in-depth cleaning of the aircraft is done.

Figure 3.4: Cleaning team performing its task.

Independently of the aircraft model the cleaning activities to be performed do not differ much. This means that any cleaning team can be assigned to any aircraft. Therefore, one cleaning team can move on to a new aircraft after they finish cleaning another. However, they need to go back to their base at some point in order to make provisions (pillows, blankets).

3.3.4 CATERING

The catering service is in charge of unloading the food and drink left in the aircraft after the flight, and also of loading new food and drink for the following own. The loading/unloading is most commonly done by means of trolleys which make the task easier, as can be observed in figure 3.5. Either the airline or a subcontractor can provide the service.

This service is not provided until no passengers are left on-board. It can take between five and seventy-five minutes, depending on the quantity of food that needs to be loaded and how it is packed.

There are liftable containers of different sizes (figure 3.5), depending on the aircraft size. This operation requires, therefore, planning which container will serve which aircraft according to the mentioned sizes (should match).

The process can take between five and seventy five minutes, depending on the amount of food and drinks required and they way they are packed. The catering teams must go back to their base between serving two aircraft so that they can empty the garbage and get new supplies.

Figure 3.5: High-loader lifting catering service trolley.

It is usually possible to do the cleaning and the catering service at the same time, unless the aircraft is too small and there is not enough space to do them simultaneously. In that case it does not matter the order in which they are undertaken.

3.3.5 FUELING

The fueling can be done by two methods. In the first one a hydrants system is required (check figure 3.6) in order to transport the combustible to the parking stand through pipelines in a subterranean manner. Then, at the parking stand a dispenser truck must pump the fuel from the pipes to fill up the aircraft. If no hydrant system exists, the fueling will be done in the more traditional way, thanks to a tanker truck.

There is not a standard dispenser truck size. We can find from large types, which can service all kinds of aircraft, to smaller ones, which can just service the smaller aircraft. The tanker trucks also do vary in size.

Fueling is incompatible with the baggage loading/unloading (fueling is usually fulfilled before the plane departs, so the interference would happen when loading normally) since both activities require the same surface around the aircraft in order to be accomplished.

The intervening vehicles in the fueling process must always count on a free way of scape so as to be able to evacuate in case of a possible fire. There are some

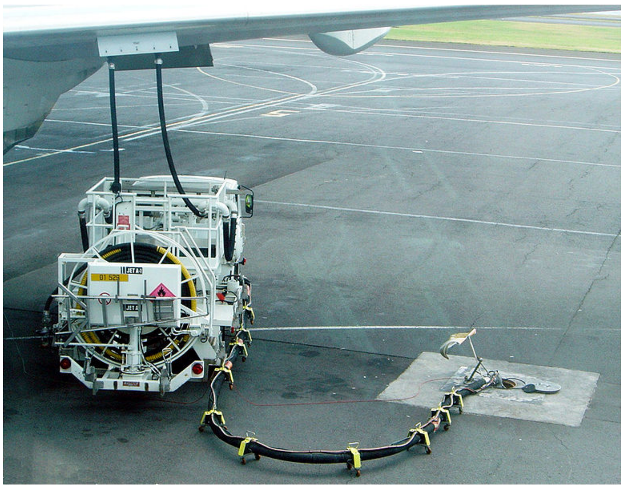


Figure 3.6: Fueling with the hydrants system method.

regulations as well concerning the fueling activity in the case that it is done with passengers on-board. To make it feasible some requirements need to be met. The fueling is often done before the beginning of the boarding process.

The fleet manager decides which team to send just after he receives the request from the pilot. Fleet assignment for the fueling activity is not done beforehand. The pilot is the person who decides how much fuel is needed and he is the one to inform the fueling company about it. The refueling time depends on the pipe capacity as well as in the amount of fuel required.

3.3.6 WATER AND SANITATION

The water that has been used during the flight needs to be removed from the plane. New clean water needs to be provided as well. This operation usually takes place at the left side of the aircraft. So, it does not interfere with the fueling or the baggage handling, therefore allowing the simultaneous development of these activities. However, they must not be performed (water and sanitation) at the same time due to safety and space constraints. The order in which they are developed is irrelevant.

3.3.7 DE-ICING

Ice and frost are big enemies of aviation. If they accumulate on top of the plane they can cause changes in its aerodynamics. That would affect its lifting capacity in a negative way. For example if there is ice on top of the wing the streamlined shape changes and less lift is generated. Also, ice and frost can cause obstruction of flexible surfaces, like the flaps or slats. That would diminish the control capacity.

For those reasons it is highly important to conduct de-icing actions if there is ice or frost on the aircraft, or if there are precipitations which could evolve into any of those.

The de-icing can be divided in two stages which we can call de-icing and anti-icing. In the first phase, the existing ice and frost are removed by means of a mixture of water and glycol (buoyant glycol mix, type 1 fluid) at a mild temperature (that makes the freezing point go under the ambient temperature making more difficult for the humidity to freeze). This stage usually lasts from three minutes to more than an hour, depending on the quantity of ice and frost accumulated. The presence of snow can extend the process in an important fashion. The second phase consists on preventing the formation of new ice and frost by means of another surface treatment with a thicker fluid (type 2 fluid). This treatment has a certain duration (hold-over time) depending on the fluid under use, the temperature and the type of precipitation. After the hold-over time the effect of the treatment vanishes. This means that the treatment cannot be applied much sooner than the take-off for obvious reasons.

Figure 3.7: Aircraft de-icing process.

It is of extreme importance that a de-icing truck is available just at the right time to perform the task on the aircraft. Otherwise, if the de-icing is performed too late there is the risk of increasing the stopover time which would result in a delayed departure. If the de-icing is performed too soon there is the risk of needing to repeat the operation, which is of course more costly and could result in a delay as well.

Like with the fueling, the de-icing is not usually pre-planned. The fleet manager receives a request from the pilot at the beginning of the stopover, assuming that all the activities will be performed with no delay. Just then the manager decides which truck is assigned. The truck arrives to proceed with the de-icing a few minutes (depending on the amount of ice/snow/frost) before the departure time.

The de-icing takes place in a specific platform meant for that purpose, due to the chemical products used which can negatively affect the apron otherwise.

Chapter 4

ACDM, PETRI NET MODELLING AND VISUAL INTERFACE

4.1 ACDM: Airport Collaborative Decision Making

4.1.1 ACDM

ACDM stands for Airport Collaborative Decision Making. This concept does only make sense if developed as a partnership involving all the intervening actors in order to improve airport performance. The idea that lies behind this concept consists in sharing all the available aeronautical information across the stakeholders in the airport processes (airports, airlines, air navigation service providers and ground handlers) so that all of them have a common perspective of the Air Traffic Management (ATM) and the airport operations.

ACDM emphasizes the need to take decisions in a cooperative manner so that a common awareness of the situation exists in order to maximize the efficiency and therefore capacity of the airports. This results not only in a win-win situation for all the players, but also for the passengers since it helps smoothing their journey. These players need to work together, sharing data in real time, in order to be more efficient and transparent. The final objective is that the appropriate information reaches the relevant agent with enough quality and in the precise moment. As a result, better decisions are made thanks to the more accurate and timely information. Ground operations need to be streamlined for this purpose, which eventually results in lower operational costs, less noise and lower CO_2 emissions.

Due to the ATM nature (network) decisions that appear to affect just locally may have further implications in other countries. A flight departure delayed in Madrid Barajas may cause trouble in London Gatwick to some extent, for instance, if the plane should be covering Barajas-Gatwick and then Gatwick-Malpensa (Milan) once the first flight is delayed the second one will most probably be delayed (or even cancelled) as well. That is the reason why ACDM seems to be a splendid tool to help solving upcoming problems through the streamlining of the predictability of event and utilization of resources. It allows to give a quick response to changes (delays, weather conditions, etc). The result is not just a local efficiency improvement, but an improvement of the network efficiency as a whole.

According to the EUROCONTROL manual [5] the goals of this method are:

- Improving foreseeability
- Improving punctuality
- Reducing the costs of the ground movements
- Optimizing the use of the ground handling resources
- Optimizing the use of the parking stands, boarding gates and terminals
- Optimizing the use of the airport infrastructures and reducing the congestion
- Reducing the waste of airport slots
- Allowing a more flexible planning prior to the flight
- Reducing the congestion on the aprons and taxiways

Not only a change of mentality regarding the way in which information is used and decisions are taken is needed in order to achieve all of these goals, but also the already mentioned agents need to possess certain abilities and/or infrastructures that allow them to make the ACDM concept possible.

There are some concepts that can be used with a different meaning at the international level, or even just at operator level. This represents a serious barrier in the understanding among the different parts, preventing fluid communication from happening. It is therefore vital to give a standardized meaning to the concepts so that the coordination becomes as easy as possible and without misunderstandings. EUROCONTROL has been in charge of laying the foundations for the successful implantation of the ACDM thanks to standardization. ACDM can be applied to different extents. Not every single airport needs to apply it to the same degree. Munich and Brussels were taken as pilot airports for its application. The situation back in 2011 can be observed in figure 4.1.

Figure 4.1: Map showing the level of implantation of the ACDM back in 2011.

4.1.2 WHY ACDM?

Currently, most countries are experimenting a global economical crisis, a situation which is clearly likely for the focus to be set on saving or spending as little money as possible. In the airport context this can be done by means of improving its performance, exactly what the ACDM proposes. These improvements can be achieved without making prominent capital investments. That is what I am working on in this project: on developing a rather non-expensive method to improve airport performance so as to increase airport capacity in not such a costly way.

As mentioned in [5], "the A-CDM concept is implemented in the airport environment through the introduction of a set of operational procedures and automated processes". That is a good reason why the current project is developed within the ACDM framework, as my main intention is to make the communication process between the ground handling operators and their managers more automated which is a manner in which airport performance can clearly be enhanced.

The basic communication concept that concerns ground handlers at airports is illustrated in figure 4.2. My idea is to extend the concept of collaborative management to each of the blocks present in the figure, and more specifically, I intend to make a simplification introducing automation in the ground handling block. This automation could be further applied to the rest of communications, but that is not the objective in this case.

Not only can ground handling management contribute to ACDM, but also it can benefit from it. As already mentioned, ACDM enhances foreseeability, which in the particular case of ground handling could mean that ground handling managers are able to anticipate the resources required by an arriving aircraft and mobilise them at the right time. Thanks to ACDM, ground handling can achieve punctuality improvement and lowering operational costs.

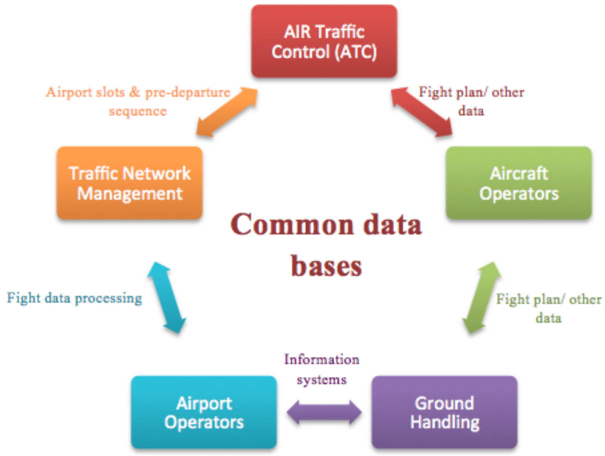


Figure 4.2: Data shared by ACDM players

4.2 PETRI NETS

4.2.1 HISTORICAL INTRODUCTION

Petri nets are a graphical and mathematical tool that can be used in a number of different fields where the knowledge about the events and simultaneous evolutions are of importance.

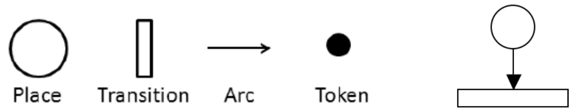
It is a relatively young theory which was born from the thesis that Carl Adam Petri defended back in 1962 (with "Kommunikation mit automaten" as its title). Petri was born in 1926 in Leipzig (Germany) and was a professor at Bonn University, where besides of lecturing he also lead numerous research studies always within the computing domain. The work developed by Petri seduced Anatol W. Holt, who promoted the creation of a research group at the Massachusetts Institute of Technology (MIT) which, between 1968 and 1976, established the basis of what are today known as Petri nets.

Petri nets have traditionally been used to model discrete systems, like *manufacturing processes* or *data communications*. Those were the most common applications of this tool until the 1990s, when biologists realized they could also use Petri nets to model *biological systems*. However, thanks to later developments, they won the ability to deal with continuous quantities as well. The use of Petri nets has become more and more widespread ever since. Some of their applications nowadays go from modelling the dynamics of a *railway system* to making a preliminary qualitative analysis of biopathways or modelling and biomedical profiling metabolic disorders, as mentioned in [20].

4.2.2 PETRI NET: DEFINITION

The formal definition of a Petri net consists of a 5 components tuple:

$$\langle \text{ P, T, A, W, } M_0 \rangle$$



(a) Place, transition, arc and token representation (b) Possible set-up

Figure 4.3: Petri nets basics

where:
P is a finite set of places
T is a finite set of transitions
A is a set of arcs
W : A $\rightarrow$ 1, 2, 3, ... is a weight function
M_0 : P $\rightarrow$ Z is the initial marking

A Petri net is also known as a place/transition net. It is a directed bipartite graph which counts with two different kinds of nodes. Some nodes represent transitions, while others represent places. The directed arcs describe which places are previous/posterior to each transition (according to the sense of the arrows). The arcs either go from a place to a transition or just the opposite, from a transition to a place. An arc never links a place with another place or a transition with another transition; it always links places with transitions and vice versa.

The places are represented by circumferences, the transitions by bars or boxes and the arcs by directed segments (arrows). This is illustrated in figure 4.3a, where we can also see that the tokens are represented by a black dot. They are contained in the places. Tokens do not really represent a physical entity (but at times, nevertheless, they may seem to). A token inside a place indicates that the place is active, that the conditions described by it are fulfilled.

Several places may be linked to the very same transition and several transitions can be linked to the same place as well. Also, a transition may have several output places and a place can be input to several transitions (which would be a non-deterministic problem).

In the graphs, arcs can be labelled indicating their weight (positive integer). An arc of weight k can be interpreted as a set of k parallel arcs. A place p is said to be an input place to a transition t if an arc is directed from p to t. Similarly, an output place of t is any place in the net with an incoming arc from transition t.

The tokens contained in the places travel through the net following different paths depending on the firing of the transitions. A place P_i is given a marking of a non-negative integer (r$\geq$0), and so it will be shown containing r tokens. A marking is defined as any distribution of tokens over the places of a net which represents a configuration of the net.

Figure 4.4 is presented in order to illustrate the above explained. In the example, place P1 is an input place to transition t1, while place P2 is an output place to t1. We can also notice that there is one token in P1, two tokens in P3 and no tokens in P2. The arcs are not labelled in this case, therefore we can suppose that there are no parallel arcs and so only one token can travel through it at a time. We can outline that in this case each transition has an only input place and an only output place. On the contrary, in figure 4.5 we notice that t1 has two input places and one output place, while t2 has two input places and three output places.

If a place contains a token it is considered as active. A place can contain more than one token at the same time, as can be observed in figures 4.4 and 4.6. An empty place P_i that is connected as input to transition t_j disables this transition from being executed. A transition is said to be enabled if and only if there are no empty places connected to it as inputs. A transition fires after being enabled and validated (explained later in this section) and the result of such firing is the removal of tokens from each of its input places and the appearance of tokens in each of its output places. In figure 4.5 t1 is not enabled since P2 does not contain a token. However, t2 is active thanks to both P3 and P4 containing tokens. Therefore, t2 can be fired. The result of firing t2 can be observed in figure 4.6, where a token has been removed from P3 and P4 in exchange of adding one to P1, P2 and P4. Now t1 is enabled, ready to be fired once validated.

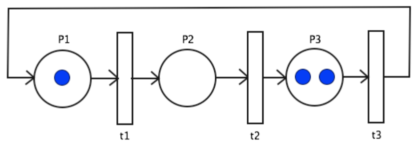


Figure 4.4: Example of a very simple Petri net

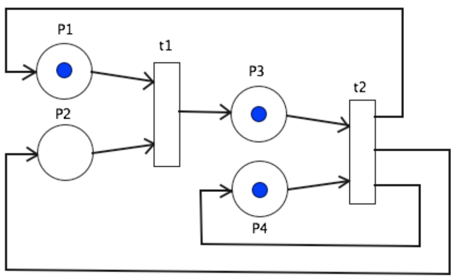


Figure 4.5: Example of a more complex Petri net than the one presented in figure 4.4

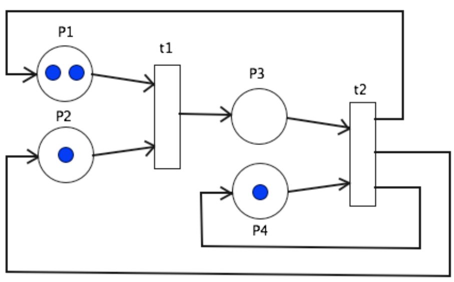


Figure 4.6: Resulting net after firing t2 in the net from figure 4.5

Places and transitions can be interpreted in different manners, depending on the context they are used at. In table 4.1 many of the most common modelling interpretations of places and transitions are presented. We will be using the interpretation from the first row. Our transitions represent events, which are actions that are executed by the system. The execution of an event depends on the system state, which is described through a set of conditions, which are modelled by places. The arcs connecting transitions and places represent the dependency among events and conditions. The verification of a condition is represented by adding a token to the place that models it.

Input places	Transitions	Output places
Preconditions	Event	Post conditions
Input data	Computation step	Output data
Input signals	Signal processor	Output signals
Resources needed	Task or job	Resources released
Conditions	Clause in logic	Conclusions
Buffers	Processor	Buffers

Table 4.1: Typical modelling interpretations of transitions and places

In order to better illustrate the interpretation of transitions and places in this work we can observe the very simple example from figure 4.7 together with the table 4.2 where the events/conditions that the transitions/places represent are explained. If we choose an event (waiter takes the order) we can see that the condition that it depends upon (clients get a table) obviously needs to be fulfilled previously.

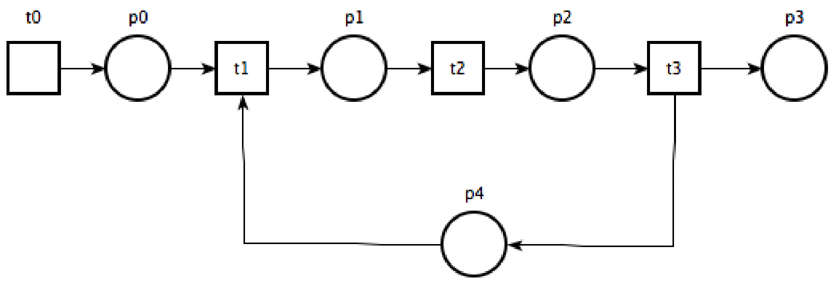


Figure 4.7: Example of how clients are served in a restaurant

The Petri nets have an initial state which is usually referred to as *initial marking*, and is labelled as M_0. For the example from figure 4.5 the initial marking is: M_0=[1,0,1,1]. The first component corresponds to place P1, the second to P2

Events (transitions)	Conditions (places)
t0 = clients arrival	p0 = clients wait for a table
t1 = waiter searches for free table	p1 = clients get a table
t2 = waiter takes the order	p2 = clients wait to be served
t3 = food is served	p3 = clients eat
	p4 = waiter is available

Table 4.2: Meaning of transitions and places in figure 4.7

and so on. The marking obtained after firing t2 (figure 4.6) would, as a result, be M_1=[2,1,0,1].

As already mentioned, events are associated to transitions. Those events are logic functions of the entry variables. When an event associated to a transition takes place (the logic function takes the value one), the transition is said to be validated. The marking varies when a transition is fired, as has already been proved. A transition needs to be enabled and validated so that it can be fired. When two transitions are enabled at the same time they can potentially cause a conflict.

4.2.3 ADVANTAGES OF THE PETRI NETS

There are different reasons that can be alleged to justify the use of Petri nets when modelling a system. Some of the reasons that match the use of them are listed below:

- Individual treatment of independent processes
- Parallel or concurrent processes
- Shared resources. Petri nets allow the modelling of systems where a certain resource is shared by two processes so that while the resource is being used in the execution of one of the processes it cannot be used by the other process. A shared resource is modelled by a place with an initial marking and transitions in conflict.

4.2.4 PETRI NETS PROPERTIES

Petri nets have a number of properties, but the four most important ones are: *reachability, liveness, boundedness and reversibility.* All of them are of vital importance for the analysis of any Petri net model. Liveness, boundedness and reversibility are completely independent properties.

- Reachability: a marking M_j is said to be reachable from marking M_i if a sequence of transitions exists that allows to go from state M_i to M_j. In the example from figure 4.5 we can certainly say that the already calculated M_1 is reachable from the chosen initial marking, M_0.

Figure 4.8: Coverability tree from the net presented in figure 4.5

The set of all possible markings that are reachable from M_0 is called the reachability set and is defined by R(M_0). The reachability set can be obtained from the coverability tree, which is later explained, but basically corresponds to illustrating the reachability set including the relation from one marking to another (transitions fired in each case). The coverability tree corresponding to the net from figure 4.5 is presented in figure 4.8.

- Liveness: a transition t is said to be live if for any marking M_i, reachable from a given M_0, there is a reachable marking which allows to fire t. A Petri net is said to be live if every and each of its transitions are live as well. Otherwise the Petri net cannot be live. A Petri net which is not live gets totally blocked.

  This property guarantees the absence of deadlocks in the Petri net. Furthermore, it also ensures that all the modelled processes may occur. Liveness, like reachability, can be observed in a coverability tree: if it contains an absorbent state (the token reaches a place that it cannot leave) then the net is not live in that state and it is said to have a deadlock. Once the net reaches a deadlock, it remains in it indefinitely.

  From figure 4.8 we can conclude that the Petri net that it corresponds to is a live one since given a possible marking, either M_0 or M_1, it is always possible to fire a transition (t_1 or t_2).

  If the net is not live for marking M_0 then at least one marking from R(M_0) does not have any enabled outgoing transitions.

- Boundedness: a place p is k-bounded for a marking M_0 if the number of tokens in p is not superior to a finite number k for any marking M_i belonging to R(M_0). A Petri net is k-bounded if the number of tokens in each of its places cannot be superior to a finite number k for any marking reachable from M_0.

  From the coverability tree in figure 4.8 we can conclude that the concerned net is 2-bounded for the given initial marking M_0=[1,0,1,1] as there is no possibility of having more than two tokens in any of the places.

  Also, a Petri net is structurally bounded if it is bounded for any initial marking M_0. A place is said to be safe if it is 1-bounded. A Petri net is safe (or binary) if all of its places are safe as well.

  Boundedness is a property of enormous interest since it guarantees that the number of reachable markings is finite. From a practical point of view, a k-bounded net can be implemented for a finite set of resources.

- Reversibility: a Petri net is reversible if for an initial marking M_0 there is a sequence of firing transitions that allows to return from any marking belonging to R(M_0) to M_0.

  Given the coverability tree from figure 4.8 we can conclude that the Petri net from figure 4.5 is reversible, since from the initial marking M_0 there is a sequence of firing transitions that allows to return to it. The sequence is t_2, t_1.

Other Petri net properties are:

- Conservativeness: a Petri net with an initial marking M_0 is said to be conservative if for any marking M_i belonging to R(M_0) the total number of tokens in the net remains constant. Conservation is related to the number of resources available, which cannot vary along the evolution of the processes in the Petri net.

- Persistence: a Petri net is said to be persistent if, for any two enabled transitions, the firing of one transition will not disable the other. A transition in a persistent net, once it is enabled, will stay enabled until it fires. Persistence is closely related to conflict-free nets.

  Two transitions t_i and t_j are said to be in effective conflict for M_0 provided the following conditions are fulfilled:

  1. there is a reachable marking belonging to R(M_0) which enables t_i and t_j at the same time
  2. when t_i (or t_j) is fired the marking which is reached does not enable t_j (or t_i).

  When two transitions are in effective conflict we can say that we have a non-deterministic problem.

4.2.5 WHY PETRI NETS?

The reason why we have chosen Petri nets as a tool for the modelling of our system is not a random one. Petri net modelling is known to be a very appropriate technique to describe the control applied to synchronous and concurrent behaviours. The Petri nets are formal models of information flows. Their concepts, properties and techniques were developed along the search for natural, simple and powerful methods to analyse and describe information flows and systems control. These characteristics match exactly with our idea in the present case, which is to model the information exchange along the ground handling operation so as to make it more automatic somehow.

We have a system where a single person (manager) needs to manage a whole fleet of vehicles, each of them performing their activity independently of each other. It seems reasonable to try and make the manager's workload lighter so that the system as a whole can become more efficient.

Through the Petri net modelling we are trying to automatize the communications between the operators of the vehicles and their manager. Substituting the voice communications by some visual warning would enhance the management of the fleet.

Also, the Petri net modelling allows us to visualise the logic of the process. We can understand better whatever is happening at each step and/or simultaneously. This is the most outstanding feature that the Petri nets provide us with in this case.

4.2.6 PETRI NET MODEL

First of all I would like to explain the work developed in order to design the model that is presented in the current thesis. The idea was to produce a model which being simple enough could be further developed so as to better represent the reality of the ground handling activities at the airports. My idea was to split the whole system into small parts that could later be integrated with the purpose of depicting the entire system in detail. The integration of those small parts should be made by means of the work developed by Dr. Fitouri-Trabelsi in her PhD dissertation [3].

In her dissertation she provides a structure to organize the ground handling management compatible with the ACDM concept, introducing the representative figure of the ground handling coordinator (GHC) which is considered as an interface for communications between the partners of the ACDM and the different ground handling managers (GHM). The relation GHC-GHM is the one that is concerned specifically in this project since that would be the way to integrate all the above mentioned small parts composing the big picture. In this case we are not taking into account the interactions between the ACDM partners (represented in figure 4.2): Air Traffic Control (ATC), aircraft operators (mainly airlines), ground handling management, air traffic network management and airport operations managers.

As explained in the Ground Handling chapter of this thesis, the ground handling is composed of many different activities. My main focus was to develop a model which would represent a single ground handling fleet of vehicles with a single manager, generically. If a manager administers more than one fleet the model would still be useful, independently from the tasks developed by each fleet being the same or different. This means that my concept for the modelling implies that the figure of the manager can be "linked" to as many Petri nets as he leads. In the end, each of the managers would be connected to the GHC. This is illustrated in figure 4.9), where N managers are linked to a coordinator and a number of Petri nets (PN) are linked to each of the N managers. The empty boxes simplify the scheme and represent other managers linked to different Petri nets (as many as vehicles there are in their fleets).

Each of the Petri nets represented in figure 4.9 correspond to the Petri net presented in figure 4.10, which is the Petri net that I eventually developed after detailed study of the ground handling system.

In the case of the places, the ones painted in red represent the different possible states of the vehicle from the beginning of the task until the end, when the manager needs to decide what to do with it. I have left place P_1 in black because I consider it a particular state, available in depot. It could also be coloured in red. All the

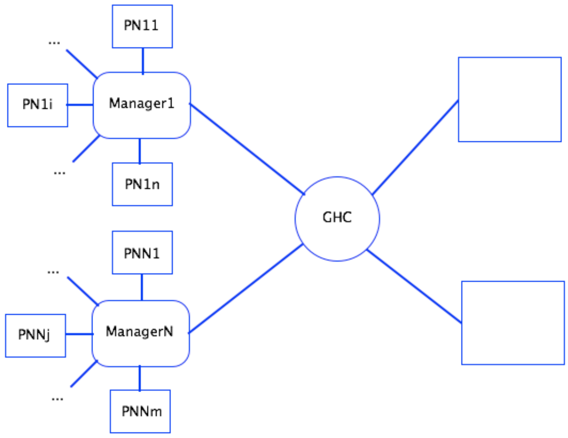


Figure 4.9: Scheme showing how the different ground handling managers are connected to an only ground handling coordinator (GHC)

already mentioned states can be reduced to three: available, busy and/or broken down. There are also two circles painted in purple. Those represent conditions that must be supposed to be always fulfilled: the aircraft must always be present so that the ground handling activities can be performed and the manager must always be present to coordinate the vehicles.

The different places P_i that appear on the Petri net are explained in the table 4.3. We can see in figure 4.10 that some of the places contain a token. That is the initial marking of the net.

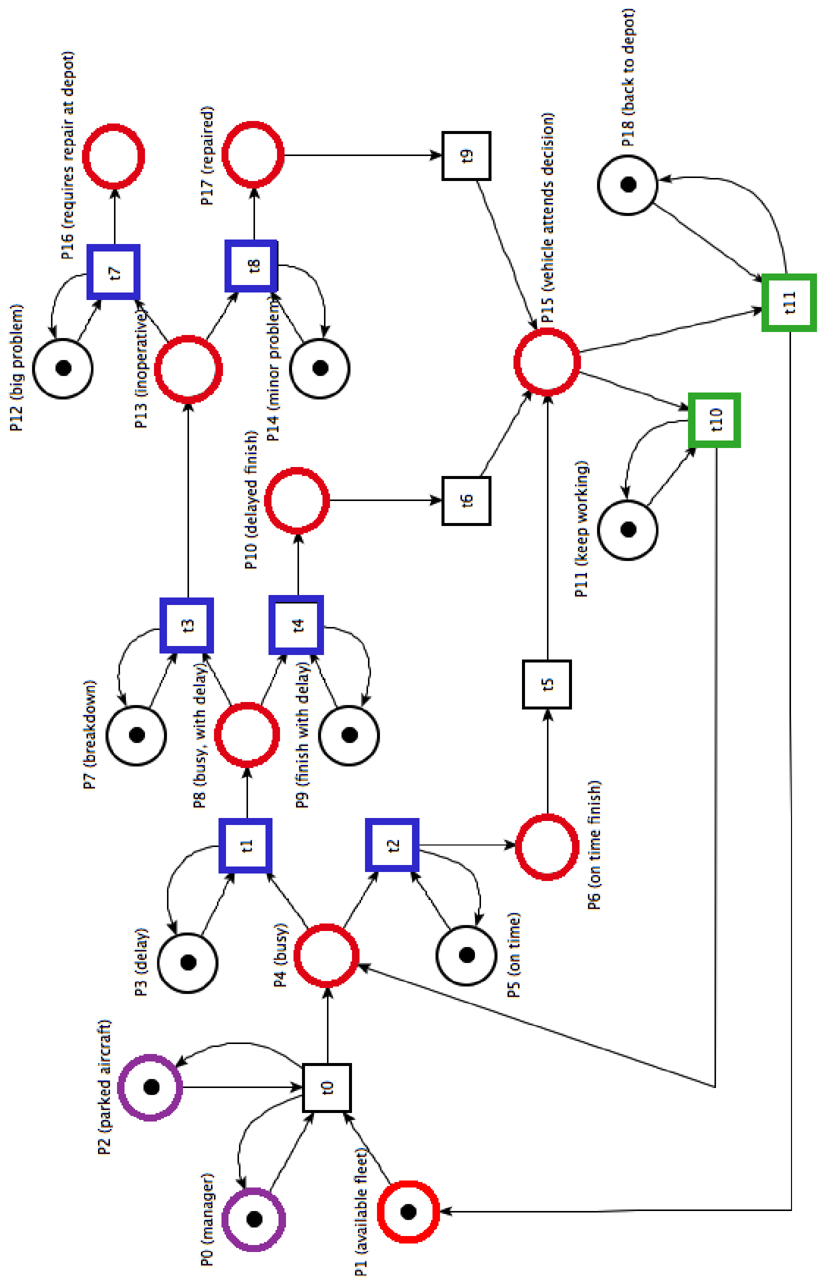


Figure 4.10: Petri net representing the system

Place	Description
P0	Manager
P1	Available vehicle at the depot
P2	Aircraft parked at the apron
P3	Task is taking more time than expected
P4	Vehicle is busy performing its task
P5	Task is taking the expected amount of time
P6	Vehicle has finished its task on time
P7	Vehicle has brokendown
P8	Vehicle performing task but already exceeded expected time
P9	Task will be done but finishing with a certain delay
P10	Vehicle has finished its task with some delay
P11	Manager sends vehicle to service another A/C directly
P12	Vehicle has suffered a major problem
P13	Vehicle is not operating for some reason
P14	Vehicle has suffered some minor problem
P15	Vehicle available waiting for manager to decide
P16	Vehicle needs to go back to the depot in order to get mended
P17	Vehicle repaired on site
P18	Manager sends available vehicle back to the depot

Table 4.3: Description of all the places from figure 4.10

In this Petri net the tokens move from one place to another and at some points they find a conflict since two different transitions are enabled. The way these conflicts should be solved is by a decision making process done either by the operator or by the manager, depending on the transition. The blue colour represents transitions which come into conflict with another and the operator is in charge of establishing the priority of one over the other depending on the situation. For the green ones the manager is the one who prioritizes the transitions. It is therefore noticeable that the conflicts appear at the following pairs of transitions: t_1 and t_2; t_3 and t_4; t_7 and t_8; and t_{10} and t_{11}, and only in the last case the manager makes the decision of which transition is actually fired; in the other cases it is the worker who selects the right option. The conflict between transitions t_7 and t_8 could be thought to be better decided on by the managers. However, I decided to leave the decision to the operators since I suppose they are the ones who have more information about the breakdown and should have enough knowledge about the vehicle so as to decide whether it is a major or a minor problem. As a matter of fact, in the case of the operator we are not truly speaking of a decision but more of reflecting the reality, the facts. The manager does decide, whether to send the available vehicle back to the depot or to send it directly to service a new aircraft.

In figure 4.10 we can see the manager represented. We must add that the Petri net only works for the communication of one vehicle operator with the fleet manager.

Transition	Description
t0	This transition allows the vehicle to pass from “available” to “busy” due to a decision made by the manager
t1	This transition allows the vehicle to stay busy after the due finish time, accumulating delay
t2	This transition is fired when the task is finished in due time, changing the state from “busy” to ‘on time finish”
t3	This transition allows the vehicle to pass from “busy with delay” to “inoperative” due to breakdown
t4	This transition is fired when the vehicle finishes its task with delay
t5	This transition is automatically fired after a vehicle finishes its task on time, allowing it to attend instructions from the manager
t6	This transition is automatically fired after a vehicle finishes its task with delay, allowing it to attend instructions from the manager
t7	This transition allows an “inoperative” vehicle to be sent back to the depot for repair due to major breakdown
t8	This transition allows the vehicle to pass from “inoperative” to “repaired”
t9	This transition is automatically fired after a vehicle is repaired, allowing it to attend instructions from the manager
t10	This transition, fired by the manager, allows a vehicle waiting for instructions to be sent to a new location, passing to “busy”
t11	This transition, fired by the manager, allows to send a vehicle which is waiting for instructions back to the depot

Table 4.4: Description of all the transitions from figure 4.10

Hence, and as I already mentioned, as a matter of fact the general scheme would have a single manager connected to as many Petri nets like the one in the figure as vehicles there are in his fleet.

The Petri net here presented was developed to be easily, intuitively understood. For that reason there could be some places and/or transitions that could seem to be redundant but which I have considered important to include in the model for the aforementioned reason. Those could definitely be deleted but that would make the understanding of the whole process more difficult by far.

In figures from 4.11 to 4.16 we can observe the evolution step by step of the Petri net from a moment when there is an available vehicle at the depot (figure 4.11) until it returns to the depot after performing the task that the manager assigned to it (figure 4.16). First, the manager decides to send the vehicle to work in a certain location (figure 4.12) but the operator does not manage to finish in time (figure 4.13). However, it does finish performing the assigned task with some delay (figure 4.14). Once it finishes it needs to wait for the manager to make a decision (figure 4.15) which in the end is to send it back to the depot.

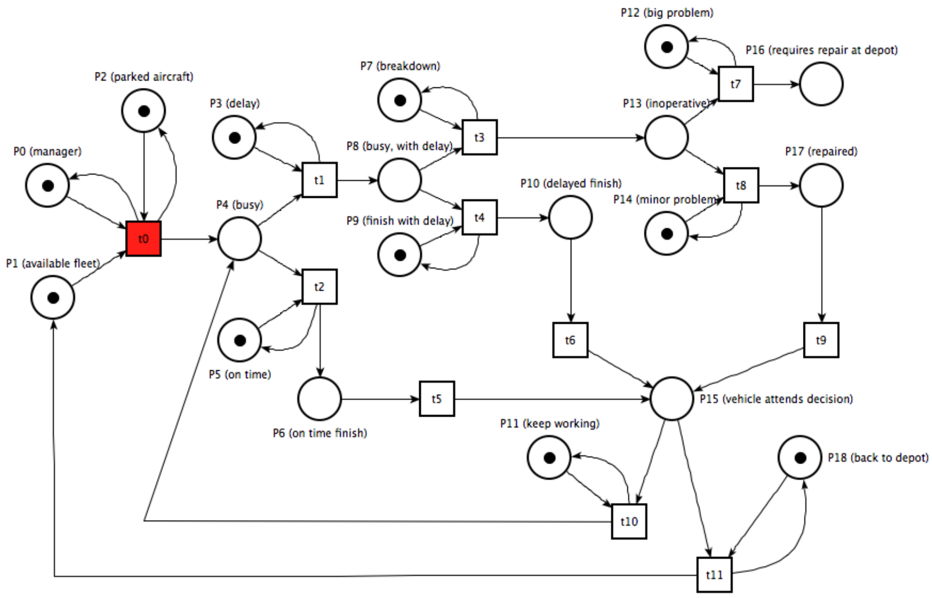


Figure 4.11: Vehicle available at the depot

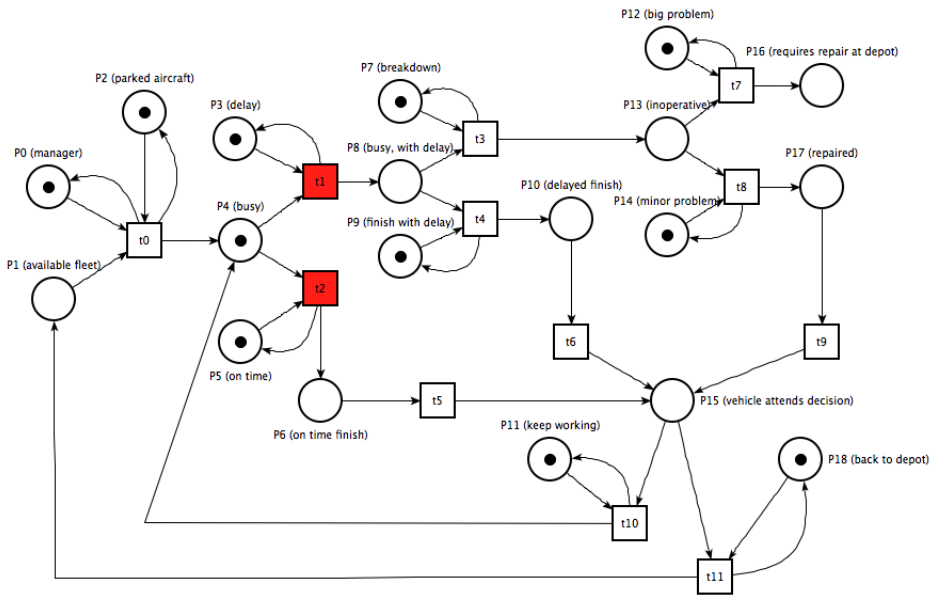


Figure 4.12: Vehicle at work

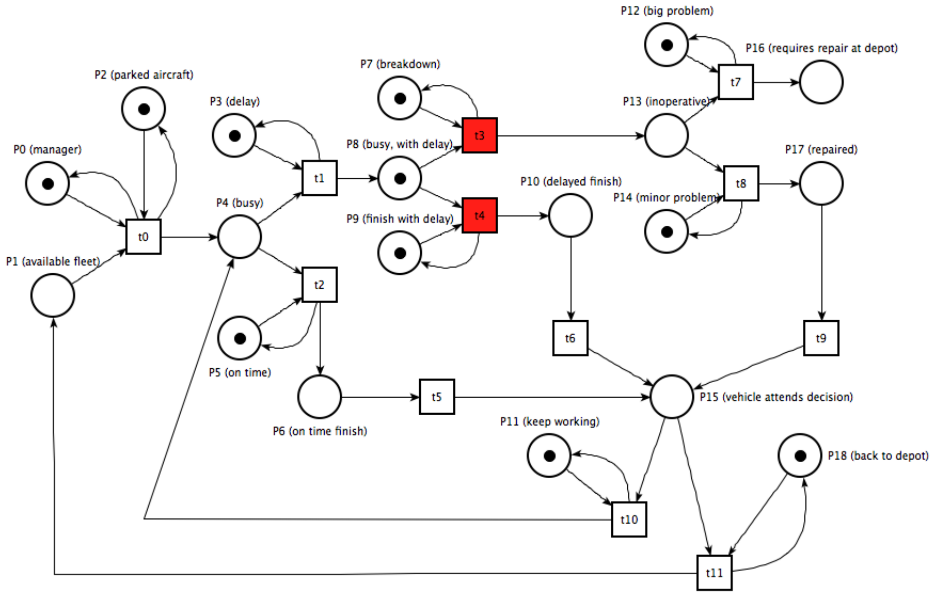


Figure 4.13: Vehicle busy, working with delay

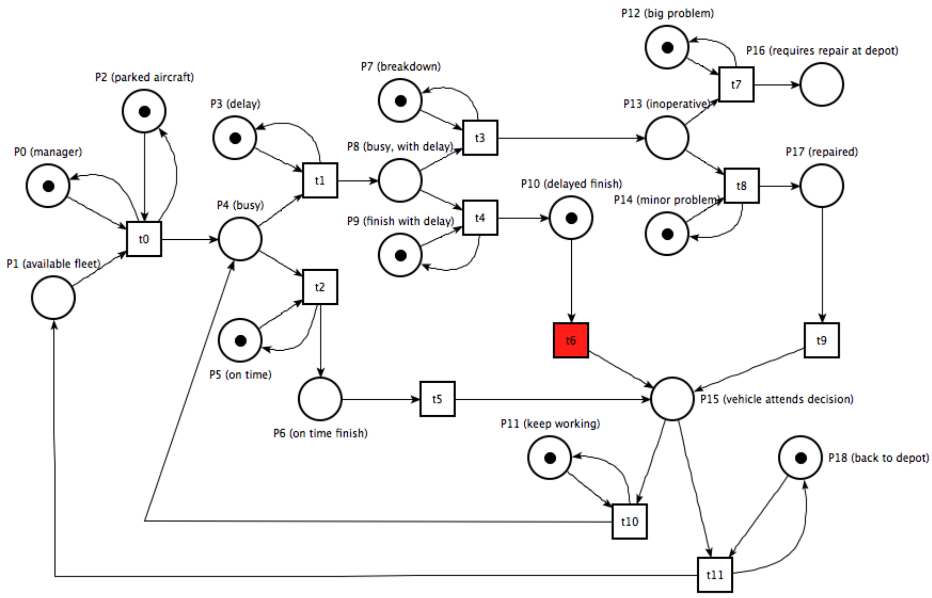


Figure 4.14: Work finished with some delay

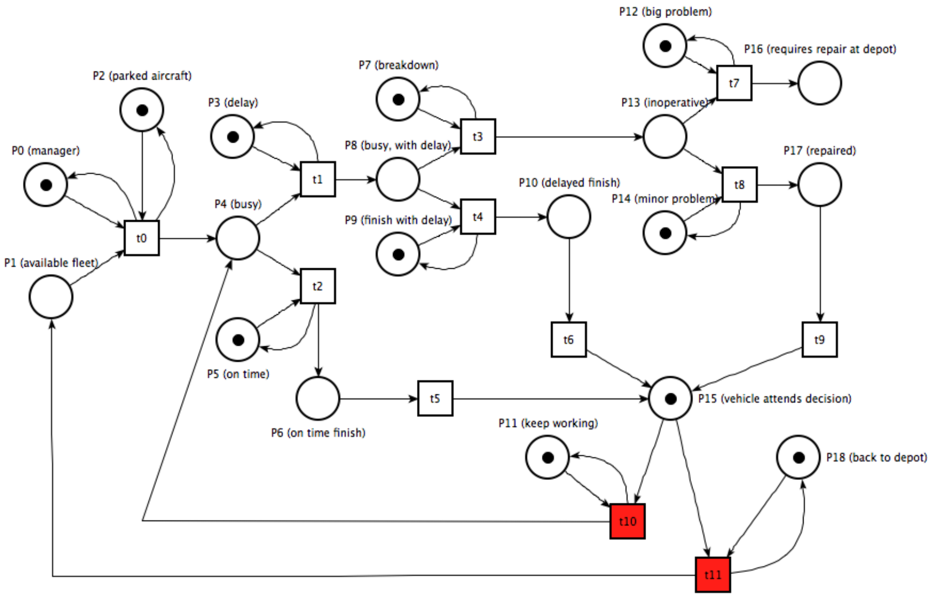


Figure 4.15: Vehicle waits for the manager to make a decision

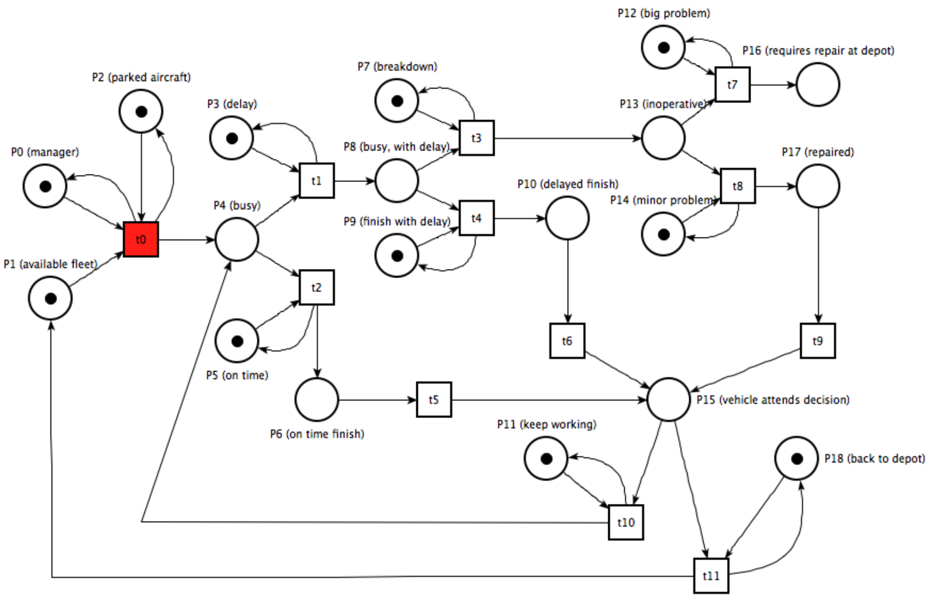


Figure 4.16: Vehicle back at the depot, available

4.2.7 VALIDATION OF THE MODEL

After exposing the proposed model we should validate it. The validation of a model consists in checking the properties of liveness, boundedness and reversibility on the net. For that purpose we are going to proceed to check them on our model, together with the reachability, which we need in order the check those other three.

The main Petri net analysis techniques are:

1. based on the coverability tree
2. based on the incidence matrix equations.

Apart from the validation shown in the next subsections I also performed some validations using a piece of software called TINA and obtaining the same results as the ones later presented in this document. TINA stands for "TIme petri Net Analyzer" and is a toolbox for the edition and analysis of Petri Nets. TINA has been developed by research groups of LAAS (Laboratoire d'Analyse et d'Architecture des Systèmes, France) and CNRS (Centre National de la Recherche Scientifique, France).

COVERABILITY TREE

The coverability tree of a Petri net represents the set of all the reachable markings from the initial state M_0. The representation of the tree is a graph, which actually resembles a real tree with its branches, in which each node is a reachable marking of the net and those nodes are connected by arcs with the transition that needs to be fired in order to evolve from one marking to another.

In order to obtain the tree we need to begin from M_0. From there we need to try the various possible options. So, in our net, for instance, from M_0 we can only fire t_0 as the first step, reaching marking M_1. However, after this first step there are two options, either firing t_1 or t_2. That means that from M_1 we can reach two different markings. If we proceed the same way until we cover all the options we obtain the tree.

The coverability tree analysis can be used to determine whether a certain Petri net is a valid representation of the modelled system, to verify the correctness of a design, to choose the best among different proposals or to predict the behaviour of a system.

In our case the obtained tree is shown in figure 4.17. The markings obtained from studying all the different possible options are presented in table 4.5 and are noted as M_i. Each of the marking vectors has 19 components. Each component represents a place from the network (P_i), for i=0,1,2...18. Each component is binary, can only take the values 0 or 1, where 0 means that there is no token in the concerned place and 1 just the opposite (token present). This is due to the fact that we are modelling the system for an only vehicle and for that reason one only condition can be met and just once at the time. It would not make sense to have two tokens in the same place indicating that the represented condition is fulfilled twice. Even though the token does not represent a physical entity it does relate very closely to a physical concept (the vehicle).

Designation	Marking
M_0	[1,1,1,1,0,1,0,1,0,1,0,1,1,0,1,0,0,0,1]
M_1	[1,0,1,1,1,1,0,1,0,1,0,1,1,0,1,0,0,0,1]
M_2	[1,0,1,1,0,1,0,1,1,1,0,1,1,0,1,0,0,0,1]
M_3	[1,0,1,1,0,1,0,1,0,1,0,1,1,1,1,0,0,0,1]
M_4	[1,0,1,1,0,1,0,1,0,1,0,1,1,0,1,0,1,0,1]
M_5	[1,0,1,1,0,1,0,1,0,1,0,1,1,0,1,0,0,1,1]
M_6	[1,0,1,1,0,1,0,1,0,1,0,1,1,0,1,1,0,0,1]
M_7	[1,0,1,1,0,1,0,1,0,1,1,1,1,0,1,0,0,0,1]
M_8	[1,0,1,1,0,1,1,1,0,1,0,1,1,0,1,0,0,0,1]

Table 4.5: Possible markings represented by vectors

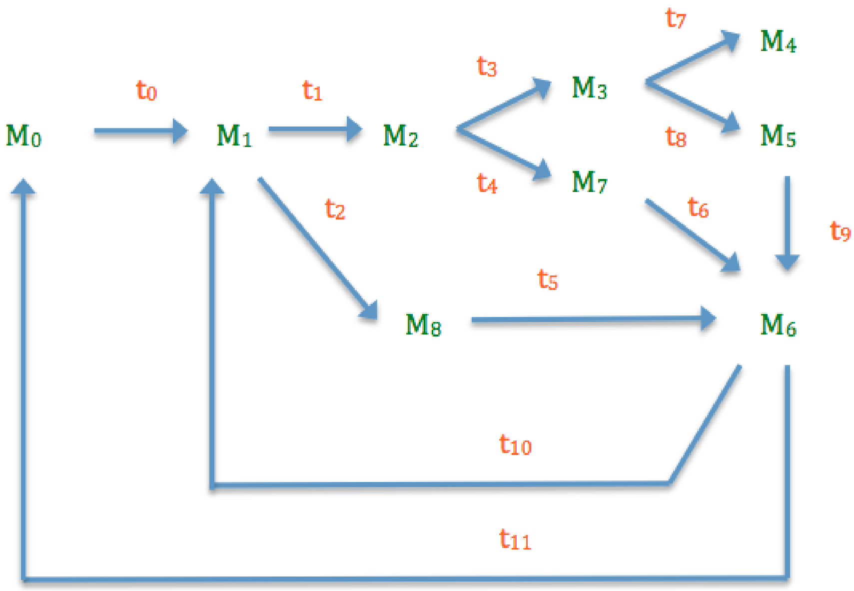


Figure 4.17: Marking tree

We should point out that there seems to be a deadlock in figure 4.17, when marking M_4 is reached. That is when the operating vehicle suffers a major breakdown and needs to go back to the depot and be mended. This is not actually a deadlock considering that after being repaired the vehicle will eventually continue operating. Then a token would be added to place P_1. The reason why it seems to be a deadlock is just because we have omitted the modelling of the repair. We can consider that after P_{16} there is a black box containing everything related to the repair and that black box is then linked to P_1. We need to bear this in mind for the following analysis of the properties of the net presented in figure 4.10.

I would like to clarify that the tree structure in figure 4.17 does not seem to resemble a real tree in this case, but as a matter of fact it does. The reason why it looks different is that whenever a repeated marking appears (already represented in the tree beforehand) the precedent marking is directly connected to the previously represented one instead of adding a new branch to the tree. This is also a proof that our tree is finite.

From the figure 4.17 we can conclude that the Petri net is live. It is easy to see that the net as a whole is live since all of the transitions are live too. We can check that from the definition that was previously provided of liveness. The structure of the net does not generate any deadlocks or dead parts. This means, for the ground handling case, that all the states represented in the net are actually attainable. The vehicle can well be busy or suffer a breakdown, for instance. No limitations in that sense.

We can also say that the Petri net is 1-bounded as there is one token maximum per place. It means, therefore, that it is a safe net. In our case this means that we have a net which is working for an only vehicle. A second token should never appear in the same place, for the net represents one vehicle, no more. Having more than one token would mean that the system is not working appropriately. This is a very important property in our case because we count with finite resources, so having a 1-bounded net is good proof of the model being correct in that sense.

The Petri net is reversible as well. Starting from the initial marking M_0 there is at least one sequence that allows to go back to the initial state (in the present case there are more than one). Actually it is reversible for any given marking M_i (for i=0,1,2,...,8) as we can always find a sequence of firing transitions that allows to return to that same marking. In the ground handling context, this means that we have a repetitive process. It is performed once and again, the same task, but every time on a different aircraft.

We can also check that the net is conservative, since for the given initial marking M_0, with 11 tokens, we can see that in all the markings from the reachability set the quantity of tokens remains constant, so 11. However, the net is not persistent as can be seen in markings M_1, M_2, M_3 and M_6 in figure 4.17. In the four cases two transitions are enabled but once one of them is fired the other one is no longer enabled.

INCIDENCE MATRIX

For the same purpose, analysing the net properties, we can find a matrix W (the incidence matrix) which can be used through the formula: $M_j = M_i + W * S$, where M_i is the marking that we take as a reference, S is the vector which represents the sequence of firing transitions and M_j is the resulting marking after firing the transitions. A Petri net with n places and m transitions is represented by two incidence matrices (W^+ and W^-) of m x n dimension which represent the connections among the net nodes. W^+ is known as the post incidence matrix and W^- as the pre incidence matrix.

The way to calculate the incidence matrix is: $W = W^+ - W^-$, where W^+ and W^- are matrices that can be calculated by representing transitions by columns and places by rows. Therefore their dimensions are 19×12, and those of W as well. The different spots in the W^+ and W^- matrices are filled in with a 0 or 1. In W^+ we choose a transition (t_i, i=0,1,2,...,11) and fill in its column by checking if it is connected forward to all the different places (P_j, j=0,1,2,...,18). If it is connected the spot takes the value 1; otherwise the value is 0. For matrix W^- we can proceed similarly only that we check backwards.

If we choose transition t_0, for instance, we can easily check that it is connected downstream to places P_0, P_2 and P_4, and upstream to P_0, P_1 and P_2. That means that the first column of the W^- matrix will be filled with zeros except for the first, second and third rows that will take value 1, while W^+ contains 1 in the first, third and fifth rows and the rest of the rows are also filled with zeros.

$$W^- = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$W^+ = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$W = W^{+} - W^{-} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Once calculated W we can check the different properties of the Petri nets by choosing different markings M_i and sequences of firing transitions S. This can easily be checked by making a simple programme on Matlab to add up and multiply vectors and matrices. The results are the same as those obtained using the coverability tree, as should be expected. As an example we can take one of the markings presented in table 4.5 randomly. If we choose M_7=[1,0,1,1,0,1,0,1,0,1,1,1,1,0,1,0,0,0,1] and a sequence of firing transitions S=[0,0,1,0,0,0,1,0,0,0,1,0], which would lead to marking M_8=[1,0,1,1,0,1,1,1,0,1,0,1,1,0,1,0,0,0,1] according to the coverability tree. This corresponds to the case of a vehicle that finishes its task with delay and after attending the instructions of its manager is sent to a new location where it finishes punctually. If we apply the previously given formula, $M_j = M_i + W * S$, we can check that indeed M_8 is obtained. That is the use of calculating W: calculating the resulting vector of applying a sequence of firing transitions to a given marking vector.

4.3 OPERATIONAL PROTOCOL

From the designed Petri net model we can figure out the communications required along the ground handling operation. However, the model should be complemented by an operational protocol which can set an standard for the manager on how to proceed to allot the available resources.

A flow chart is presented in figure 4.18. The flow chart corresponds to a situation where N aircraft are waiting to be serviced (the same task in every case or at least tasks with shared resources) and there are M vehicles available for that purpose. We are supposing that we have a vector t which has N components. Each of its components is the time left until the required task becomes “critical” for each of the N aircraft. The task becomes “critical” when there is just enough time left to perform all the remaining tasks before departure, with no extra time at all. Obtaining the t vector is relatively simple. The off-line schedule (theoretically designed beforehand, with no perturbations considered) is needed. In the off-line schedule the order in which the ground handling operations are performed is established. With the current time, departure time and the tasks durations it is easy to calculate t (we would obtain a different t depending on the moment along the ground handling operation chosen). The departure time minus the current time (duration of stopover left, in minutes) minus the total of minutes required to finish performing the remaining ground handling tasks is the time left until the concerned task becomes “critical”. Through the implementation of the algorithm schematically represented in the chart, the components of the t vector are arranged in descending order, in vector w. Once arranged, the aircraft from the M last components of w (unless M > N; then all the aircraft would be serviced) get serviced. Hence, the main idea is that the aircraft with less time left to have the ground handling operations done before departure need to be given priority.

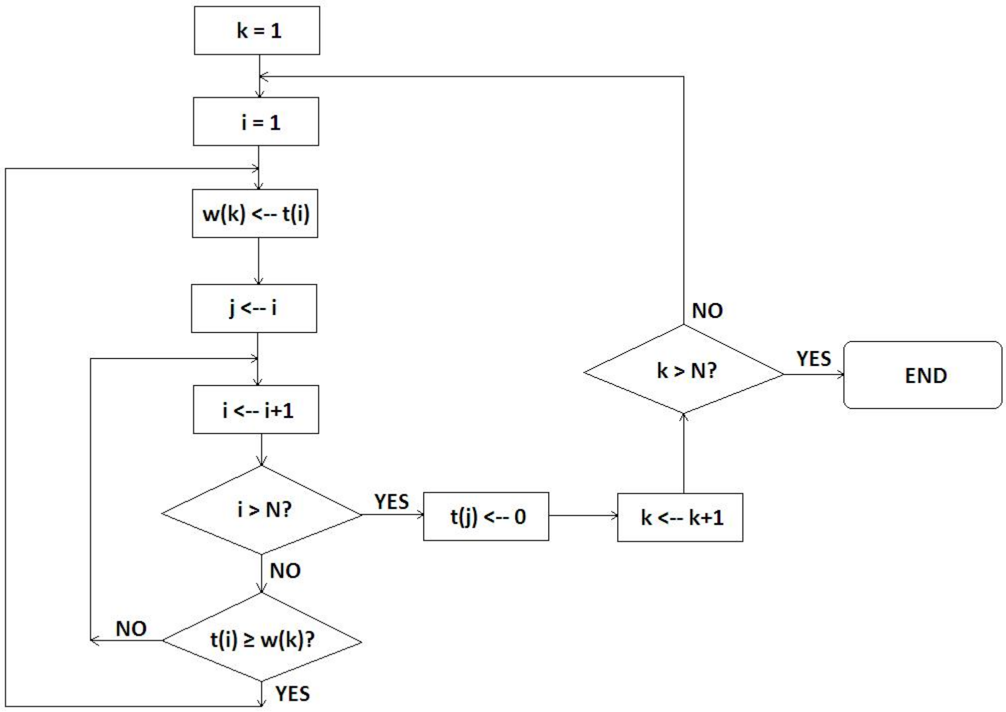


Figure 4.18: Flow chart

The results obtained from applying the flow chart are indicative, a mere guideline which does not need to be followed strictly. As a matter of fact, it is for the manager to evaluate whether the decision to be made is in the end in harmony with those results. It may be the case that having an only vehicle available and two aircraft waiting to be serviced, the manager decides to send the vehicle to the opposite vehicle to the one indicated by the results obtained from applying the chart. The reason to make such a decision could be, for instance, that the available vehicle is closer to the chosen aircraft and there is another vehicle about to finish its task which could service the other aircraft before exceeding the “critical” time for that one.

We shall give an example of application of the protocol, regarding the application of the algorithm from the flow chart. We can suppose we have two aircraft with equivalent characteristics (same duration of all the ground handling activities, shown in table 4.6). The first aircraft has 40 minutes left until departure, while the second one has 45. They both require the catering service and there is just one vehicle available. The first aircraft will have the priority since the catering and fueling activities need to be performed before the boarding, and that adds up to 30 minutes, which means that obviously the first aircraft is closer to its critical time to start the catering service.

Activity	Duration (min)
Deboarding	15
Sanitation	5
Cleaning	10
Unloading	15
Water	5
Catering	5
Fueling	10
Loading	20
Boarding	20

Table 4.6: Hypothetical durations of ground handling activities

However, the manager can decide to send the vehicle to the second aircraft at their discretion. That could be done if the vehicle is closer to the second aircraft and there could be another vehicle servicing the first one within less than 10 minutes. We can suppose that aircraft 1 is in parking stand A, aircraft 2 in stand B, the available vehicle at the depot and a vehicle about to finish its task in stand C. From table 4.7 we can observe that if the available vehicle is sent to stand B and the other one (when it finishes) to stand A the total distance covered by them will be lower than if we follow the results from the flow chart in figure 4.18. In this case, the manager could choose the option they find the most appropriate, which seems to be the one exposed in this paragraph.

Related positions	Path length (m)
Stand A - Depot	1500
Stand B - Depot	1300
Stand A - Stand C	100
Stand B - Stand C	500

Table 4.7: Hypothetical distances among different positions

4.4 VISUAL INTERFACE FOR THE MANAGERS

After developing the Petri net model, I found that the idea could be complemented with a visual interface so as to make the manager's work easier. Presenting the information visually can be of great help for someone who needs to coordinate a number of vehicles. Since the concept presented in this project basically consists in improving the communication between the manager and the operators, allowing the manager to be aware of the status and position of each of the vehicles he coordinates just by monitoring those variables in a screen seems to be a very important development. Through the use of this interface the manager would also be able to send messages to the operators, in order to indicate where they should be headed for after they finish their tasks.

Mainly, I have tried to capture the spirit of the states shown in the Petri net (the three states to which we can reduce all of them). In the net, there are different points where a non-deterministic problem arises. Firing either t1 or t2, t3 or t4, t7 or t8, or t10 or t11 is a non-deterministic problem, as any of the transitions from those pairs could be fired. In those places, either the concerned operator or the manager (already explained before) needs to take a decision on which transition should be fired next. In the interface, this decision is reflected in the choice they make through the interface.

The interface has two different layouts, one for the operators and another one for the manager. In the case of the operators, they can choose to vary their position and working status instantaneously. That way the manager can be up-to-date with the situation of the fleet. The operators can also receive instructions from their managers through the interface. On the other hand, the managers can use their interface to monitor the position and status of each of the vehicle they coordinate, while they can also decide what to do next with the vehicles that have finished working, either send them to a new location or send them back to the depot. In the managers' interface each of the vehicles appears on a new line, and the information is presented in columns, just like in the workers' interface. The status and position can be changed by means of a pull-down menu, where all the predetermined status and positions are presented. However, when the manager wants to send instructions to an operator a chat window appears and the message he sends is displayed in the operator's interface.

The first approach to the application of the above described concept is to create a web page that would only be accessible from a computer connected to an internal network provided by the company itself. Each one of the users (managers and operators) would be able to sign in with a personal username and password. When the operators enter the site a picture of themselves is shown as well as their personal details, which he can of course modify. They can update their status any time so as to keep their managers informed. The managers are able to make decisions at once and communicate them to the operators.

In the case that one manager coordinates vehicles which perform different tasks those tasks should be clearly presented to the manager in the interface too. In some cases one vehicle can be used for different purposes and for that reason the operator needs to be able to change the task by means of the interface.

The web page has been developed in *Joomla*, which is free and open-source. Joomla is a content management system (CMS), which allows to build web sites and powerful on-line applications without much knowledge of scientific programming. A content management system is a piece of software that keeps track of every piece of content published in a certain website. It is possible to include document texts, photos, images, etc. A major advantage of using a CMS is that it requires almost no technical skill or knowledge to manage. Since the CMS manages all the content, you do not have to do so. I have selected this piece of software because it is powerful and, in addition, it is an open-source solution that is freely available to everyone.

The platform can be downloaded in any machine from their official website: **http://www.joomla.org**

Once installed in the computer that will be used as server machine, many extensions are available to cover all the special applications for any web page. For the application we are interested in, I found that the extension called *Fabrik* is the best. Fabrik allows to create beautiful forms to allow different users to enter data, then display the data in lists, map, calendars, timelines, charts etc. This extension is also free and can be downloaded from their official page: **http://fabrikar.com/**

Using Joomla with the Fabrik extension I have developed a website corresponding to the needs of the ground handling fleet management. First of all, so as to start using the application the users need to log in and for that purpose they have a username and password. The front end to the application is shown in figure 4.19.

In figure 4.20 we can observe the information that the managers have access to once they log in. In the main window a list of all the operators is presented, together with their status and location as well as the last message sent by the manager to them. Each of the operators have an identification code and if the manager clicks on them he has access to their picture and some personal data, as shown in figure 4.21. If the manager ticks the box at the end of a line he can choose the edit option and send a message to the chosen operator, usually in order to provide him with the details about how to proceed. The edit menu is shown in figure 4.22.

In figure 4.23, on the other hand, the view a certain operator would have is presented. An operator can just see its own information and can proceed similarly to the manager in order to edit his status and location. Hence, the edit menu they have access to is basically the same one but, however, they can edit different options.

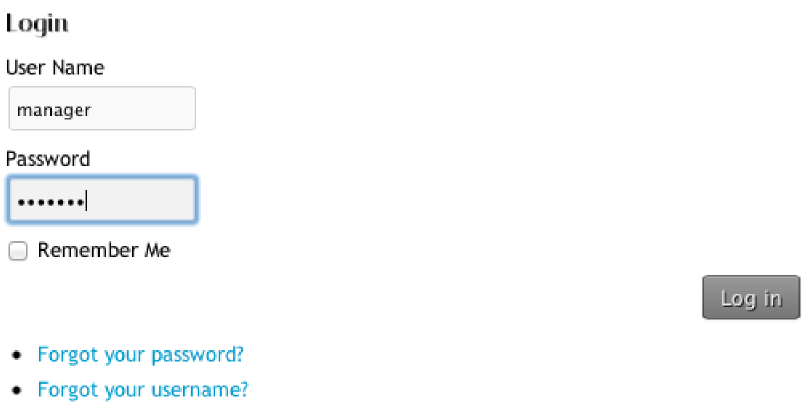


Figure 4.19: Log in, front end

date time	Worker ID	LOCATION	STATUS	ORDER	
2014-01-27	ID-1	site 2	Broken down	Return to depot for repair	
2014-01-27	ID-2	site 1	Available	Go to gate 3	

Figure 4.20: What the manager sees once he enters the application

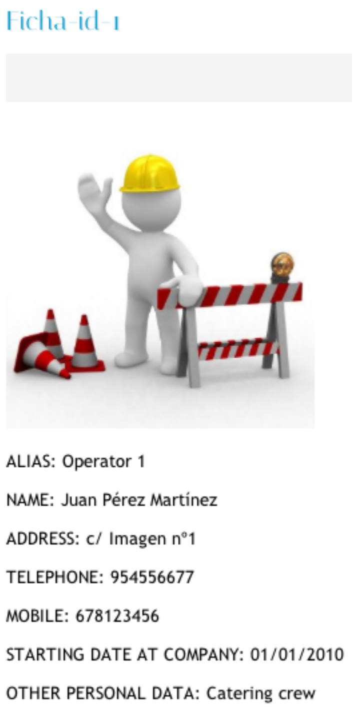


Figure 4.21: Operator information on display for a certain identification code

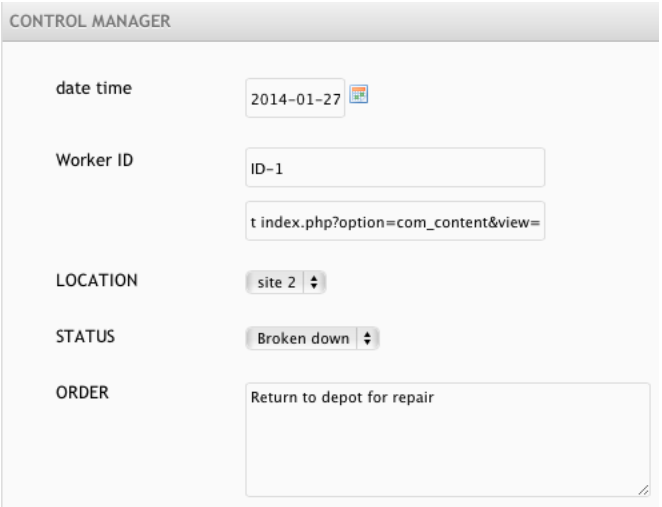


Figure 4.22: Edit menu accessible to the users

date time	Worker ID	LOCATION	STATUS	ORDER	
2014-01-27	ID-1	site 2	Broken down	Return to depot for repair	

Figure 4.23: What an operator sees when connected to the application

Chapter 5

CONCLUSIONS AND FURTHER RESEARCH

5.1 CONCLUSIONS

Ground handling is known to be one of the most important sources of delays at the airports nowadays. However, it was not until quite recent times that this fact was acknowledged. For this reason not many thorough studies have been developed in this area that is only becoming much more popular at present.

The innovation that I decided to introduce in this case was making use of a tool called Petri net which has not been widely used for this purpose so far at all. It seems reasonable to tackle the congestion problem that started to arise in many airports worldwide along the last decades of the 20^{th} century and the beginning of the 21^{th} century this way, since it does not involve high investments and can be easily implemented.

Along my study of the ground handling activities I developed different Petri nets and eventually chose the best option which is the one presented in this work in chapter 4. It is a simple net, easy to understand intuitively, which contains information about the status of the ground handling operator and allows to follow its evolution along time without any efforts. The decision making steps can also be identified at the moments when a non-deterministic problem appears. In the end, we can resume the virtues of Petri net modelling in this case saying that it makes the communication process between manager and operator simpler, quicker and more automatic.

As a matter of fact, the net I have hereby presented is of course based on a number of hypothesis which have helped me simplify the ground handling problem to a great extent. I decided to make the problem as simple and general as possible. This means that my net could be applied to any managers, independently of the tasks their fleet perform or how many vehicles it is composed of, for instance. In general we will assume that an only operator is represented in each net, and therefore it is not difficult to figure out that we can connect a several Petri nets to a single manager, of course.

Apart from presenting a Petri net I also proceeded to its validation. For that purpose I checked, both by computer simulations and by hand, that all of the main properties of the Petri nets were present in my net. I can affirm that the net is lively, reversible and bounded, and all of the states are accessible from the initial marking.

In order to illustrate the idea that lies behind Petri net modelling I chose to develop a conceptual model of a visual interface that would be based on the Petri net. The visual interface allows the managers to keep track of the operators from the fleet they coordinate as well as sending messages to them making so as to provide them with the instructions on what to do. The operators can change their location and status via the application, and that is how they keep the managers up to date. As the operators set their status and/or the managers send their messages the above mentioned non-deterministic problem has been solved by the person who needs to take the decision in each case.

5.2 FURTHER RESEARCH

The current work leads to various new research paths which could help reaching a still more efficient and inexpensive operational procedure thanks to improved communication techniques or through the introduction of new, currently non-existent, features.

Firstly, instead of using normal standard Petri nets, timed Petri nets could be more advantageous since they would allow observing whether the activities in progress are accomplished correctly in an acceptable time range. That would definitely allow checking the quality of the ground handling service, which is what is of our interest in the end.

Secondly, the interpretation of the problem here presented is a very simplified one. Further developments should be made considering a wider range of options, going from a very specific situation to the most general possible. In the current thesis the simple problem presented corresponds to a ground handling fleet which is in charge of an only activity and is managed by a single person. We should eventually consider the case of fleets which work on different tasks at different points of time and several managers that need to interact with each other, for instance.

Thirdly, the conceptual design of the visual interface proposed is a basic idea and could easily be improved. The use of GPS to locate each of the fleet vehicles in order to represent the location on a display for the manager to control them would surely be highly advantageous and not necessarily costly. Also, the interface could be developed in more detail broadening the possibilities for the manager. If the manager controls more than one different type of activity at the same time it would be beneficial to be able to choose which activity should be shown on screen and then be able to see the resources to be controlled.

And last but not least, I find that making possible to do a statistical control of the ground handling activities could help finding out where the most delaying issues arise and then they could be tackled more easily. Duration of each activity according to the aircraft model, displacement duration from depot to the different parking stands or among them, or time lapse from breakdown until repair could be some of the parameters to be measured and later analysed.

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