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Decision-support methodology to manage the efficiency of ground movements in a critical environment

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Resumo

Em ambientes complexos, como é o caso de um aeroporto, os controladores devem ser continuamente informados sobre as operações que estão a decorrer. Este facto requer a implementação de um mecanismo de controle capaz de dar suporte, em tempo-real e de forma eficiente, à gestão dos movimentos que ocorrem no solo. Hoje em dia, os avanços tecnológicos já permitem a implementação de diferentes níveis de serviços baseados na localização por forma a assegurar a segurança e eficiência dos movimentos no solo do aeroporto independentemente do fluxo de trânsito, do nível de visibilidade e da complexidade do espaço aeroportuário. No entanto, a maioria dos aeroportos modernos ainda sofrem determinadas ineficiências operacionais nas situações mais complexas (por exemplo nas horas de ponta e em condições meteorológicas adversas), causadas pela organização ineficiente dos sistemas e recursos envolvidos, levando por sua vez a uma gestão deficiente do aeroporto, o que compromete o nível de segurança exigido. Por forma a resolver este problema, esta tese apresenta uma análise detalhada sobre uma metodologia que implementa os níveis de encaminhamento e guiamento especificados no conceito A-SMGCS, definido pela ICAO e o EUROCONTROL. Esta análise inclui a implementação da metodologia proposta com dados de tráfego do aeroporto de Lisboa, assim como a apresentação de um algoritmo capaz de lidar dinamicamente com os conflitos entre os movimentos e os desvios das rotas que foram atribuídas a cada avião.

Palavras-chave: A-SMGCS, Serviços baseados na localização, Encaminhamento, Guiamento, Problema do caminho mais curto.

Abstract

In complex environments, as it is the case of an airport, decision-makers need to be continuously informed about ongoing operations. Such service requires the implementation of a control mechanism capable of providing an effective support at managing traffic ground movements in real-time. Nowadays, technology became available for the implementation of different levels of location-based services aiming to ensure the safety and efficiency of airport surface movements under all circumstances with respect to traffic density, visibility and complexity of the airport layout. However, the majority of modern airports still allow a set of operational inefficiencies in extreme situations (e.g. rush hours, bad meteorological conditions) caused by an inefficient orchestration of all the intervenient systems and resources, leading in turn to a dysfunction of the airport that compromises the required level of safety. In order to address this problem, this thesis presents an in-depth analysis of a methodology that implements the routing and guidance requirements specified by the A-SMGCS concept defined by ICAO and EUROCONTROL. This includes the analysis and discussion of a site test implementation of the proposed methodology with traffic data from the Lisbon airport, in addition to an algorithm to dynamically deal with conflicts and deviations from assigned routes.

Keywords: A-SMGCS, Location-based services, Routing, Guidance, Shortest path problem.

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Acronyms

AAS Integrated Airport Apron Safety Fleet Management

AIRNET Airport Network for Mobiles Surveillance and Alerting

ADS-B Automatic Dependent Surveillance Broadcast

A-GPS Assisted-GPS

AoA Angle of Arrival

AP Access Point

A-SMGCS Advanced Surface Movement Guidance and Control System

ASR Approach Surveillance Radar

ATC Air Traffic Control

ATCO Air Traffic Controller

ATGS Advanced Taxiway Guidance System

ATM Air Traffic Management

ATOPS A-SMGCS Testing of Operational Procedures by Simulation

AVOL Aerodrome Visibility Operational Level

BS Base Station

CDMA Code Division Multiple Access

CTPN Colored Timed Petri Net

DB Database

D-GPS Differential-GPS

EGNOS Geostationary Navigation Overlay Service

EMMA European Airport Movement Management by A-SMGCS

EUROCONTROL European Organization for the Safety of Air Navigation

FAA Federal Aviation Administration

ICAO International Civil Aviation Organization

I&D Investigation and Development

ITS Intelligent Transportation Systems

GHMI Ground Human Machine Interface

GIS Geographic Information Systems

GLONASS Global Navigation Satellite System

GNSS Global Navigation Satellite Systems

GPRS General Packet Radio Service

GPS Global Positioning System

GSM Global System for Mobile Communications

HMI Human Machine Interface

HSGPS High Sensitivity GPS

LBS Location Based Services

LEONARDO Linking Existing ON ground, ARrival and Departure Operations

LVO Low Visibility Operations

MILP Mixed-Integer Linear Programming

MLAT Multilateration

NAS National Airspace System

NAVSTAR Navigation Satellite Timing and Ranging

NVO Normal Visibility Operations

OBU On-Board Unit

OGC Open Geospatial Consortium

R&D Research and Development

RIMCAS Runway Incursion Monitoring Collision Avoidance System

RFID Radio Frequency Identification

RTLS Real Time Locating Systems

RTT Round-Trip Time

RWY Runways

SAMS SMGCS Airport Movement Simulator

SBSS Surveillance and Broadcast Services System

SMR Surface Movement Radar

SSR Secondary Surveillance Radar

TDOA Time Difference of Arrival

TETRA Terrestrial Trunked Radio

TWY Taxiways

UAT Universal Access Transceiver

UML Unified Modeling Language

WGS World Geodetic System

WiMAX Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

XML Extensible Markup Language

Chapter 1

Introduction

This chapter introduces the problem of the dynamic management of traffic movements in critical environments, where the likelihood of incidents must be maintained as low as possible. The compliance with a set of business rules must be guaranteed by the continuous monitoring of ongoing operations, triggering an alert whenever a safety hazard is detected. However, existing safety management procedures do not allow controllers to efficiently coordinate and schedule operational tasks, for instance in airports. This thesis proposes a methodology that intends to contribute to this problem by providing decision-support tools that will increase the airport capacity by avoiding delays and minimizing conflicts, while reducing the workload of airport stakeholders.

1.1 Motivation and problem statement

With the advent of wireless technologies and embedded systems, a large number of complex environments adopted a network of sensors as an innovative monitoring and alerting system. It is the case of ports and airports, where ships and aircrafts, respectively, have to comply with a set of safety and security procedures to move along predefined pathways within a restricted area [1]. Such movements are performed under the supervision of specialized controllers and have to follow strict business rules to avoid conflicts among moving objects within the monitored area. The non-compliance of these rules might lead to unexpected emergency situations, compromising the safety of operations. For instance, two boats with containers sailing towards each other should trigger an alert, specially if they carry flammable products. In airports, a similar situation may occur if there is a lack of coordination between an aircraft and a vehicle. These situations have to be dealt in a responsive manner, aiming to avoid conflicts between uncoordinated and concurrent movements.

Airports are considered as very large, dynamic and complex systems that have to deal with emergency situations that must be resolved as soon as possible. There is a need of a permanent surveillance of ongoing operations in order to report every single incident to safety managers. The major challenge is to efficiently detect infringements, providing a reliable situational awareness to ATCOs, which are responsible to manage the ground movements within the airside of an airport. This thesis mainly focus on airport surface movements, where 82% of the accidents occur. This percentage is very high, considering that only 18% of the flight time is spent taxiing on the ground [2].

In an airport, the movement area is composed by a manoeuvring area and a restricted area called apron. The manoeuvring area is used by aircrafts to take-off, land or travel along their path. The runway is the track where the aircraft takes-off and lands, surrounded by a protection area for safety purposes. On the other hand, the apron is the area of the airport that enables the loading of passengers, the maintenance and parking of aircrafts or other ground handling activities. The apron is the heart of the operational area of the airport, organized by a set of taxiways and roadways used by aircrafts and airport vehicles, respectively. Within the apron area, aircrafts and vehicles are the main monitored targets that must be coordinated in order to efficiently manage their movements. Aircrafts have to follow a route from the runway to the gate (or vice versa), while vehicles are used to provide support to the aircraft (e.g. push-back). Thus, there is a need to guide the aircraft along the route, while considering the location of other moving objects. This guidance mechanism will improve the turnaround process, which corresponds to the lifecycle of the aircraft since it arrives until it leaves the aerodrome [3].

Along the last decades, the growth of air traffic caused an increase of the workload of both field and control personnel, which have to manage and coordinate all the ground movements to achieve tied schedules. Such complexity leads to the lack of resources and very often the pressure imposed by airline companies causes safety breaches, in particular those derived from human error [4]. In such stressing environments, surface operations mostly rely on the principle "see and be seen" to maintain a safety spacing when trailing another target or even to identify intersections. Furthermore, visual and voice aids enable pilots and vehicle drivers to follow their assigned route, becoming responsible for avoiding conflicts. However, relying on visual observations becomes complex and often misleading, particularly at rush hours when many operations must be managed simultaneously, sometimes under low visibility conditions [5].

Furthermore, the management of the involved organizations is performed independently, without having a collaborative view of ongoing operations. Such lack of coordination leads to a limited knowledge about the current traffic situation, preventing a proactive contribution from stakeholders (e.g. ATCO, handling agents supervisors, pilots, vehicle drivers) involved in the decision-making process [6]. Consequently, incidents are difficult to identify, as well as the field worker responsible for it. At the same time, stakeholders are not aware about the positioning of each field worker due to absence of electronic monitoring means in some moving objects. This lack of efficiency may increase the likelihood of congestions and consequently the number of incidents.

Existing safety management procedures do not allow stakeholders to timely make efficient decisions to business service demands. Therefore, recent technological advances in mobile computing are to be considered in the surveillance of moving objects through location based services by providing solutions capable to overcome operational constraints [7]. In this context, the airport layout is represented in a map-based display with the spatial context and a set of metadata associated, representative of the operational business rules. Such environment requires the ability of a GIS engine to correlate spatial information with operational rules, while representing continuous positioning data about moving aircrafts and vehicles that are equipped with a location device [8].

Moreover, the congestion resulting from increasing flows of traffic is reducing airports capacity. This problem affects both the economy, reducing the turnaround efficiency, and the environment, with emissions polluting the air. The congestion also affects the workload of each stakeholder, probably increasing the occurrence of safety hazards. All these factors contribute to the need of developing automated tools to control ground movements more efficiently, while releasing controllers workload [9].

1.2 Location based services

In complex environments, there is a real-time requirement in continuously monitoring moving objects, where services are dependent on the location of each one. LBS is defined by the international OGC as a "wireless-IP service that uses geographic information to serve a mobile user". In other words, LBS is the service requested by a user located in a given geographic position at a certain point in time. For instance, the guidance of a moving vehicle or the detection of a conflict requires the continuous tracking of the movement, while considering the current traffic situation and other parameters such as the pretended destination, circulation direction and current speed. These services are supported by the interaction between a set of components that form a network infrastructure, which is represented in Figure 1.1. This network is the support to the interaction and communication among the involved entities, which share the required information to provide location-based services [10].

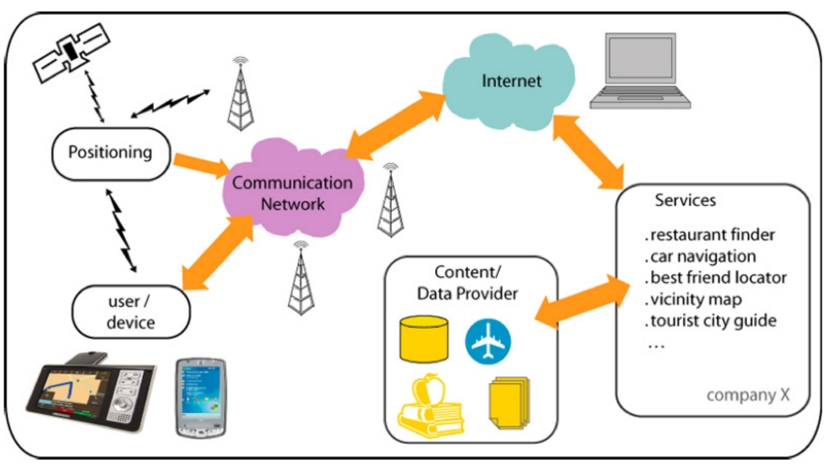


Figure 1.1: LBS components and their interaction [10].

As represented in Figure 1.1, the typical flow of information passes by gathering the real-time position of every moving object through location technologies, which are sent to the central control unit through wireless communication networks over the Internet. The Services and Content/Data Providers are then responsible to process the service request and return the requested information to the user. The main LBS components are described in more detail below:

- **Positioning:** Technology (e.g. GPS) that calculates the precise location of moving objects.
- **Mobile Device:** OBU installed in mobiles that communicates with the service provider through the wireless communication network. The required information is often related to the real-time position of the target, its speed and movement direction, or even the driver identification.
- **Wireless Communication Network:** Network that provides a link between the mobile device and the service provider through wireless communication technologies (e.g. Wi-Fi).
- **Service Provider:** Server that collects location data from the mobile devices. The data is verified in order to guarantee its reliability and is then processed and converted into a standard format, to be delivered to the application provider. The service provider is also responsible for answering user's requests.
- **Application Provider:** The application provider receives the location data from the service provider and represents it on a graphical interface. This component is divided into two operational modes: online management of the ground movements and offline analysis of logs and reports.
- **Content and Data Provider:** Database that stores information about mobile terminals, movements scheduling, operational tasks, personnel information, allocation of resources and operational status.

Although this infrastructure allows to improve the situation awareness of controllers, it only provides the basic support to detect safety hazards. Such hazards are met by recent ITS systems that aim to maintain a coordinated and automated transportation system, where personnel interact transparently with each other without incidents. ITS is a transportation system that becomes intelligent by using wireless technologies to enhance the safety and operational performance [11]. For instance, in the airport domain, several ITS solutions were proposed with respect to the main important safety issues: speed limiting, proximity detecting, bad weather warning, runway incursion and push-back warning [12].

Furthermore, the ITS is also capable of automatically recognizing transitions between indoor and outdoor environments, where the term indoor relates to a place where the satellite signal can not be reached (e.g. inside a building) and outdoor represents the other places where it is possible to maintain a continuous line-of-sight to the satellite. This mechanism is particularly useful when a vehicle crosses a tunnel and requires an automatic and fast switch between indoor/outdoor technologies to avoid the loss of signal and to maintain a continuous monitoring. Another situation, for instance in an airport, is the detection of an undue movement of a passenger bus into an unauthorized area or a runway incursion [13].

The ITS is then a benefit regarding guidance functional requirements, since it allows to detect unpredictable events while guiding a mobile. This means that the system is fitted with intelligent mechanisms that are able to continuously provide support to monitoring activities. Situations compromising the safety of operations, such as deviations from the pre-defined route or speeding, automatically trigger an alert to allow the controller to make a decision.

1.3 Advanced Surface Movement Guidance and Control System

Current air traffic movements outlines the need to find a way to improve the airport safety, mainly regarding the incidents caused by uncoordinated ground movements. Such approach is addressed by EUROCONTROL with the A-SMGCS concept [14]. The A-SMGCS consists of a set of mechanisms and safety rules that aim to improve the safety and efficiency of all ground movements in the airport. The ICAO also defines the concept as a "system providing routing, guidance, surveillance and control to aircraft and affected vehicles in order to keep movement rates under all local weather conditions within the AVOL whilst maintaining the required level of safety" [3].

The A-SMGCS implements four distinct services [5]:

- **Surveillance:** positioning of moving objects within the airside area of an airport.
- **Control:** detection and resolution of safety hazards and other conflicts.
- **Routing:** generation of a route for each aircraft and vehicle, allowing to adapt a possible path deviation.
- **Guidance:** indications to allow the pilots and vehicle drivers maintaining their assigned path.

The four-phase implementation levels of A-SMGCS are represented in Figure 1.2, which provides detailed information about operational functionalities required in each level. The implementation complexity increases from level I to level IV, where functionalities are incrementally deployed. For instance, level I provides surveillance capabilities to the controllers by representing real-time positioning data about aircrafts and vehicles in a map-based display. In level II, this functionality is enhanced with basic features from control and guidance services. Then, level III already includes a route planning service that allows to assign specific paths to aircrafts and vehicles. This level also provides a conflict detection function and a automatic switch of ground signals for guidance assistance to pilots and drivers. Finally, the overall implementation of A-SMGCS includes the functionalities of previous levels, improved by a set of additional features such as the resolution of conflicts or the extension of situation awareness also to pilots and vehicle drivers.

Levels	Surveillance		Control		Route Planning	Guidance	
	Users	Mobiles and areas covered	Users	Conflicts detected	Users	Users	Type
0	Strict application of SMGCS						
1							
	Controller	All vehicles in the manoeuvring area All aircraft in the movement area					
2							
	Controller	All vehicles in the manoeuvring area All aircraft in the movement area	Controller	RWY incursions		Drivers	Airport Static Map & mobile position on a screen as an option
3							
	Controller All participating mobiles	All vehicles in the manoeuvring area All aircraft in the movement area	Controller Equipped mobiles	All conflicts	Controller	Pilots Drivers	Airport Dynamic Map (with runway status,...), mobile position on a screen Automatic switch of ground signals
4							
	Controller All participating mobiles	All vehicles in the manoeuvring area All aircraft in the movement area	Controller All participating mobiles	All conflicts + Conflict Resolution	Controller Equipped mobiles	Pilots Drivers	Airport Dynamic Map (with runway status,...), mobile position & route from route planning function on a screen Automatic switch of ground signals

Figure 1.2: A-SMGCS implementation levels [3].

The dependencies between A-SMGCS services are represented in Figure 1.3. The surveillance function is responsible for providing the traffic situation in real-time. This information is used by the control service to detect and resolve conflicts, while the route planning function computes a route to be assigned to each authorized mobile. The guidance service is then responsible for providing instructions to pilots and vehicle drivers, based on control and route planning information.

Furthermore, the four implementation levels of A-SMGCS are organized in a layered architecture, composed by a set of subsystems interacting with each other in order to provide surveillance, control, routing and guidance services. The layered architecture is represented in Figure 1.4, where the location data about moving objects is collected from the movement area and delivered to the above layers. The surveillance and data fusion layer is responsible for managing all the information gathered from sensors and other information systems. As represented in Figure 1.4, the bold arrows are the most relevant interactions. For instance, the location data is received by the control layer that is responsible for warning the controller whenever an

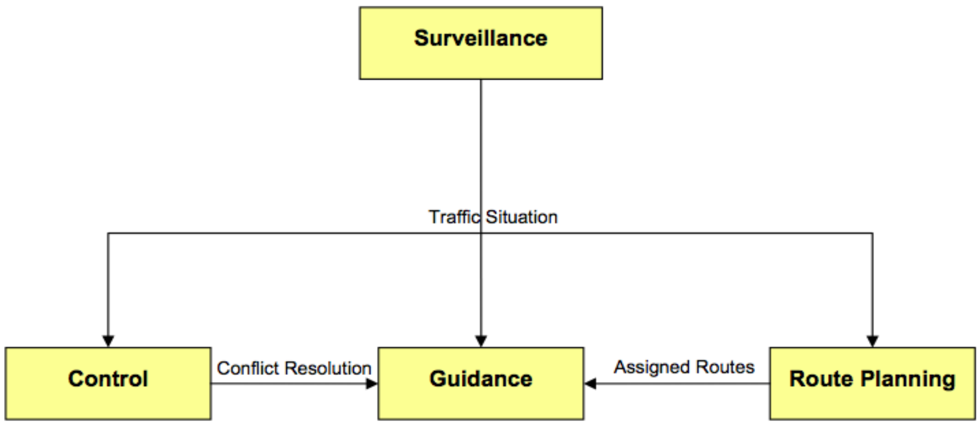


Figure 1.3: Dependencies between A-SMGCS services [3].

incident occurs. Moreover, the routing function generates possible routes for each moving object, based on the location data, and provides them to the controller who will make a decision about which route should be assigned. On the other hand, the guidance layer analyzes the data and provides assistance to the ground movements by guiding the pilots and vehicle drivers.

However, only a limited set of airports are equipped with the first two levels of A-SMGCS, for instance Frankfurt Main (Germany) or Charles De Gaulle (France) have invested in new electronic means to provide accurate and reliable positioning information. On the contrary, levels III and IV are only predicted to be implemented from 2015 onwards [16]. For the time being, the main challenge is to mature levels I and II to allow the transition to levels III and IV [15]. In other words, surveillance and control functions must achieve a certain level of reliability that will not compromise the routing and guidance accuracy. For that purpose, a survey about location technologies is described in Chapter 2 in order to understand which technology best captures the position of a target within different operational scenarios. Such information about moving

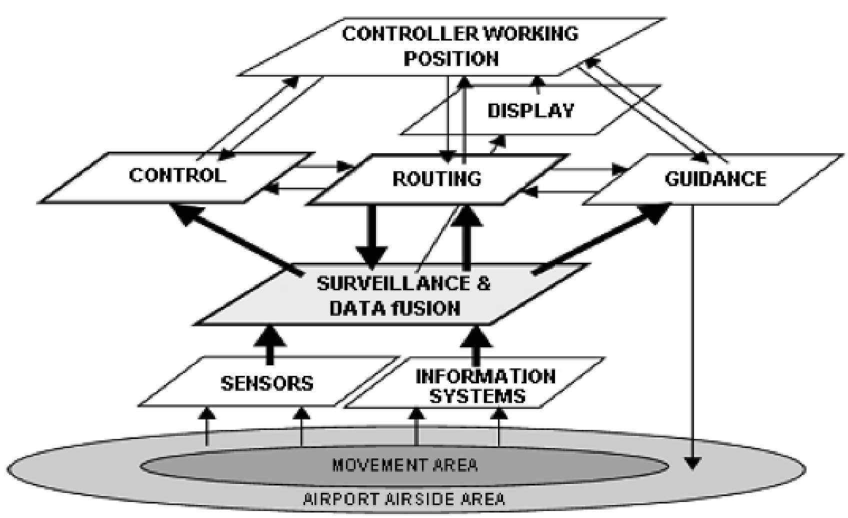


Figure 1.4: A-SMGCS operational layers [8].

objects will improve the situational awareness of the ATCOs, while releasing their workload. A graphical interface allows the controller to monitor targets moving along the airport spatial context, together with an alert mechanism that triggers an alarm whenever the operations safety is compromised. In addition to the surveillance and control functions, it is required to improve the surface movements efficiency. Then, a routing mechanism should generate a set of path possibilities to assign to each moving object, improving the controller knowledge about conflict-free routes generated automatically. The guidance capability is another requirement, in order to maintain pilots and vehicle drivers traveling along their assigned route [4].

1.4 Contributions

The main contribution of this thesis is to provide a decision-support methodology to manage the efficiency of airport surface movements. It is intended to extend an existing platform, namely A-Guidance, to routing and guidance functionalities, complying with A-SMGCS operational and performance requirements. This project is experimentally deployed at Lisbon and OPorto airports in Portugal, already equipped with an LBS infrastructure providing surveillance and control services. Based on the real-time positioning data about aircrafts and metadata about the airport layout, the proposed methodology aims to optimize TWY operations by routing and scheduling each movement within the movement area.

The proposed methodology is based on the representation of the airport TWY guidance lines as a directed weighted graph with nodes and arcs. Each node of the graph represents an intersection between two or more TWY, where the arcs are the segments between each node. Over that representation, a routing algorithm is applied in order to find the shortest path between two nodes. Thus, a static path planning function determines which route will be assigned to each aircraft. However, such approach may generate a set of conflicts between uncoordinated movements that have to be handled by a dynamic scheduling function. There are three types of conflicts that can occur: two aircrafts crossing an intersection, a persecution in which the separation distance decreases due to speeding, and two aircrafts moving towards each other [17]. These conflicts are avoided by scheduling each pathway taking into account the other movements as time passes by. Then, a continuous monitoring of each movement allows to detect deviations from assigned routes or non-compliance with business rules, resolved by re-routing to alternative paths or by defining a set of holding points in strategic places.

The main goals of this thesis are:

- Increase the airport capacity and efficiency by avoiding delays and minimizing conflicts.
- Optimize turnaround times by computing shortest paths.
- Reduce the airport stakeholders workload.

The mentioned contributions and goals intend to respond to the increasing complexity of modern airports, by improving the ability to manage simultaneous operations while complying with safety and security rules. The extension of existing solutions to levels III and IV of A-SMGCS will contribute to reduce the energetic consumption with an efficient guidance lighting system, as well as to reduce operational costs by improving the turnaround efficiency. Thus, the number of allocated resources required to provide support to the aircraft and the likelihood of safety hazards would considerably decrease.

1.5 Document structure

The remaining of this document is organized as follows. Chapter 2 presents the related work about wireless location technologies and performs a survey about existing routing algorithms. This chapter intends to discuss the state-of-the-art about existing solutions contributing to the implementation of the A-SMGCS concept. Chapter 3 provides an in-depth analysis of the proposed methodology, describing the architectural model and the implementation conception. The methodology was applied to the airport domain as the case study, presented in Chapter 4. Chapter 5 provides a detailed assessment to the implemented solution in order to validate the compliance with operational and performance A-SMGCS requirements. Chapter 6 ends with a set of conclusions about the contributions made along this thesis, as well as a reflection about the future work.

Chapter 2

State of the art

In the last decades, the improvements made to RTLS[1] have evolved in order to take advantage from mobile devices as a network of sensors to detect moving objects within restricted areas. In this context, this chapter makes a survey about existing location technologies used to provide support to an LBS infrastructure. The accuracy and reliability achieved by those technologies are then assessed to evaluate if the level of surveillance is adequate to proceed with routing and guidance functionalities.

The resulting spatio-temporal context is then represented in a map-based display and managed by a GIS engine, which description will allow to understand how the provided metadata allows to implement a path planning system. This system will be based on one of the surveyed routing algorithms addressing the shortest path problem. Nevertheless, the assignment of static optimal paths must operate under a dynamic programming model that is able to simulate the time evolution and schedule non-conflicted movements over that representation.

2.1 Location technologies

2.1.1 Non-cooperative technologies

There are two main categories of moving objects: cooperative and non-cooperative. Targets are considered cooperative when they are equipped with a transponder that is able to communicate its precise location to the service provider, while the monitoring of non-cooperative objects requires the ability to detect any mobile within the operational area without the collaboration of the target. Focusing primarily on non-cooperative technologies, their surveillance is performed by electronic means without requiring the installation of any electronic device within the object. This means that it is possible to detect the location of a moving object without being intrusive. For instance, in the case of an airport, it is very useful to detect aircrafts, vehicles and other obstacles that may appear on the ground [3]. The following non-cooperative technologies are considered:

[1]RTLS are systems designed to detect, in real-time, the positioning of active mobiles that are equipped with a device able to interact with the system [18].

– **Magnetic Sensing:** This is a technology that allows detecting the passage of ferromagnetic objects through a magnetic sensor. The sensors are usually installed on the ground, in order to capture every interaction with the earth's magnetic field at considerable distances. However, that distance is limited since the magnetic field sources decrease with the inverse cube of distance [19]. The magnetic signature of a vehicle may be stronger than an aircraft due to its closer distance to the ground. This remark may be useful to automatically distinguish between different classes of non-cooperative targets. For instance, an European project, ISMAEL, used that technology to improve the capability of larger airports to detect aircrafts and to provide a stand-alone and inexpensive solution to small and medium airports [20].

– **Image-based tracking:** This technology is a image-based solution that captures the presence of mobiles by analyzing and computing images obtained from cameras. The most common algorithm used is based on the comparison between the real-time frame and a gray static image of the background of a specific operational area. Besides gathering information about the location, movement direction and size of the target, there is a way to identify the aircraft through a tail number recognition technique. The characters of the tail are computed, recognized and then browsed in the airport database [21].

– **Surface Movement Radar:** SMR is based on the transmission of radio frequency signals that are echoed by moving objects. Typically, the transmitter is a rotating antenna that broadcasts electromagnetic waves that are reflected by any object present on their path. Then, the reflected signal is received by a sensor that measures the location, shape and direction of the moving object. This technique allows to detect up to 400 objects at the same time. Depending on the size of the monitored area, one or more antennas should be used in order to cover the entire surface. There are different types of radars with their own characteristics, such as frequency range, size, transmission power and cost. For instance, W-band radars achieve a large coverage area (up to 3000m) in clear weather conditions, working at 95 GHz. This type of radar is mainly used at airports for surveillance of ground movements, requiring one to four sensors to cover the entire movement area [22].

These technologies are able to detect moving objects in a passive way, without being intrusive or requiring cooperation. The magnetic sensing is a robust solution as it does not require maintenance, uses small and relatively cheap sensors and works in all weather conditions. However, it does not provide a reliable distinction between categories of targets and missed detections may occur, especially with vehicles [19]. On the other hand, the image-based solution has a better detection performance, since its high resolution allows to distinguish between different shapes and sizes. Although the image-based tracking system is accurate, it presents a lot of weaknesses. Very often the targets are occluded by each other (e.g. a vehicle is hidden by the airplane wing) because the camera views horizontally and does not have a satellite perspective. Another problem is the variation of the airport visibility along the day, due to the meteorological conditions or simply due to the illumination transitions [21]. On the contrary, the SMR technology detects any type of object with an high accuracy, while covering the entire movement area. However, it is an expensive solution, triggers false alarms and is affected by bad weather conditions [22]. Furthermore, a large object may be recognized as several smaller ones or even two objects can be identified as only one (due to their proximity). Another problem with SMR is the fact that it does not provide the mobiles identity [21].

2.1.2 Cooperative technologies

The cooperative surveillance can be divided into two distinct categories: dependent and non-dependent. The first one is related to the automatic broadcast of the mobile position to the service provider, whereas the other is not dependent on the mobile initiative and forces the service provider to ask for its coordinates [3]. The most common way to determine such coordinates (longitude, latitude and altitude) is to use GNSS to determine accurately the geo-spatial position of a stationary or moving object, in real-time. Other location techniques are also addressed in this section, namely MLAT and ADS-B. On the other hand, as discussed in Section 1.2, the transmission of positioning data to the service provider requires a communication link. The most common wireless communication networks are also described below, as it is the case of Wi-Fi and WiMAX.

– **Wireless Networks:** Wi-Fi is based on IEEE 802.11 standards, used in WLANs. Several antennas or APs serve the mobile terminal through high frequency radio links, allowing the wireless transmission of information about the location of the moving object to the service provider. Besides being a private network and allowing a custom service implementation, this technology has significant advantages in the airport domain. For instance, it is possible to implement security features, such as data encryption and authentication. Also, the ability of performing fast handovers between APs and the large bandwidth available allows high bit rate transmissions, useful for image or video monitoring requirements. Furthermore, the system supports until hundreds of APs controlled by a single central entity and may provide data redundancy in order to recover from an electronic failure [23]. Moreover, WLANs may be extended by the WiMAX broadband wireless system. Instead of hundreds of meters achieved by IEEE 802.11 standards, this technology reaches up to 20 km [14]. On the other hand, Wi-Fi can also be used as a location technology. Two main techniques are used: trilateration and triangulation. The trilateration considers the distance between the AP and the mobile, calculated by a location sensing technique, such as the TDOA. This technique estimates the movement direction and the distance between the AP and the mobile by measuring the RTT between them. Using at least three APs, the TDOA intersects the hyperbolas of the distance between each AP and the mobile to determine the precise location of the mobile. On the other hand, the triangulation technique uses the AoA signal received by the AP from the mobile. The straight line connecting the AP and the mobile gives an estimation about the direction of the mobile position. By intersecting the straight lines of two APs to the mobile, the position is determined. However, these techniques suffer from multipath interference and it is not the more reliable positioning method [24].

– **Radio Frequency Identification:** Identification system composed by sensors and unique identification tags. Each target is pre-equipped with an electronic device (tag) that exchanges beacons with the sensor (reader unit). Passing close to a reader unit, the tag exchanges its data with the sensor, that will deliver it to the server [15]. There are two major types of RFID tags: active and passive. Active tags are often autonomous devices containing a battery and allowing higher communication ranges, while passive tags are smaller, cheaper and do not require much maintenance [25]. Hence, the RFID may be the most appropriate technology for automatic login validation procedures. For instance, the vehicle drivers authentication when entering a restricted area can be accomplished by an RFID tag inside the vehicle that informs the service provider about the location of that specific mobile.

– **Global Positioning System:** Within the GNSS domain, the GPS was the first system providing positioning, later enhanced by several improved solutions. The NAVSTAR GPS was firstly deployed in the United States, providing a worldwide system both to military and civilian users. Afterwards the Russian GLONASS was developed as an alternative to the American system. Recently, the European Civil Satellite Navigation Program (Galileo) appeared as an inter-operable solution together with the GPS and the GLONASS [26]. Several GPS improvements are being investigated in order to reach a more accurate and reliable positioning system. EGNOS is the most promising one, based on three geostationary satellites and many ground stations. This system provides an accurate positioning signal by gathering information about the GPS and GLONASS satellites, such as its position or clock. The computed signal reaches an accuracy of two meters, in the worst case [14]. Moreover, D-GPS is an inexpensive and simple system that broadcasts the corrected value of the absolute position. This value corresponds to the difference between the real position and the position given by the satellite [27]. Finally, HSGPS is considered to be the most accurate GPS-based technology able to support indoor LBS. The receiver is powerful enough to acquire weaker signals (until 10 dBHz), even without line-of-sight to the satellite [28]. When the connection between the mobile and the satellite is lost, the above GPS systems do not recover quickly and a significantly delay is introduced. In order to improve the efficiency of that disconnection problem, the A-GPS is used to speed up the connection process in real-time, by assisting the mobile with a BS unit. This unit is a server that maintains updated information about the location of each known mobile. In few seconds, the mobile then receives its location through a telephony link, such as the GSM [24].

– **Automatic Dependent Surveillance Broadcast:** ADS-B is an example of a dependent cooperative technology, since aircrafts automatically broadcast their flight information for the other ADS-B capable systems. That information includes the geographic coordinates (obtained from GNSS), the current speed and the flight identification (or the aircraft address), sent twice per second. The permanent sending of the updated location of the aircraft allows an accurate and continuous surveillance on the target movements [29]. Such location parameters are organized in a state vector that will be delivered to other ADS-B capable aircrafts and to the ADS-B ground station, called the SBSS. That vector or ADS-B message is used by two different functions: ADS-B-out and ADS-B-in. The ADS-B-out represents the transmitter installed on the aircraft that broadcasts the ADS-B message to the other ADS-B receivers. On the other hand, ADS-B-in is the receiving function that enables the pilots to receive on-board information about the other aircrafts [30]. Furthermore, two types of data links can be used in the United States: the 1090 MHz Mode S Extended Squitter, primarily used to commercial aircrafts; and the 978 MHz UAT, suitable to general aircrafts [31]. In Europe, the preferred data link for ADS-B is the 1090 MHz Extended Squitter, since it uses the transponders already installed on the aircrafts and is interoperable with the American system [32].

– **Multilateration:** MLAT consists of a set of antennas installed in the operational area that broadcasts *interrogation* signals to the airspace. The targets equipped with SSR and ADS-B transponders, both aircrafts and vehicles, will answer with a *reply* signal. The RTT between the antenna and the target is then used by the TDOA technique that estimates the precise position of the target. Evaluation tests performed at the Narita International Airport during 2009 revealed that the MLAT performance is not affected by bad weather conditions, does not require additional equipment to be installed on the aircrafts and also provides identification information about the target. However, multipath can degrade the signal propagation, causing false or missing detections [33].

Other cooperative RTLS could be considered, such as Bluetooth or Infrared for indoor environments. Although Bluetooth and Infrared technologies are inexpensive and do not require much power, they only support short communication ranges ($<$ 15 m) and are affected by multipath [34]. On the other hand, TETRA and CDMA are two interesting wireless technologies for outdoor environments, but were not considered due to their low bandwidth capacity [23].

2.1.3 Performance assessment

Table 2.1 summarizes the location technologies characteristics, identifying the working environment (indoor or outdoor) and evaluating several performance parameters (accuracy, reliability, range and cost).

Although RFID is the more accurate technology, it only provides a very short communication range. However, it is the most promising one for indoor environments. On the other hand, ADS-B and GPS seems to be the most suitable technologies for the detection of aircrafts and vehicles, respectively. Besides their high reliability and large coverage range, these outdoor technologies achieve an accurate and cost-effective positioning. Furthermore, SMR is an expensive solution that captures every moving object in a large coverage area, with a medium level of reliability.

Table 2.1: Location technologies performance.

Technologies		Indoor	Outdoor	Accuracy	Reliability	Range	Cost
Non-cooperative technologies	Magnetic sensing [19]		✓	< 10m	High	< 20m	Low
	Image-based [21]		✓	–	Medium	–	Medium
	SMR [22]		✓	< 5m	Medium	2-3km	High
Cooperative technologies	GPS [34]	✓[2]	✓	5-10m	High	[3]	Med./High
	RFID [15]	✓		5cm-5m	High	3cm-10m	Low
	Wi-Fi [24]	✓	✓	2-100m	Medium	50-100m	Medium
	ADS-B [29]		✓	–	High	≈ 3km	Medium
	MLAT [33]		✓	6-60m	High	–	Medium

2.2 Geographic Information Systems

In order to improve the situational awareness of controllers, a graphical representation about the operational area is required to maintain a continuous monitoring of ongoing operations. In this context, GIS were designed to represent the cartographic context of a traffic operational area, such as the airport movement area. This engine allows decision-makers to handle large flows of data by providing them with visualization and management tools.

The GIS engine provides an abstraction of the layout complexity as a set of independent thematic layers, each one representing a specific operational area or providing particular features. In an airport, these layers include TWY, RWY, stand parking areas, but also traffic information labels that are refreshed every second. In other words, the map is structured as a set of overlapped operational areas and other functionalities that are independently managed. So, the system defines the features of each layer as a set of metadata. For instance, TWY have a set of metadata associated, such as the length of each segment, traffic circulation rules or the speed limit. This information is used by several routing mechanisms, where the geographical organization and traffic circulation rules must be well-known in order to calculate the shortest path between two points in the map.

Furthermore, a GIS engine is also a powerful tool that improves the situational awareness of the ATCO by representing the airport layout on a GHMI. The GHMI is the interface where the thematic layers are represented with the updated information about each moving object. In order to maintain the accurate positioning of moving objects, the system must work in real-time, i.e. it has to continuously refresh the interface to provide a realistic perspective of the ground movements. In addition to the interface, GIS also provides several features that improve the ability of the user to interact with the map. Besides the user is able to customize the layers appropriate for the tasks he performs, GIS allows to dynamically zoom in, zoom out, get information about a specific target or select an operational area for inspection. This tool then improves

[2] Only for HSGPS.
[3] Anywhere a satellite signal can be reached.

stakeholders capabilities with simple mouse clicks that are sufficient to perform main ground handling tasks, without leaving the seat. Another important feature about GIS is its capability for detecting safety hazards within the operational area. Whenever the safety performance is compromised, an alert is triggered out. For instance, this feature is very useful to avoid collisions when guiding an aircraft along a route.

The graphical representation of the Oporto airport in Portugal is presented in Figure 2.1, where the layers provided by GIS are represented with different geometry shapes and colors. For instance, the apron is represented by a grey surface on the right-hand side of the image, whereas the runway is on the left-hand side, represented by a dark route surrounded by a rectangular protection area. Furthermore, the TWY guidance lines are the most important layer, represented in the figure by lines linking the runway exits to the apron taxiways and stands. In the apron, vehicles are identified by a label that contains their ID, speed and other configurable parameters. Additionally, the status of each target is characterized by a specific color. For instance, it can be green if there is no safety threat, yellow if it is causing a soft incursion or red if there are more severe incursions [14]. Another feature represented in Figure 2.1 is the status of the stand occupation. It is represented by a light gray polygon if empty, while a dark gray means that there is an aircraft blocked-on.

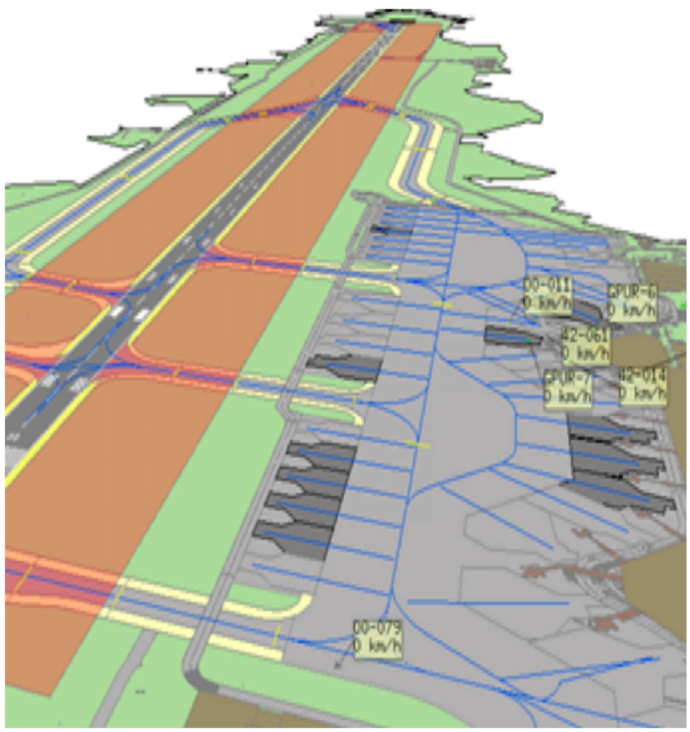


Figure 2.1: The Oporto airport layout [35].

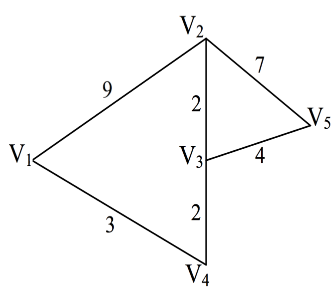
Finally, GIS also considers safety and business rules. These rules determine operating procedures according to the current status of the system, such as the available resources at the airport, the level of visibility or the traffic flow. As an illustrative example, if dense fog and rain suddenly occur, the system must react according to the visibility conditions business rules. For instance, GIS must automatically switch from normal visibility operations to low visibility operations. This change implies a different behavior, such as defining a lower speed limit or increasing safety requirements. Moreover, these rules are also to be considered, together with traffic circulation rules, when using algorithms to find the best path [35].

2.3 Routing algorithms

2.3.1 Graph theory

Although GIS provides an accurate and reliable situational awareness, it must be enhanced with a path planning function that automatically generates a set of optimal routes for each moving object. Such requirement leads to the construction of an abstract representation of the operational area as a set of nodes and arcs forming a graph network. In the case of the airport, this graph is the representation of the TWY guidance lines, where a node is the intersection between two TWY and arcs (or segments) are the routes linking two nodes [36]. This representation is frequently used by routing algorithms to solve the shortest path problem, that consists of finding the best path between a source node and a destination node. Usually, a cost is associated to the path which corresponds to the sum of the estimated weights of each segment of the path, where the weight is commonly related to the length of the segment.

An illustrative example of a weighted graph is shown in Figure 2.2(a), where a node is represented by V_i ($i \in \{1, 2,...,n\}$) and the weight associated to each segment is represented by an integer beside the arc. These integers are represented in a adjacency matrix $W[i][j]$, where each cell (i, j) corresponds to the length of the link between nodes i and j (see Figure 2.2(b)). For instance, $W[1][2]$ is the distance from node 1 to node 2, represented by the 9 in the first line, second column. The weight is marked as ∞ when the distance between two nodes is unknown, or 0 if it is the distance for the node itself [37].



(a) Weighted graph

$$W = \begin{bmatrix} 0 & 9 & \infty & 3 & \infty \\ 9 & 0 & 2 & \infty & 7 \\ \infty & 2 & 0 & 2 & 4 \\ 3 & \infty & 2 & 0 & \infty \\ \infty & 7 & 4 & \infty & 0 \end{bmatrix}_{5\times5}$$

(b) Adjacency matrix

Figure 2.2: Weighted graph representation [37].

2.3.2 The shortest path problem

There are several algorithms resolving the shortest path problem, as it is the case of Dijkstra [38], A* [39] or Floyd [37]. Dijkstra determines the shortest path between a given node and the remainder nodes, while A* is based on Dijkstra but uses an additional heuristic function to select the node that will firstly lead to the destination. On the other hand, Floyd computes all-to-all shortest paths. A brief description of the steps of each algorithm is presented below.

– **Dijkstra** solves the shortest path problem by searching the minimum length from a given source node to all the other nodes in the network. The algorithm uses two vectors: one for the set of unprocessed nodes, called vector U, and a second vector F with the shortest path distance found between the origin and each of the other nodes. It is assumed that the initial distance F is 0 for the source node and infinity for the remaining. So, starting from the first node, its immediate successors k are checked and the distance $W[0][k]$ is the updated value of $F[k]$. Then, the source node is considered processed and is removed from the vector U. The next iteration belongs to the nearest node from the origin, the node i with the smallest $F[i]$. Its job is to update the $F[k]$ value of each k immediate successors by choosing the minimum value between $F[k]$ and $F[i] + W[i][k]$, that represents the shortest length $F[i]$ for the node i being processed plus the arc $W[i][k]$ connecting i and k. When all the successors are updated, the node i is considered processed and is removed from U. This process is repeatedly applied to each of the nodes contained in the vector U, allowing to obtain a vector F with the shortest length from the source node to all the other nodes in the network. With that vector F, it is possible to determine the path between the source and the destination. From the end to the beginning, the algorithm compares the $F[j]$ of the current node j with the $F[p]$ of its immediate predecessors p plus the distance $W[p][j]$ separating them. The predecessor that satisfies $F[j] = F[p] + W[p][j]$ is the node that precedes the current node j in the path [38].

– **A*** follows the same principle as Dijkstra, but uses an heuristic function that estimates the more promising node that will allow to reach the destination first. While Dijkstra have to check every node of the network to make a decision about the direction to follow, A* is based on a prediction that indicates which node is closer to the destination. Thus, the shortest length $F[i]$ in node i is represented by the expression $F[i] = G[i] + H[i]$, where G is the length cost from the source node to the node i and H represents the optimal path from the node i to the destination node estimated by the pre-determined heuristic. Then, the algorithm uses the F function to decide which of the immediate successors will be the next node to be processed. Although selecting the heuristic function is an important decision regarding the algorithm performance, it is not covered by the scope of this work. The better the estimation accuracy is, the better the performance of the searching algorithm is, comparing to Dijkstra [39].

– **Floyd** was designed to provide the shortest length between each pair of nodes in a weighted network. The algorithm works in three sequential steps: first, it computes the shortest distance between each pair of nodes, then updates a route matrix that contains the intermediate nodes connecting each pair of nodes, and finally the optimal path is determined. Considering the initial weighted matrix W, the first step of the algorithm updates a matrix S that, in the end, will contain the shortest distance from each node to all the other nodes. $S_{ij}^{(k)}$ represents the weight of the shortest distance between the node v_i and the node v_j, only considering the set of nodes $\{v_1, v_2, ..., v_k\}$ as intermediate nodes. S is initialized as $S^0 = W$. For each $k \in$ {1, 2,...,n}, $S^{(k)}$ is updated according to the equation (2.1). The algorithm checks if there is a shorter path between v_i and v_j than the one already found in $S_{ij}^{(k-1)}$, considering the node k that is being processed as intermediate node.

$$S_{ij}^{(k)} = min\{S_{ij}^{(k-1)}, S_{ik}^{(k-1)} + S_{kj}^{(k-1)}\} \tag{2.1}$$

The second step of the algorithm consists in saving the best route found while checking the shortest distance from node to node. Initialized with 0, $R^{(k)}$ is the matrix that keeps information about the k node that provided the shortest distance from node i to node j. This means that, each time a shortest path is found between node i and j, the respective $R_{ij}^{(k)}$ is updated to the k index of the node that was used as intermediate node in the path, according to the formula:

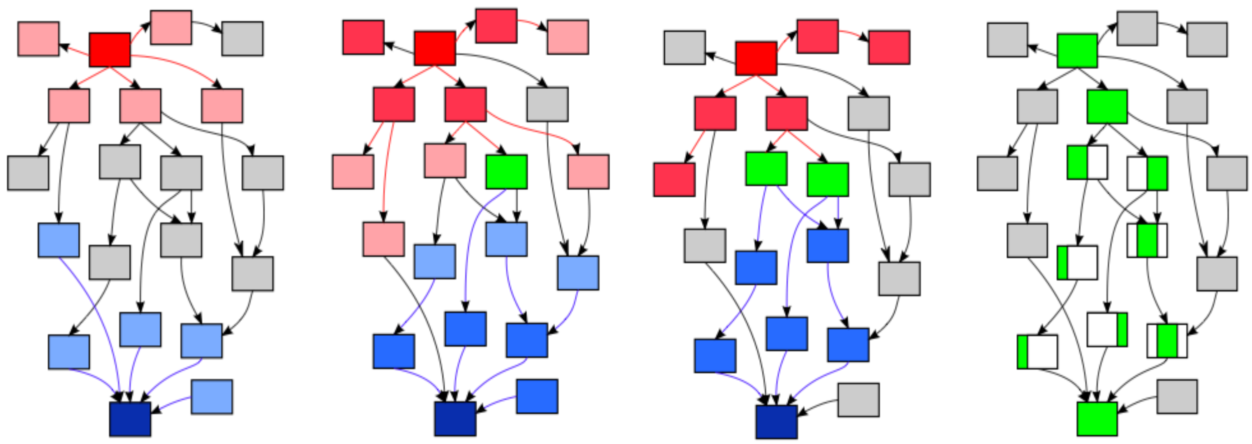
$$R_{ij}^{(k)} = \begin{cases} k & \text{if } S_{ij}^{(k-1)} > S_{ik}^{(k-1)} + S_{kj}^{(k-1)} \\ R_{ij}^{(k-1)} & \text{else} \end{cases} \tag{2.2}$$

The last task in Floyd is to determine the shortest path from a given source i to a destination j. Based on the S and R matrices, the algorithm first finds the intermediate node between nodes i and j, denoted as t. It then verifies if there is another node between i and t. If not, it continues to the other piece of the path, between t and j. This verification is recursively applied until there is no other intermediate nodes. It must satisfy the condition $R_{pq}^{(n)} = 0$, representing there is no other intermediate node between two nodes p and q during the path construction. The shortest path is therefore the set of intermediate nodes between the source i and the target j [37].

2.3.3 The *k* shortest paths problem

Assigning routes to simultaneous movements at the same time requires the ability to find alternative paths when there is a conflict. The computation of k shortest paths to the same destination is an efficient solution that provides a list of k alternative routes, where k is an arbitrary natural number. These routes are sorted in an ascendent order with respect to their lengths. The following of this section makes a survey about three algorithms resolving the k shortest paths problem:

- **k-PathA** resolves the k shortest simple path problem by following a forward/backward chaining approach to generate loop free pathways from a seed node to a target node. This mechanism is based on successive expansions and reductions operations starting from the two opposite nodes. The expansion consists in searching forward from the seed for outgoing links and backwards from the target for incoming links, as represented in Figure 2.3(a). The added nodes from the seed are then compared with every node added from the target and, if there is a common node, the pathways are connected, evaluated and stored (see green node in Figure 2.3(b)). This step is repeated until there are no new nodes to add or the length of the paths reached a pre-defined threshold. For each iteration, the number of added nodes is reduced to a user-defined value. As shown in Figure 2.3(b), the expanded nodes were reduced to the 4 nodes with lower distance weights, followed by a new expansion cycle. Figure 2.3(c) represents the stop condition, where no other new nodes can be added and common nodes were found.



(a) Expansion from seed and target nodes

(b) Reduction to k shortest pathways (k=4); expansion

(c) Reduction, no expansion

(d) k shortest pathways

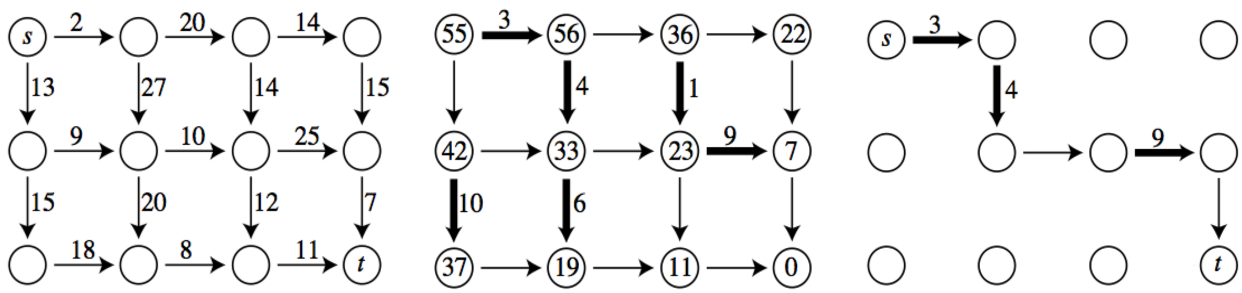
Figure 2.3: k shortest simple Path Algorithm. Dark Red = Seed Node. Dark Blue = Target Node. Red = Expanded Node (forward). Blue = Expanded Node (backward). Light Red = Added Nodes (forward). Light Blue = Added Nodes (backward). Green = Common Node [40].

Finally, all possible combinations between pathways from the seed to the common node are generated, as well as from the common node to the target. Thus, if there are m pathways from the seed to the common node and n pathways from the common node to the target, $m * n$ shortest paths are produced. The length of pathways is computed and sorted by their cost, from which the k shortest paths are selected (see Figure 2.3(d)) [40].

– **Eppstein** first applies Dijkstra in the reverse sense, searching backwards from the terminal t to all the other vertices in the graph (Figure 2.4(a)). The result is a shortest path tree T with the shortest path from any vertex in G to t, represented in Figure 2.4(b) [41]. Ignoring the bold arrows, every vertex is provided with the shortest length and path to t. On the other hand, bold arrows are represented with $\delta(e)$ values, which are obtained from the equation (2.3).

$$\delta(e) = \ell(e) + d(head(e), t) - d(tail(e), t) \tag{2.3}$$

$\ell(e)$ is the length of an edge e, $d(s,\, t)$ is the length of the shortest path between two given nodes s and t, while $head(e)$ and $tail(e)$ represent the start and end points of the edge e, respectively. $\delta(e)$ measures then the difference between following the shortest path and deviate to the edge e. Such deviation is called a *sidetrack* along e.



(a) Weighted directed graph G

(b) Shortest path tree T with length to t in G; $\delta(e)$ values for edges in $G - T$ (bold arrows)

(c) Path p and *sidetracks*(p) (bold arrows)

Figure 2.4: Eppstein algorithm [42].

Considering the k shortest paths problem applied to the path $s - t$, the shortest path is represented by the thin arrows linking s and t in Figure 2.4(b). The following k shortest paths are outlined in Figure 2.4(c), each one taking a different *sidetrack* from the shortest path p [42].

– **K*** is inspired in Eppstein, but was designed to perform on-the fly[4] while being guided by heuristic functions. Whereas Eppstein uses Dijkstra in a backwards manner, K* determines the shortest path tree by applying the A* algorithm in the forward sense, from a given source s to a target t in G. The heuristic is based on $\delta(u, v)$, which represents the disadvantage of taking the edge between vertices u and v as the deviation from the shortest path. However, the shortest path and $\delta(u, v)$ are not known during the search. This problem is solved by applying concurrently Dijkstra to generate shortest path solutions before A* ends its execution. Decisions on-the-fly can only rely on an evaluation function f that determines an estimated value for $\delta(u, v)$ [41].

2.3.4 Performance assessment

Table 2.2 provides an estimation of the runtime execution complexity in the worst-case for every surveyed routing algorithm, where n is the number of vertices, m the number of edges and k the number of shortest paths in the case of the k shortest paths problem. It can be noted that A* solves the shortest path problem much faster than Dijkstra since it uses an heuristic function to estimate the node that will first lead to the destination [43]. On the contrary, Floyd is mathematically more complex than Dijkstra and A* because it has to compute the shortest route from every node to all the others. However, it only requires a single execution to find all-to-all shortest paths, whereas Dijkstra and A* require the analysis of almost all the nodes to compute a single path between two nodes. Floyd is then considered the most appropriate static path planning algorithm for complex traffic environments.

On the other hand, the k shortest paths problem introduces the variable k that influences the runtime complexity. Comparing K* and Eppstein, the most advantageous algorithm is Eppstein in terms of runtime

[4] On-the-fly represents an activity that has to be dynamically adapted to operational changes during its execution, without requiring the graph to be explicitly available on main memory [41].

Table 2.2: Routing algorithms performance.

Algorithms		Runtime complexity	Contribution
Shortest path algorithms	Dijkstra [38]	$\mathcal{O}(n^2)$	One-to-all shortest path
	A* [41]	$m + n\log(n)$	Dijkstra improved with an heuristic function
	Floyd [37]	$\mathcal{O}(n^3)$	All-to-all shortest path
k shortest paths algorithms	k-PathA [40]	–	Forward/backward chaining approach
	Eppstein [42]	$m + n\log(n) + k$	Reverse Dijkstra search and shortest path tree
	K* [41]	$m + kn\log(kn)$	On-the-fly search based on heuristic functions

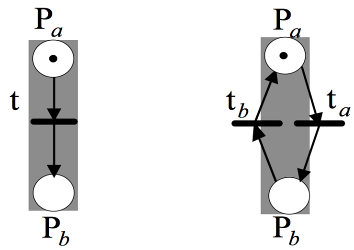
complexity. The on-the-fly search of K* multiplies the complexity by a factor of k in the $n\log(n)$ portion [41]. On the contrary, the assessment made to k-pathA in [40] was based on a distributed network where nodes communicate with each other by message passing. Although they do not provide the runtime complexity of the algorithm, it can be concluded that the algorithm scales linearly in large networks but is computationally heavy to smaller ones. Thus, Eppstein is considered the faster algorithm providing k shortest paths.

2.4 Dynamic management of traffic environments

The dynamic, or time-dependent, management of traffic environments requires the ability to schedule different movements taking into account the current traffic situation. These movements are based on continuous routing decisions along the time. The dynamic nature of the problem implies a regular planning to deal with unexpected situations, such as deviations from assigned paths. This section considers two different models with dynamic features, capable of scheduling and coordinating concurrent movements within a traffic environment:

– **Petri Net** is a particular representation of the weighted graph, modeling the system with three different components: places, transitions and arcs. A place represents a discrete element, such as a taxiway segment or a runway in the airport movement surface. The transition, as the name implies, is the passage from one input place to an output place. The transition is fired when a set of conditions are satisfied. The arcs are the connecting links between places and transitions. The Petri Net model is represented in Figure 2.5, where places (P) are represented by circles, transitions (t) by bars and arcs by arrows. The solid dot inside the place P_a in Figure 2.5(a) is called *token* and represents an active object, such as taxiing aircrafts on the airport surface. The transitions, like any other road in a traffic transportation system, can be unidirectional (Figure 2.5(a)) or bidirectional (Figure 2.5(b)).

  The authors of [44] present an improved Petri Net model, known as CTPN, that distinguishes different types of *tokens* by assigning specific colors. This representation allows to manage dynamic movements of each active node through the network. In [44], aircraft movements on the ground are characterized as dynamic and concurrent, where synchronization is essential to avoid conflicts. The dynamic adaptation



(a) Unidirectional (b) Bidirectional

Figure 2.5: Petri Net model representation [44].

of the system is based on a set of constraints, where the state of the system is continuously verified in order to predict conflicts and provide a resolution. A constraint is defined as a condition that must be satisfied in order to fire the transition. The main concern of constraints is to avoid conflicts, for instance restricting a single *token* (or aircraft) in the runway or a mandatory separation distance between two aircrafts trailing each other. The aircraft is not allowed to cross a transition until all the conditions are satisfied. In the case there is a conflict, the aircraft is retained a delay time that will assure the synchronization between all movements. Otherwise, the transition is fired and the *token* passes from the input place to the output place [44].

– **MILP** represents a traffic movement surface as a space-time network, where the occupancy of each node changes over the time. This model first assigns an individual ideal route for each mobile and then solves the conflicts by re-routing or holding the mobile in a certain holding point. The network is represented in Figure 2.6, where nodes are circles and segments are straight arcs linking two nodes. Furthermore, traffic circulation rules are shown by arrows and bold nodes represent eventual starting and ending points of routes, for instance gates and runways of the airport. This representation is illustrative of the allowed ground movements within the movement area of the airport, where traffic circulation rules must be followed. For instance, the example shown in the figure represents an airport with the following characteristics: there are both unidirectional and bidirectional taxiways; there is an inner and an outer taxiway to allow the taxiing in both directions; and aircrafts travels either clockwise or counterclockwise.

The algorithm considers a planning interval [t, t+T] which is the set of periods where each target has associated a route for a certain time within the planning horizon T, the last period scheduled by the system. The time of that interval is subdivided into smaller equal discrete slices, each one representing a pre-defined amount of time (e.g. 10 seconds). If a movement takes 17 seconds, the time needed to complete it is rounded to two periods, instead of working with non-linear values[5]. At t_0, the information about the number of periods needed to travel between every pair of nodes is known, based on the length of each link (in meters) and the traveling speed, for instance 16m/s for a fast aircraft and 8m/s for a slower one. The list of aircrafts and its associated taxiing information is also available,

[5]Values below 1 are represented by one period.

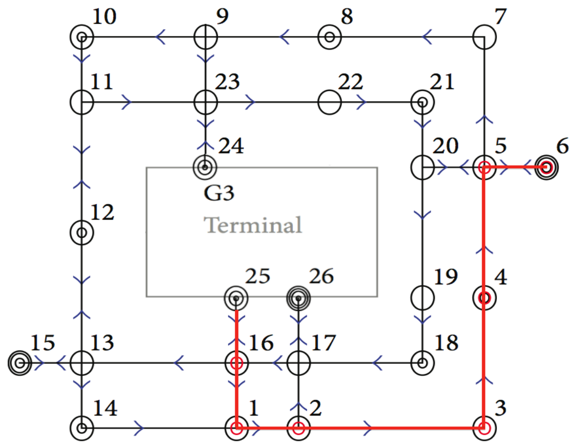


Figure 2.6: Space network representation of an airport [36].

such as the starting and ending points, the estimated arrival/departure times and the taxiing speed. This information is the input for the planning algorithm that will generate the shorter (or easiest) path between the origin and the destination, for each aircraft. This step relies on the static routing algorithms described in the previous section to find the path. For instance, the shorter route between the node 25 (terminal gate) and the node 6 (departure runway) is represented by the bold path in Figure 2.6.

After planning the ideal movements, there is a need to detect and solve the conflicts. The algorithm verifies, for each period of the planning interval, if there is more than one target using the same link or if there are two targets crossing each other. The conflicting routes are re-routed to an alternative path to the same destination or a delay is applied to avoid such conflict. The conflict-free output may cause a target to travel along a longer path, whereas others may follow its ideal planning. In order to dynamically deal with such conflicts, the MILP algorithm checks periodically the current state of the system and the predicted traffic movements within the planning horizon. Typically, the update period is a multiple of six of the period interval. This means that, for a period of 10, the system checks for conflicts every 60 seconds (or 120, 180, ...). This mechanism allows to continuously solve the constraints while maintaining the global performance. Furthermore, the computing time of the algorithm increases with the number of routes to be assigned and the conflicts to be solved. It is then important to define a fixed planning horizon in order to maintain an efficient response time [36].

The Petri Net approach follows a principle of prediction to detect incidents, monitoring each movement by defining a set of constraints that have to be validated whenever an operation takes place. On the other hand, MILP primarily assigns shortest paths that will not collide and then provides alternative routes or holding points to resolve unexpected events. This model is more scalable than the Petri Net since it only considers a finite planning period, avoiding wasting computation effort scheduling movements in a long-term [9]. Furthermore, it addresses the dynamic scheduling problem in a simpler manner, with a more efficient and more accurate mechanism.

2.5 Research projects

2.5.1 Programmes and implementations

This section presents the main conclusions derived from the survey about existing projects related to the study of A-SMGCS recommendations and how it may improve airport safety. In this context, the following programmes and implementations describe the major A-SMGCS operational concepts as part of the state-of-the-art research from EMMA in Europe, where were identified the main European airports: Heathrow (London), Frankfurt Main (Frankfurt), Charles De Gaulle (CDG, Paris) and Schiphol (Amsterdam) [15]. EMMA is the project aiming to achieve an harmonized implementation of A-SMGCS in Europe by implementing, testing and evaluating current A-SMGCS solutions. It is divided in two implementation phases: the first aims to validate and consolidate levels I and II, while the second is the preparation and definition of levels III and IV [2].

- **Linking Existing ON ground, ARrival and Departure Operations:** LEONARDO was a project awarded by the European Commission in the 5th R&D Framework, beginning in December 2001 with a duration of two years. The main concern of this project was the operating cost resulting from uncoordinated and inefficient ground movements in the airport surface. LEONARDO aimed to define a planning tool for managing arrival, departure and ground operations. The system was tested under real conditions, at Madrid-Barajas and Paris-CDG airports. The efficiency, safety and capacity of the airport operations were improved and the workload of the controllers was reduced [15].

- **Integrated Airport Apron Safety Fleet Management:** The AAS was a project co-funded by DG TREN in the Aeronautics and Air Transport Research 7th Framework Programme, that aimed to improve and increase the efficiency of vehicles movements within the movement area of the airport. This project is under development since 2008 for a duration of three years, which tests have been conducted in two airports, namely Berlin Tegel (TXL) in Germany and Oporto (OPO) in Portugal. One of the major components in AAS is the A-Guidance, a software that enables controllers to manage ground movements in real-time by providing accurate and updated positioning data about aircrafts and vehicles. The A-Guidance is basically a graphical application that displays the airport spatial context with the current traffic situation, providing a set of functionalities (e.g. triggering alerts when a safety infringement occurs) that allow a dynamic interaction with the system [35].

- **A-SMGCS at Milan-Malpensa and Stockholm-Arlanda airports:** The Italian Milan-Malpensa (MXP) airport provides levels I and II of A-SMGCS, initially supported by the ASR and SMR surveillance technologies and then enhanced with an MLAT solution and a conflict detection tool [2]. On the other hand, the Swedish Stockholm-Arlanda airport is more or less at the same A-SMGCS level, but provides both SMR and ADS-B capabilities [15].

- **A-SMGCS at Paris-CDG and London-Heathrow airports:** CDG and Heathrow airports are also equipped with the first two levels of A-SMGCS, providing surveillance and control functions. Both have installed an SMR system for detecting unidentified targets, more than one ASR to identify air targets, a RIMCAS as an incursion alerting function and a Multilateration Mode-S for tracking identified ground targets. Whereas Heathrow provides a very reliable surveillance service, CDG has the problem of false detections that affects the controllers performance [15].

In the American context, the NAS programme in the United States aims at improving the operational performance under all weather conditions, enhancing the ground movements coordination and providing a better situational awareness for either controllers and drivers. NAS purposes that ADS-B should be extended to a non-cooperative surveillance service, allowing the reliable detection of intruders and the surveillance of targets without an ADS-B transponder [15]. Furthermore, the FAA has designed the ATGS prototype, as described below.

Advanced Taxiway Guidance System: Automated taxiway lighting system that helps guiding aircrafts along their route on the airport surface. It was evaluated at the Atlantic City International Airport (ACY, New Jersey, United States) with twelve microwave detectors installed on the ground and four RFID antennas and reader units, each aircraft equipped with an identification tag. These relatively cheap sensors allow to first detect the passage of an aircraft over a specific segment of the taxiway and then gather information about its identification.

The system is composed by a host computer, a light control system and the sensors. The host computer is the master controller of the system. It receives information from the sensors (aircraft identification, position and direction) and decides which lights must be turned on. The light control system receives instructions from the host computer to turn on the lights that will guide the aircraft and to turn off those behind the aircraft that are no longer necessary. The system also detects conflicts between aircrafts and provides a warning function to alert the controllers. Through a HMI, the controller is able to hold the aircraft at certain microwave barriers by voice communication or turning off the lights ahead.

ATGS allows the coordination between aircrafts, each one following its assigned route by voice instructions from the controller and by visual support of the lights on the ground. Ground movements are then safer and easier operations, since runway incursions are avoided and pilots are guided to follow the right path without mistakes. This is particularly true when operating under LVO conditions [45].

The A-SMGCS concept proposed by ICAO is being promoted by global entities, such as EUROCONTROL and FAA, which aim at maturing levels I and II of A-SMGCS in order to prepare the next step: extend current implementations with routing and guidance functions. The main goal is to support and improve existing projects in order to achieve a robust and stable A-SMGCS system in almost all airports in the world, from 2020 onwards [15].

2.5.2 The surveillance strategy adopted in Europe

In Europe, much effort is being performed in order to achieve the requirements addressed by A-SMGCS. However, only surveillance and control functionalities are provided in major airports and have not achieved the required level of reliability yet. For that reason, EUROCONTROL planned the surveillance strategy for the next decade, aiming at defining the technological path that will provide safer, interoperable and cost-effective solutions, leading to routing and guidance functions. Such path refers to the passage from levels I and II to levels III and IV of A-SMGCS, by continuously maturing the surveillance technologies. The strategy is divided into several periods, as described below [16]:

- **From 2008 to 2010:** SMR and MLAT Mode-S are the main technologies used to detect both aircrafts and vehicles location. Furthermore, MLAT, combined with ADS-B, allows ground controllers to have information about the identification of the aircraft.
- **From 2010 to 2015:** It is intended to continue the implementation of levels I and II of A-SMGCS, extending the airport traffic situational awareness to both pilots and drivers. It is also required that aircrafts are widely equipped with ADS-B-out transmitters and the airport with ADS-B sensor infrastructures in order to support applications such as ADS-B-APT. Another challenge that will be studied is the ADS-B-in that will provide an accurate and reliable guidance to pilots.
- **From 2015 to 2020:** In this phase, the main effort will focus on the implementation of levels III and IV of A-SMGCS. By 2020, MLAT methods will be replaced by innovative surveillance techniques that will provide more reliable and more accurate positioning of all moving objects. Investigators are already thinking about passive surveillance technologies and Multi Static Radars.

The surveillance evolutionary path is represented in Figure 2.7, where it is possible to notice the transition from SMR and MLAT solutions to a more sophisticated ADS-B system (on the top of the figure) that also provides a more reliable picture to pilots and vehicles drivers. At the bottom of Figure 2.7, the surveillance data processing and distribution refers to the continuous improvement of methods used to process the surveillance data and respective sharing between the infrastructure components.

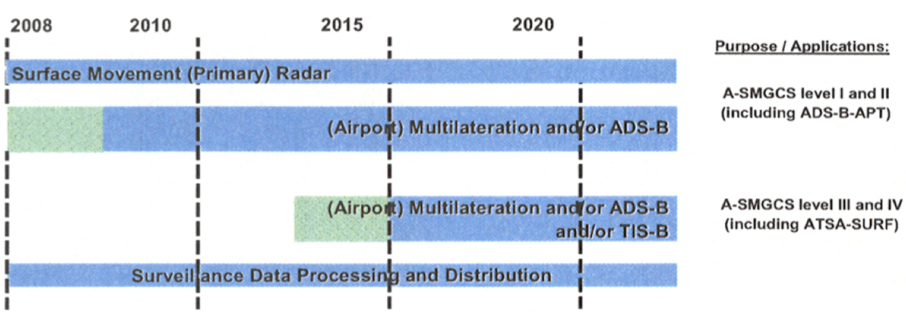


Figure 2.7: The EUROCONTROL surveillance strategy [16].

On the other hand, the transition between levels I and II and levels III and IV of A-SMGCS is explicitly shown in Figure 2.7, where levels III and IV are only predicted from 2015 onwards. This fact is due to the A-SMGCS operational needs, requiring to primarily focus on the surveillance and control services in order to provide reliable and accurate information to routing and guidance functionalities.

Chapter 3

Methodology

This chapter describes how the problem stated in Chapter 1 was solved, based on the existing solutions discussed in the previous chapter. The first section starts by presenting the main A-SMGCS requirements when developing a system providing routing and guidance functionalities. The proposed methodology is then presented, specifying which decisions were made and how the overall system works. Afterwards, a detailed description of the implementation is provided, focusing separately on each feature of the system.

3.1 A-SMGCS requirements

3.1.1 Operational requirements

ICAO established a set of requirements related to the development and implementation of an A-SMGCS [5], aiming to enhance the capacity and safety of surface movement operations in any aerodrome. The main objective of this section is to outline which requirements should be considered while implementing the proposed solution. Later on Chapter 5, the solution will be evaluated according to the requirements defined here.

Table 3.1 presents the basic functional requirements, defined by ICAO, that must be taken into account while implementing an A-SMGCS, with a special emphasis on routing and guidance functions. As shown, each requirement is identified by an unique numbered label (e.g. S2), classified according to the respective function. The outlined requirements are the strictly necessary to be considered within the scope of this thesis, regarding the proposed objectives. For this reason, the surveillance function should provide accurate and continuous positioning about every moving object within the movement area, while the control function mainly handles the aerodrome capacity and detects the conflicts and provides a resolution. If these functions are correctly implemented, the routing and guidance goals will certainly be successfully accomplished. On the one hand, the routing function should designate routes for each moving object within the movement area, allowing for a change of a route or destination at any time. Some of the main concerns are related to the path length and to avoid the conflicts between each movement. On the other hand, the guidance function should improve the compliance of each assigned route by providing clear instructions to the pilot. The system should be prepared to deal with a change of a route at any time, while adapting the traffic flow in order to avoid any conflict or safety hazard.

Table 3.1: A-SMGCS operational requirements [5].

Function	Requirements
Surveillance	• S1: Provide accurate positioning about all moving objects within the monitored area. • S2: Cope either with moving and static objects. • S3: Update moving objects' position along the time.
Control	• C1: Have the capacity for planning the requested movements within a period of up to one hour (static capacity). • C2: Have the capacity for supporting the maximum authorized movement rate at any time (dynamic capacity). • C3: Detect conflicts and provide resolutions.
Routing	• R1: Be able to compute a route for each authorized moving object. • R2: Allow for a change of destination at any time. • R3: Allow for a change of a route to the same destination at any time. • R4: Cope with large flows of traffic at complex aerodromes. • R6: Minimize the length of computed paths. • R7: Minimize the conflicts. • R8: Ease of adaptation to operational changes (e.g. routes closed for maintenance, temporary hazards or obstacles). • R9: Use standard terms and symbols. • R10: Be capable of validating routes.
Guidance	• G1: Provide guidance for every authorized moving object, for any assigned route. • G2: Provide clear instructions to pilots to help them following their path. • G3: All pilots should be continuously aware about their position on their assigned routes. • G4: Allow for a change of a route at any time. • G5: The system should detect routes and areas that are restricted or not available for use. • G6: Allow monitoring the operational status of all guidance aids.

3.1.2 Performance requirements

In Table 3.2 are represented the performance requirements to be considered in the implementation of the proposed solution. These parameters were specifically defined by ICAO to be applied in an airport movement area. The first specification is that the surveillance function should provide the position and identification of every moving object in real-time, by refreshing the information at least once per second. This information must be as accurate as possible, within a radius of 7.5 m. Moreover, the control function must remain extremely reliable, as it should detect above 99.9% of the conflicts and the probability of triggering a false alert is almost 0%. The precision and reliability of these two last functions are crucial to allow a good performance expected from the routing and guidance functions. This is due to the close relationship between the accurate detection of the position of the moving object, the detection of a conflict and consequently the route computation efficiency and the dynamic re-routing and adaptation to tactical changes. Therefore, the routing function should compute the optimal path in less than 10 seconds and recompute an alternative path within 1 second. For the guidance function, it is required that its overall initialization takes less than 2 seconds and that the reversion time spends a maximum of 0.5 seconds.

Table 3.2: A-SMGCS performance requirements [5].

Function	Requirements
Surveillance	• S1: Be capable of detecting an aircraft within a radius of 7.5 m. • S2: The position and identification of a moving object should be updated at least once per second.
Control	• C1: The probability of detection of an alert should be greater than 99.9%, whereas a false alert should be triggered with a probability less than 10^{-3}. • C2: Be capable of responding within 0.5 seconds.
Routing	• R1: The initial route should be computed in less than 10 seconds. • R2: Recompute the path for a moving object should not exceed 1 second. • R3: The optimal routes should be processed with a taxi distance resolution better than 10 m and a timing better than 1 second.
Guidance	• G1: The guidance function should initialize within a maximum of 2 seconds. • G2: The reversion time should not exceed 0.5 second.

3.2 Methodological proposal

3.2.1 Architecture

This section provides a first overview of the proposed methodology, designed to meet the requirements outlined in Section 3.1 and to resolve the problem stated in Chapter 1. Following a top-down approach, the main components of the methodological architecture are primarily described and then each step of the implementation process is explained. The architecture is presented in Figure 3.1, where there are four main components: Surveillance, Routing, Guidance and Application Server. As shown, the first three components interact actively with the Application Server, which manages the real-time incoming data to provide a spatio-temporal context to the controllers and other end-users. Such context includes the positioning of the moving objects in real-time within a specific cartographic representation. Over that representation, it is intended to provide routing and guidance functionalities in order to improve the controllers ability to manage the traffic flow. For this purpose, the Routing and Guidance functionalities will be described in detail.

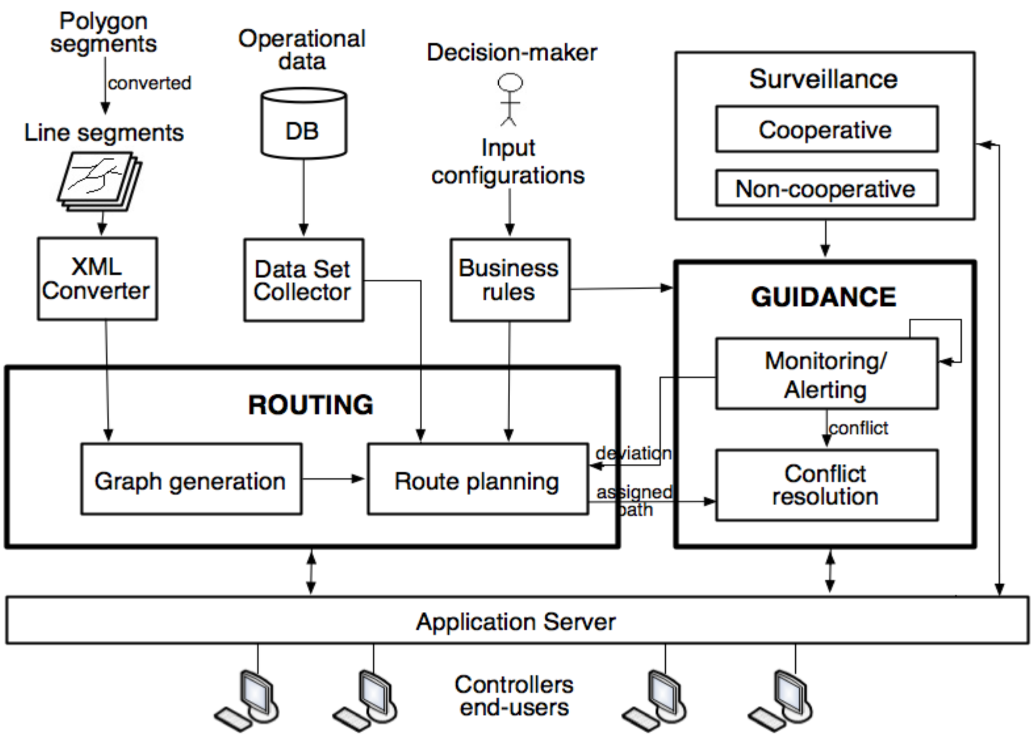


Figure 3.1: Architecture diagram.

The Routing component is responsible for providing static route planning for a set of operational data. As represented in Figure 3.1, the Routing component receives as input data a XML with the cartographic metadata, operational data and a set of business rules. The XML is obtained through a GIS engine that is able to get the guidance line segments of the polygons represented in the traffic area. These line segments are converted to a structured document that is easily readable by any programming language (see Section 3.4.1). Such conversion allows to generate the correspondent graph of the movement area layout, described in more detail in Section 3.4.2. On the other hand, the operational data corresponds to the traffic schedule stored in a database that maintains information about each moving object, for instance its origin, destination, category and type. This information is required to compute a route to each moving object from its current position to its assigned destination, in order to improve the controllers' decision-making. Finally, the business rules include a set of circulation rules and several unauthorized operations, configured by the decision-makers (see Section 3.4.3). These rules must be strictly accomplished in order to avoid incidents incoming from unauthorized movements. For this reason, the route planning function computes routes taking into account these rules, for instance avoiding a route with tight turns or unavailable segments. The Routing component is then responsible for computing static routes to be assigned to each moving object, taking into account the business rules defined for that specific traffic network (see Section 3.4.4). Its interaction with the Application Server allows to inform the controllers about the assigned routes.

Floyd was adopted to compute optimal routes, further to the survey about existing routing algorithms resolving the shortest path problem in the previous chapter. As argued in Section 2.1.3, Floyd only requires a single execution to determine the shortest path between any origin and any destination, although it has the higher runtime complexity comparing to Dijkstra and A*. Thus, a path can be generated whenever it is required and extremely fast. On the other hand, the k shortest paths problem was overcome by computing alternative paths based on the K* algorithm, which will be described in detail later.

The Guidance component is responsible for providing dynamic guidance to each moving object on the traffic movement area. This function requires the Surveillance positioning data in real-time, in order to have geographic knowledge about each moving object every second. The accuracy achieved by the Surveillance component can then compromise the efficiency of the guidance function, which relies on the location of each object to detect deviations from the assigned paths. The main concern of this component is to correlate the static route planning with the current traffic situation, while resolving the conflicts resulting from the uncoordinated movements. So, the Routing component provide the assigned path to each moving object and the Guidance component resolves the conflicts with the other movements by re-routing the object through an alternative path or by applying a waiting time in a pre-defined holding point. The scheduled movements are then monitored to enable the detection of deviations from the assigned paths, for instance when a pilot misses a runway exit. A deviation implies the computation of an alternative path, which will be evaluated with respect to the conflicts with the other movements. The Guidance and Surveillance components also interact with the Application Server, providing real-time information about the location of each moving object and the guidance indications to the drivers (see Section 3.4.5).

The dynamic management of traffic movements was based on the MILP model, previously discussed in Section 2.4. This method firstly determines the shortest path to be assigned based on discrete decisions about predetermined pathways, then monitors the scheduled movements with continuous decisions. Such approach allows a continuous and accurate scheduling of movements based on the allocation of resources (e.g. TWY segments) as time goes by. Furthermore, this model is scalable because it only considers one ”window” at the same time, instead of wasting effort planning for a distant future [9]. The implementation is described in detail in Section 3.4.5.

3.2.2 Implementation flowchart

The flowchart represented in Figure 3.2 highlights the main steps of the implementation of the proposed methodology. Prior to explain each step of the flowchart, let us consider a generic description of the schema to understand the basic mechanism. The metadata provided by the GIS engine allows to generate a weighted graph and its corresponding adjacency matrix. This information is used by Floyd to compute the optimal path between every pair of nodes in the graph. Then, as shown in Figure 3.2, the routing and guidance functionalities are repeatedly applied along the time. The first main dashed block represents the routing mechanism, where the optimal path is assigned to every moving object that will pull out during the next window interval. If a conflict is detected, this path is recomputed. When all moving aircrafts are processed, the guidance mechanism begins. This second dashed block processes every active (i.e. processed) moving object individually, in order to verify if the moving object is following its assigned path correctly. When a deviation is detected, the routing function is called over again to compute an alternative path and to re-insert the mobile in the system. Furthermore, it should be noted that the guidance function is processed for each time interval, that corresponds to the pace of the simulation, explained in detail later in this chapter. Still, the window interval represents the periodic scheduling time, when the next active mobiles are processed.

The proposed solution is composed by 8 main steps, as follows:

- **Step 1:** The cartographic information provided by the GIS engine serve as an input to the generation of the weighted graph. This metadata contains information about the shapes' geometry of the airport surface configuration, such as the length and identification of each segment, the geographical coordinates of every sub-point in the segment and even the maximum speed allowed for each specific segment.

- **Step 2:** The Floyd algorithm is initialized based on the adjacency matrix, created from the weighted graph. The algorithm computes two additional matrices, containing information about the optimal paths between every pair of nodes, for the current network configuration. Whenever the network changes its configuration, for instance due to a closed route or temporary hazard, this step is repeated.

- **Step 3:** This step corresponds to the acquisition of the moving objects that will start taxiing within the next window interval. This information is stored in the flights' database, containing each object identification, category, flight type and the coordinates of the origin and destination points for that specific object.

- **Step 4:** Based on the information mentioned in step 3, the optimal path is assigned to each moving object, without considering the other movements.

- **Step 5:** The system verifies if the path assigned in step 4 is conflicted with the other movements. If a conflict is detected, the less priority of the two involved mobiles is re-routed or is ordered to wait in an hold point. This reorganization can cause another conflicts, forcing the detection of conflicts over again. Furthermore, this step guarantees that all movements are coordinated and there is no possibility of an hazard, if and only if every mobile strictly follows its assigned path.

- **Step 6:** When all moving objects have a path assigned and there is a time schedule to each movement, the guidance function will monitor each active object movement. This step allows to get the first active object currently moving on the ground.

- **Step 7:** The moving object deviated from the assigned path, meaning that it followed a different segment than the expected. In order to avoid conflicts, an alternative path to the same destination is computed and the moving object is re-inserted in the system, returning to step 5.

- **Step 8:** The moving object reached its destination and is removed from the system.

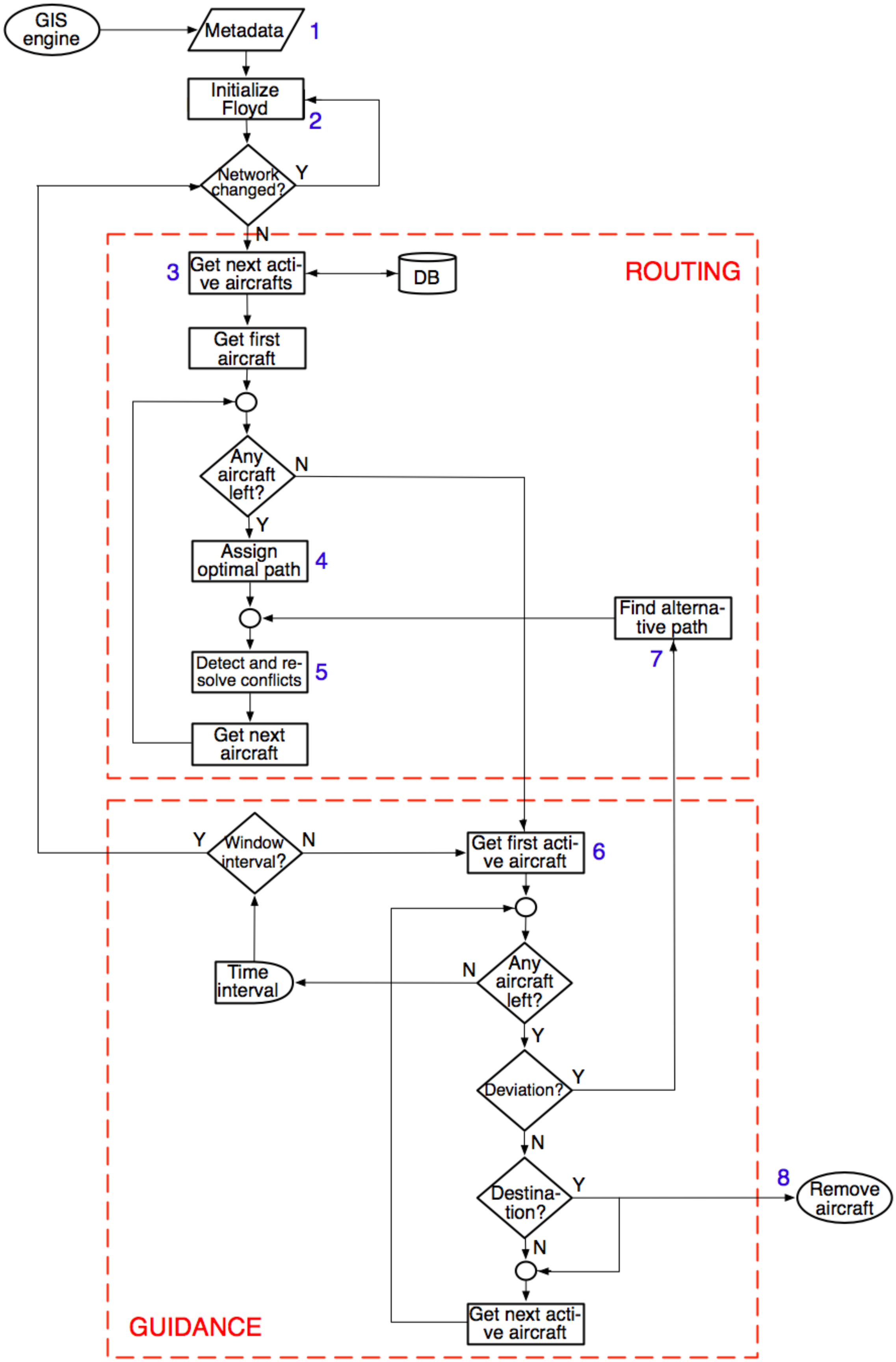


Figure 3.2: Proposed solution flowchart.

3.3 Domain model

The first approach to implement the proposed methodology passed by designing a domain model, describing how the classes of objects are correlated. The model was developed in UML and consists of four main components/objects: RouteGuidance, Floyd, MILP and MovingObject (see Appendix A.3). These components will be described in detail below, but let's consider the sub-components first: Point, Segment, Path and Matrix. A Point represents a point in space in the coordinate system, while a Segment corresponds to a line with a start and an end point, with a length associated. A Segment is decomposed in sub-segments, marked by a list of points. Both the Point and Segment classes are identified by an unique integer. Furthermore, a Path contains the information about a route, but not the route itself. This means that a Path provides the origin and destination points of a route, but does not have knowledge about the route segments. When a Path is assigned to a MovingObject, a *callSign*[6] is generated, the *startTime* is marked and the expected *endTime* is calculated. Finally, a Matrix is a two-dimensional vector of integers with a specified size.

The main components of the model are:

- **RouteGuidance:** This is the main class of the project. It is responsible for managing the metadata provided by GIS, by reading the XML and generating the respective graph and adjacency matrix. First, the XML is read and the segments are saved in the *segments* Dictionary (see Section 3.4.1). Then, the graph is generated and the coordinates of each node are saved in the *graphPoints* variable. With the *segments* and the *graphPoints*, the adjacency matrix is created (see Section 3.4.2). Then, after searching for *endSegments* and *wrongTurns* (see business rules in Section 3.4.3), the RouteGuidance instantiates the Floyd and MILP algorithms.

- **Floyd:** This class manages the data related to the Floyd algorithm. Taking the *adjacencyMatrix* as the input, it generates the *sMatrix* and the *rMatrix* matrices (see Section 3.4.4). These matrices contains the information about the shortest path between every pair of nodes. For instance, the method *ComputePath()* returns a list of integers, each integer corresponding to the ID of a segment. When a valid path is computed, the boolean *pathFound* becomes true and the *pathCost* is marked with the length of the route.

- **MILP:** The MILP is the heart of the project, since it is where the paths are assigned to each MovingObject, the movements are coordinated and the conflicts are detected and resolved (see Section 3.4.5). This class maintains information about each mobile and periodically assigns a path to the next active moving objects (obtained from the DB). The SortedDictionary *pathsSchedule* represents the table of the assigned paths, continuously updated to maintain the information about all movements in real-time.

- **MovingObject:** This class holds the information about each moving object, for instance its ID, category, type and speed. The Category can be either Small, Medium or Large, while the Type is

[6]A callSign is a string that uniquely identifies a movement of a MovingObject (e.g. TP315).

Arriving or Departing. Furthermore, the moving object receives a non-conflicted path when entering the system. This path must be followed by the driver/pilot in order to respect the movements schedule.

This domain model was based on an object-oriented paradigm, where each object maintains information about itself individually. However, these objects are directly related. For instance, the RouteGuidance stores a list of Points and a Matrix that corresponds to the graph information, a list of Segments with the line segments metadata, and a reference to the Floyd and MILP objects. Furthermore, the Floyd object has two Matrices used to the path computation, in addition to the adjacency Matrix that was previously created by the RouteGuidance. On the other hand, the MILP object is composed by two main lists, namely the Moving Objects that are stored on the database and the active objects that are currently moving. Finally, the MovingObject has a Path associated, with a origin and destination Points. This domain model was designed to cope with each functionality individually, structured to allow the RouteGuidance to manage the global variables (e.g. graphPoints, segments, matrix and wrongTurns) to be accessible from the Floyd and MILP, which has a specific task to perform.

3.4 Implementation framework

3.4.1 Metadata extraction from the segments layer

This section pretends to describe in detail the implementation process of the proposed methodology. The first step consists in collecting the geographic information of the movement area, in order to construct a graph corresponding to its spatial context. This context is managed by a GIS engine that extracts the metadata from the geographic representation. The GIS software used was the ArcGIS 9 from ESRI, which provides the possibility to export a geodatabase feature class to a XML document. A geodatabase is composed by a set of thematic layers, each one described in a feature class. A feature class organizes a set of geographic features with the same characteristics in a shapefile, where each feature has the same geometry type (e.g. point, polygon, line), the same attributes and the same spatial reference. Then, the feature class can be exported to a XML, considered to be the most powerful language to represent the data due to its simplicity and universality structuring information. The XML organizes the metadata by attributes, with a specific geographic coordinate system associated. ArcGIS uses WGS 1984 (or WGS84) as the default coordinate system, in a two-dimensional spatial reference with a resolution of approximately 8.983 x 10^{-10} decimal degrees [46].

The structure of the XML is a RecordSet Object, defined by ESRI (see Figure 3.3). The document is composed by a set of fields and a set of records. Each record is composed by a set of values, one for each field in the record set. The number and order of values for a record must correspond to the set of fields. Each value, in turn, consists of a set of attributes which are the parameters of the current field.

As an illustrative example, a sample of the XML used in the implementation is presented in Appendix A.1. This XML was generated by ArcCatalog - Arc Editor, the component of ArcGIS responsible for storing and managing the databases and other ArcGIS related data. The document follows the structure presented in

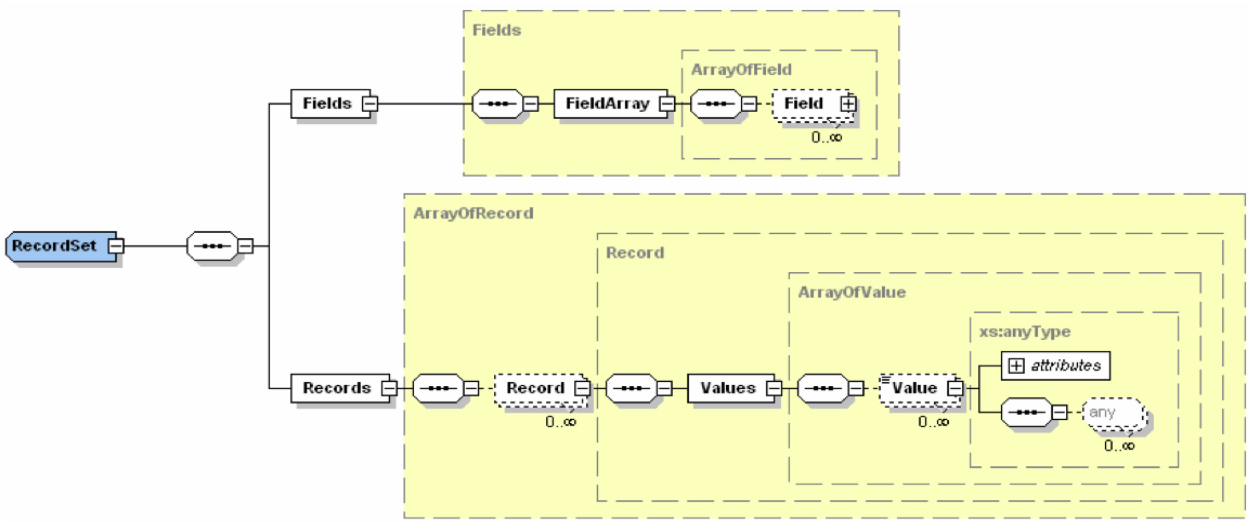


Figure 3.3: ESRI RecordSet Object [47].

Figure 3.3, where each record contains the metadata correspondent to a line (or segment) in the transportation network. The Appendix A.1 shows one of the records, where some of the values were omitted because they are not required for the current analysis. The record is composed by four main values: record ID, path array, shape length and stand specification. The record ID is an integer that uniquely identifies the shape. The path array is a specific type of ESRI, for instance PolylineN, that defines the shape configuration: the minimum and maximum x and y values, and the array of points of the shape. Each point is a (x,y) pair with a 14 decimal cases precision, georeferenced in the WGS 1984 coordinate system. Furthermore, the shape length is represented by a double (in decimal degrees). The last value is a string that indicates if the segment is a stand or not.

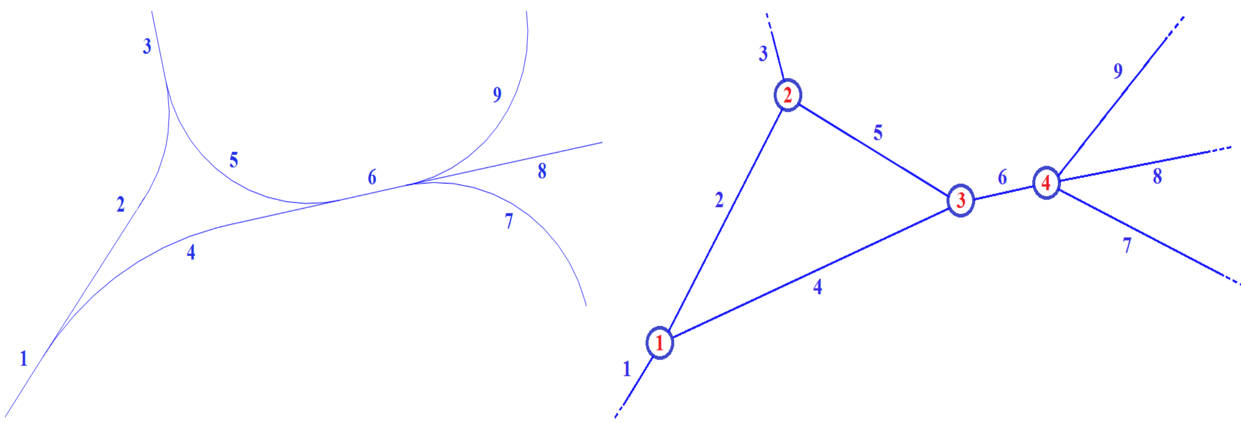
Moreover, part of the code for accessing the XML file is presented in Appendix A.2, which corresponds to the read of the path array value. Using the C# XML library, the XmlTextReader type allows to read each node of the stream at a time. Then, for the example shown, the coordinates of each point are collected and added to a list of points belonging to that specific record (or segment).

3.4.2 Graph and adjacency matrix generation

The metadata provided by GIS allows to generate the graph correspondent to the transportation network, where each record is represented by an arc and the nodes represent the intersections between different segments. These nodes are basically the extremity of a segment touching the extremity of another segment, or even the end of a route. In order to apply a path planning algorithm to the graph, the nodes should be numbered. For this purpose, a graph point is generated for each extremity of every segment. This feature was implemented by computing the distance from a given point to all the other graph points, according to the formula (3.1) [48].

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{3.1}$$

Since the coordinates of each point are in decimal degrees, the result was converted into meters[7]. Two distinct points were considered the same point if the distance between them was less than 10 cm (configurable value). Then, for each new segment, both extremities were compared to the graph points generated so far. If an existing graph point was close enough to the extremity, this last one was registered with the same ID. Otherwise, a new sequential ID was generated. The graph conception is shown in Figure 3.4, where the segments represented by GIS (Figure 3.4(a)) are converted to a graph with arcs and nodes (Figure 3.4(b)). As shown in Figure 3.4(b), every intersection between two or more segments is represented by a numbered node. For instance, segments 4, 5 and 6 converge to a common point, which has the number 3.



(a) Map segments

(b) Graph representation

Figure 3.4: Segments representation in a graph.

The passage from the spatial layout representation to a graph is illustrated in Figure 3.5, where the Lisbon airport is represented on the left hand side as a set of overlapped layers. The layer of the TWY guidance lines is highlighted on the right side screen, where the nodes corresponding to TWY segments have been added as well as arrows representing traffic circulation rules.

Furthermore, the adjacency matrix was also generated. This matrix has information about the length between every pair of nodes belonging to the graph. Thus, the matrix was created by assigning the length of each segment to the respective position in the matrix. For instance, if a given segment is 15 m long and has the start point 8 and the end point 23, then the cell (7, 22)[8] and the cell (22, 7) will be filled with the number 15 (assuming the segment is bidirectional).

[7] A decimal degree represents 111319.9 meters at the equator on the WGS84 coordinate system [49].

[8] This numeration is due to the vector's structure: [0, n-1].

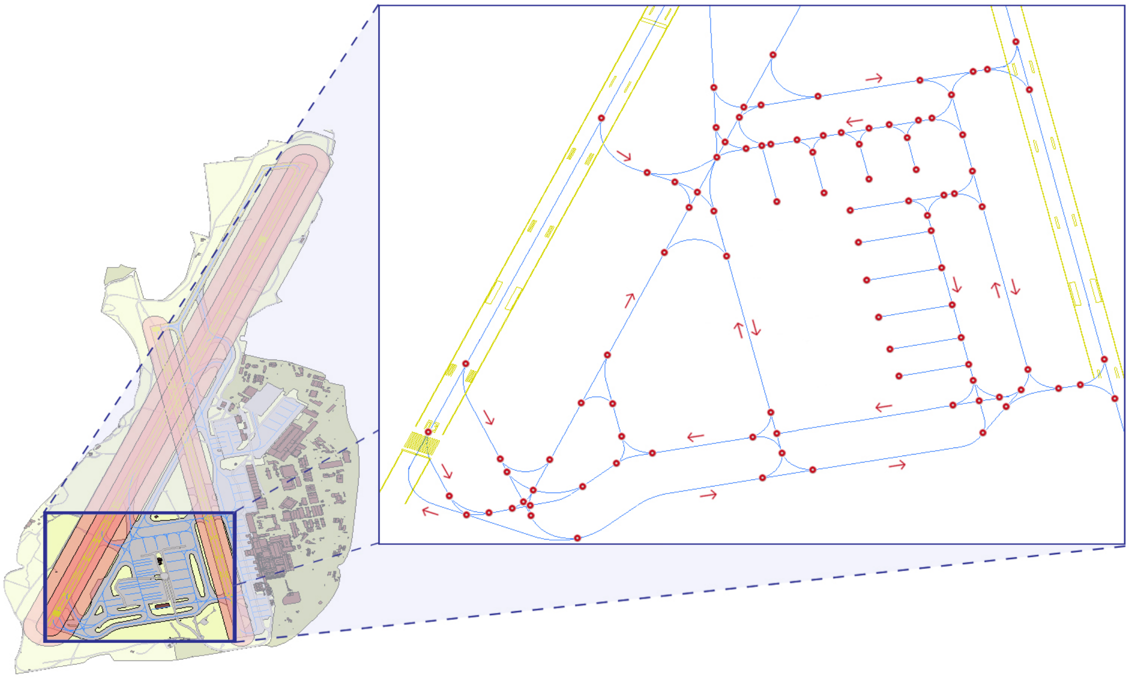


Figure 3.5: Graph representation of the TWY guidance lines in an airport.

3.4.3 Business rules

Although the graph representation allows to compute optimal paths by applying a routing algorithm, there are a set of business rules that should be considered in the implementation process. A business rule is a "statement that defines or constrains some aspect of the business. It is intended to assert business structure or to control or influence the behavior of the business" [50]. In other words, a business rule defines how a specific feature of the business should be performed. This section presents which business rules were considered and how they were implemented.

Circulation rules: In a traffic environment, the authorized moving objects must fulfill a set of circulation rules that allows to uniform each driver behavior. For instance, each segment has a speed limit allowed that is defined according to the type of road or even to the visibility constraints. Furthermore, the circulation senses and signaling are used to improve the drivers awareness about the circulation rules. Another important circulation rule is the priority given to each moving object. There are a set of rules defining which moving objects have more priority, with respect to their type, size and other specific characteristics (see Section 4.3.2). Finally, it was also considered, in the case of the airport, that the aircrafts are not allowed to reverse, forcing to go around and find another path when the route can not be crossed. Another remark is that all segments were considered bidirectional.

Unauthorized turns: A moving object should not make a tight turn. For this reason, turns making an angle between 0° and 100° were disabled[9]. The angle of a turn is the angle between two linked segments, where each segment represents a vector. As represented in Figure 3.6, A and B are segments and p3 is the vertice for $\widehat{\mathrm{AB}}$. We are interested on the calculation method of the angle θ from the three vertices.

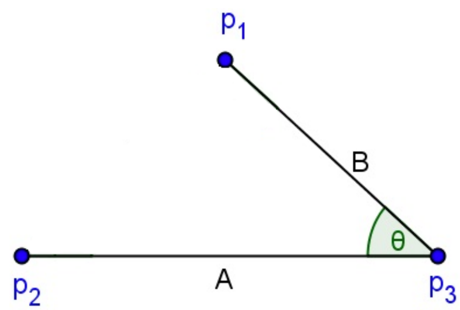


Figure 3.6: Angle between three points [51].

The first formula of the equation (3.2) defines the dot product between A and B, from which was mathematically deduced the angle θ (the third formula of equation (3.2)). The |A| represents the length of the segment A, previously defined in equation (3.1). Then, to convert from radians to degrees, θ is multiplied by $180/\pi$.

$$
\begin{aligned}
&A.B = |A||B|cos(\theta) \\
&\theta = \arccos \frac{A.B}{|A||B|} \\
&\theta = \left[\frac{(x_2 - x_3)(x_1 - x_3) + (y_2 - y_3)(y_1 - y_3)}{|A||B|} \right]
\end{aligned}
\tag{3.2}
$$

An illustrative example of the types of turns is represented in Figure 3.7, where the turn A represents a tight turn with an angle of 22° and the turn B represents a normal turn with an angle of 152°. As shown, the turn A is extremely tight to be performed by an aircraft, for instance. On the other hand, turn B is much smoother and does not require an abrupt change to the trajectory.

[9]Turns that are directly linked with stand parking areas were not disabled because they are represented with an angle of 90° to make the routing easier.

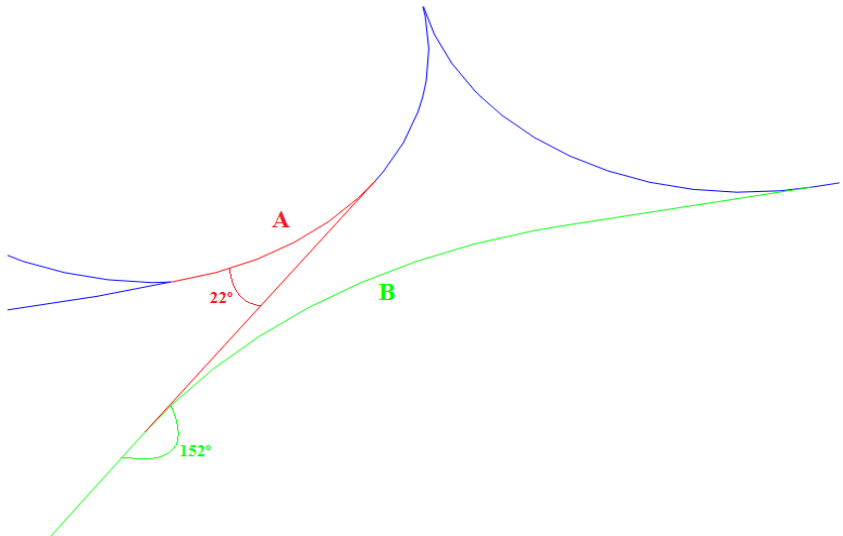


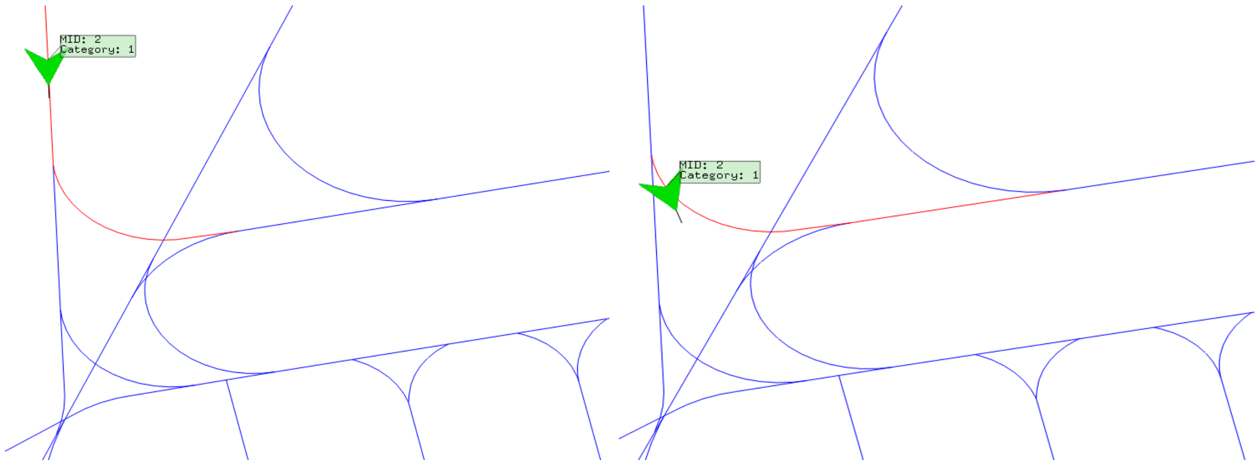
Figure 3.7: Types of turns: tight (A) and normal (B).

Intersections: An intersection between two line segments is not detected when their extremities are coincident. So, segments having an intersection point that is not an endpoint of the line can cause a conflict between two moving objects because the system did not detect that the routes cross each other. In order to avoid such conflict, intersections were detected through a method that considers the endpoints of each line segment. Let us consider a segment A with the endpoints p_1 and p_2 and a segment B with the endpoints p_3 and p_4. Each point is represented with two-dimensional coordinates, for instance $(x_1,\ y_1)$ for p_1. The segments A and B have an intersection point if and only if $0 \leq U_a \leq 1$ and $0 \leq U_b \leq 1$ (see equation (3.3)). These equalities guarantee that the lines end on their extremity, instead of considering infinitely long lines. If so, the lines have always an intersection point in the infinite if they are not parallel [52].

$$
\begin{aligned}
U_a &= \frac{(x_4 - x_3)(y_1 - y_3) - (y_4 - y_3)(x_1 - x_3)}{(y_4 - y_3)(x_2 - x_1) - (x_4 - x_3)(y_2 - y_1)} \\
\\
U_b &= \frac{(x_2 - x_1)(y_1 - y_3) - (y_2 - y_1)(x_1 - x_3)}{(y_4 - y_3)(x_2 - x_1) - (x_4 - x_3)(y_2 - y_1)}
\end{aligned}
\tag{3.3}
$$

Guidance lighting system: Aiming to provide guidance instructions to the drivers, an automated lighting system was implemented based on the American ATGS [45]. The system follows a n+1 policy, meaning that only the current segment and the segment immediately ahead are considered. This feature allows to provide visual information to the driver in real-time, improving his/her capacity to decide which road to take. As represented in Figure 3.8, the n+1 segments are highlighted to allow the driver to follow the correct path.

This system implements an inexpensive solution, which only considers the strictly necessary lights, instead of turning on the whole set of lights belonging to the path to be followed. In Figure 3.8(a), the moving object is guided to make the turn, since the current segment and the next segment (turn) are switched on. As soon



(a) Guidance to follow the turn.

(b) Guidance to go straight.

Figure 3.8: Guidance lighting system.

as the mobile passes from one segment to another, the lights concerning the previous segment are turned off and the lights of the next segment in the path are turned on. This transition is represented by the passage from the Figure 3.8(a) to the Figure 3.8(b), where the previous segment is turned off and the next one is turned on.

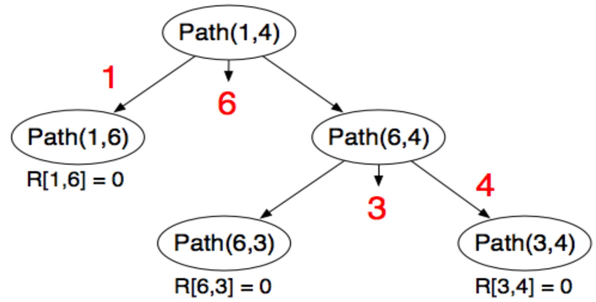
3.4.4 Routing algorithm

Floyd uses the adjacency matrix generated from the XML to create the S and R matrices. Initialized with $S^0 = W$ (W is the adjacency matrix), the S matrix is consecutively updated with the minimum length between every pair of nodes. Nevertheless, the unauthorized turns business rule introduces an obstacle to the default mechanism of the algorithm because it does not distinguish between a tight and a normal turn, since it only works with nodes that are linked over a network. So, this problem was solved by implementing an alternative mechanism to compute a path containing tight turns.

On the one hand, the default path computation of the Floyd's algorithm is based on the Figure 3.9. Figure 3.9(a) represents the final matrix of the algorithm execution, containing the routing information between every pair of nodes. For instance, there is a direct link between nodes 3 and 4 with a length of 2 and there is a non-direct path between nodes 3 and 5 with a length of 5, with the intermediate node 4. Using this information, the path between nodes 1 and 4 was then computed and the intermediary steps are shown in Figure 3.9(b). The path between 1 and 4 has an intermediary node 6, according to the cell (1,4) of the matrix. The next step is to find the path between 1 and 6 and between 6 and 4. This process is repeated until there is no other intermediate nodes, verified by the equality R[origin, destination] = 0. In this example, the path is 1 - 6 - 3 - 4. Another example is presented in Appendix A.4, where the shortest path between two points A and B is illustrated.

	1	2	3	4	5	6
1	0	2(6)	2(6)	4(6)	3	1
2	2(6)	0	2(6)	4(6)	5(6)	1
3	2(6)	2(6)	0	2	5(4)	1
4	4(6)	4(6)	2	0	3	3(3)
5	3	5(6)	5(4)	3	0	4(1)
6	1	1	1	3(3)	4(1)	0

(a) S and R matrices (in parenthesis are the R values).



(b) Path computation between nodes 1 and 4.

Figure 3.9: Floyd path computation.

This routing mechanism allows to determine a path extremely fast because the Floyd matrices are always the same, unless there is a change on the network configuration. So, the time spent at the beginning to create the matrices is insignificant, comparing to the real-time requirement of computing a path. Nevertheless, a mechanism was implemented to speed up the initial creation of the matrices. These matrices are only computed once, storing the routing information on a file on the computer's disk. The following executions use this information from the file, without computing anything. If the graph network suffers a modification, the initial computation must be redone.

On the other hand, the alternative mechanism to compute paths without unauthorized turns aims to solve the problem presented in Appendix A.5. The shortest path between A and B contains a tight turn (represented with a circle), so the system should find an alternative path that avoids such turn. The solution passes by ignoring paths with unauthorized turns, meaning that the value contained in the S and R matrices for a specific path between two nodes remains unchanged if there is no other route. If some of the conditions presented in equation 3.4 is satisfied, there is some tight turn between the nodes i and j. The k represents the intermediary node being executed, while the expression R$[i, j]$ represents the value on the cell (i, j) of the R matrix. UT(i, k, j) represents an unauthorized turn starting from i and ending with j, passing by k.

$$\begin{aligned} &UT(i,k,j) \\ &UT(R[i,k],k,j) \\ &UT(i,k,R[k,j]) \\ &UT(R[R[i,k],k],k,j) \\ &UT(i,k,R[R[k,j]]) \end{aligned} \tag{3.4}$$

These conditions guarantee that paths with unauthorized turns are ignored by the routing algorithm, keeping the cell (i, j) without a value. These cells are treated in another way, which route is computed from the destination to the origin. This process determines the alternative shortest path between nodes i and j.

It was inspired in K*, but uses the A* algorithm in the backward sense by applying an heuristic decision in each iteration. The decision consists in selecting the closest node to the destination (in this case, the origin i). This means that, among the linked nodes, the node that is less distant to i is chosen and belongs to the path. So, starting from the destination j, each linked node is inspected. This last node repeats the process, and will eventually reach the origin i. The result is the reverse path between i and j.

In the case there is a conflict between two moving objects and an alternative path is required, Floyd is not able to compute an alternative route different than the initial one because it only considers the shortest path. Considering that the mobile requiring an alternative path has already started moving, it needs a different route than the initial one computed by Floyd. So, the same mechanism as in the case of unauthorized turns is applied, computing the k shortest paths on-the-fly while being guided by an heuristic function, where k refers to the number of the nodes that are directly linked with the destination node. The resulting k shortest paths are sorted by their length, where the routing function selects the shorter to be assigned as the shortest path.

3.4.5 Guidance programming model

MILP allows to assign static routes for each moving object, coordinate the movements in order to avoid conflicts and then dynamically adapt them to cope with deviations from assigned paths. As previously explained in Section 2.4, the path planning procedure is executed every window interval (configurable value). This interval represents the amount of time in which the targets that will start moving receive a path. So, the paths are assigned to each moving object every 5 minutes, for example. On the other hand, the simulation has also a time interval associated, defining the pace of the simulation (configurable value). This means that the simulation is executed every second, for instance. As an illustrative example, Figure 3.10 presents the time scheduling for 4 different moving objects. Each moving object has a segment ID associated for every time interval (1 second), allowing to compare to other movements in order to detect conflicts.

As shown in Figure 3.10, there are two conflicts where the segments are highlighted. The first conflict is between mobiles 1 and 3 because they are using the same segment at the same time, which can cause a persecution or a frontal collision. The second conflict is between mobiles 2 and 4 because they are using segments that belong to the same intersection. In order to avoid such conflicts, MILP determines which moving object has more priority and re-routes the other through an alternative path or holds it for an amount of time. The choice between re-routing and the holding point is made based on the time spent by each one, meaning that the re-routing is preferable if the difference to the original path spends less time than the holding time. For instance, if the moving object 3 has more priority than the first one, then the moving object 1 start time is delayed for a conflict interval period, if and only if the alternative path takes too long. This conflict interval is configurable and allows to separate the two movements for 20 seconds, for instance. This guarantees that the moving objects involved will use the same segment at different times. In this case, the moving object 1 would be delayed 20 seconds.

Once the movements are scheduled and coordinated, a simulation thread is launched. This thread is

	Moving object			
Time (s)	1	2	3	4
0:00	330			
0:01	330			
0:02	330			
0:03	330		330	
0:04	330		330	
0:05	330		330	
0:06	330		330	
0:07	330		330	
0:08	500		330	
0:09	500		504	
0:10	500		504	
0:11	500		504	
0:12	500		166	
0:13	155	10	166	
0:14	155	10	166	
0:15	155	10	166	
0:16	155	17	166	15
0:17	155	17	166	15
0:18	155	17	166	15
0:19	177	17	122	15
0:20	177	17	122	76

Figure 3.10: MILP path planning schedule.

used to manage the simulation, including the path planning scheduling and the conflicts resolution. It is also responsible for counting the time, creating a new thread to each moving object when it is time to start moving. This last thread, in turn, manages the information related to a single moving object. It is responsible for monitoring the movement along the assigned path, providing guidance assistance through the guidance lighting system. In case of a deviation from the assigned path, this thread notifies the simulation thread that an alternative route must be computed to that specific mobile, repeating the initial path planning process.

Chapter 4

Case study

The case study focuses on the airport domain, more precisely on the ground movements of the aircrafts on the airside of the airport. This chapter first gives an overview of the airport context, providing technical information about the performed business procedures within the movement area. Then, the historical evolution of the A-Guidance system is presented, which has been extended with routing and guidance functionalities. Such extension faced a set of implementation issues related to the cartographic precision, the business rules compliance and other performance constraints, that are representative of the required adaptation of the proposed methodology to this particular case study.

4.1 Airport contextualization

Airports are considered as very large, dynamic and complex systems that involve aircrafts, support trucks, maintenance vehicles, baggage-handling equipment and many other systems that simultaneously operate in the same surface movement area [35]. The required interoperability between these systems forces the stakeholders (e.g. ATCOs, airport managers, handling supervisors, pilots and vehicle drivers) to spend a huge effort synchronizing ongoing ground operations. Although each stakeholder group operates in different fields and with different goals, they act proactively and collaboratively towards a collaborative monitoring system that improves the situation awareness about safety breaches. However, incidents happen and stakeholders are not always able to efficiently react to business services demands when working under time pressure.

Nowadays, the usual procedure to manage airport ground operations is based on the manual positioning of vehicles and aircrafts in predefined locations. Therefore, decision-makers are not prepared to deal with unexpected schedule changes, operating without being informed about current operational needs. The triggering of non-planned events must then be enhanced with dynamic mechanisms to allow decision-makers to accurately respond to task changes, instead of relying on voice communications to synchronize each target movement [8]. These mechanisms include being continuously aware about every situation that may delay turnarounds. Situation awareness must then be improved through location-based services to accurately provide a real-time picture of aircraft and vehicle movements [53].

In fact, the A-SMGCS strategy aims to improve the traffic flow and the capacity management in any aerodrome, while reducing the operational incidents. The A-SMGCS should be implemented according to the level of complexity of the aerodrome, namely the layout complexity, traffic density and visibility conditions [3]. The aerodrome layout complexity is based on the routing network defined by the TWY and RWY, used respectively by the aircrafts and the vehicles. This network is obtained from the guidance lines, which are represented in the center of each route. The Appendix A.6 illustrates the TWY guidance lines, including the intersection points between TWY, the RWY exits to the TWY and even the holding points where the aircrafts have to wait to avoid conflicts.

Moreover, the movement area of an airport is composed by a manoeuvring area and a restricted area called apron, which are represented in Figure 4.1. The manoeuvring area is used by aircrafts to take-off, land or travel along their path. The RWY is the track where the aircraft takes-off and lands, surrounded by a protection area for safety purposes. On the other hand, the apron is the part of the airport that enables the loading of passengers, the maintenance and parking of aircrafts or other ground handling activities. Aircrafts have to follow a route from the RWY to the gate (or vice versa), while vehicles are mostly used to provide support to the aircraft (e.g. push-back) [6].

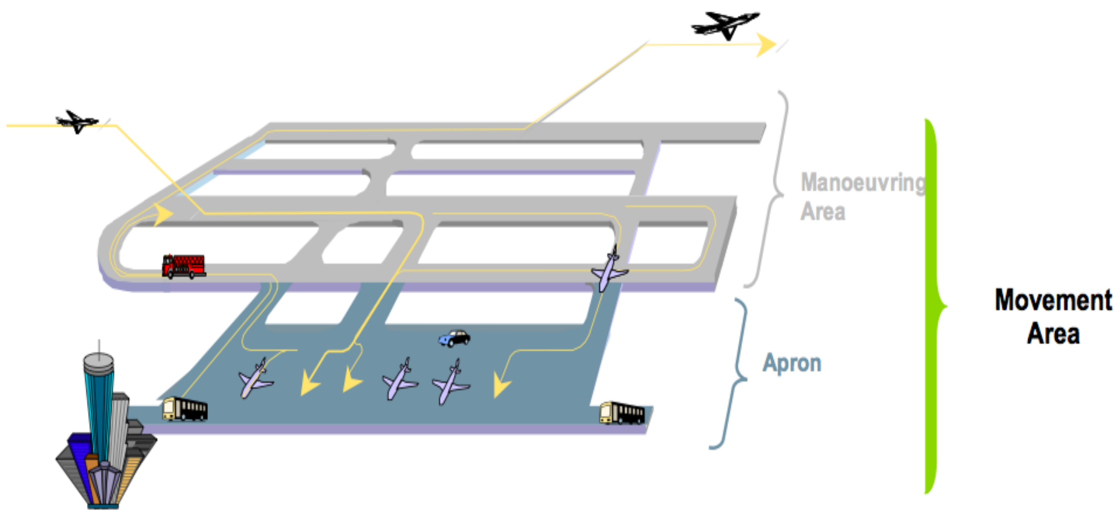


Figure 4.1: Airport layout [6].

The methodology presented in the previous chapter will be applied to the TWY guidance lines network, aiming to provide routing and guidance assistance to the aircrafts. The network is represented by the light lines in Figure 4.1, where the taxiing aircrafts must comply with a set of business rules. These rules are extremely sensitive in such a critical environment, considering that a single failure may compromise the operational safety. The most relevant business rules, previously presented in Section 3.4.3, are the circulation rules, the unauthorized turns and the conflicts resolution priorities. In particular, the conflicts are solved considering the category and type of the aircraft. The largest aircrafts have priority since they carry more passengers, as well as the departing aircrafts which are releasing airport resources.

Furthermore, the methodology mainly focus on taxiing aircrafts, from landing to take-off. However, only taxi-in and taxi-out processes are considered as part of the whole turnaround process. The taxi-in is the period between the exit of the RWY and the arrival at the gate, while the taxi-out corresponds to the reverse travel from the gate to the departure assigned RWY [17].

4.2 A-Guidance

4.2.1 Project scope

The A-Guidance is an implementation of the A-SMGCS concept, being developed by the INESC-Inovação research team in collaboration with the ANA-Aeroportos, the main airport management authority in Portugal. This platform complies with levels I and II of A-SMGCS and is experimentally deployed in Lisbon and Oporto, the major airports in Portugal [53]. This thesis aims to extend its functionalities to support levels III and IV by implementing the proposed methodology applied to the Lisbon airport as the test-bed. Such implementation required a set of information such as the cartographic metadata, the positioning of moving objects in real-time and a set of business rules. The following sections make an overview of the A-Guidance architecture and main components, describing how the routing and guidance functions were implemented based on the technologies and data already embedded in the existing platform. However, several issues affecting the implementation were detected, the resolution of which is presented in detail in Section 4.3.

On the one hand, A-Guidance is recognized as an integrated GNSS/EGNOS low-cost portuguese solution that provides a set of services for the airport management in low-visibility and emergency situations. These services include monitoring, control, support to decision-making and interoperability within the airside of the airport, which will be discussed in Section 4.2.3. This project is being progressively deployed at the national airports managed by ANA, being altogether a modular and interoperable solution that complies with the ICAO requirements and recommendations [1].

On the other hand, this solution was based on the know-how acquired from several European I&D projects, namely AIRNET (2004-2006) [6], LocON (2008-2010) and AAS (2008-2011). These projects are related to the efficiency and safety of ground movements within the airside of the airport, which have been improved with innovative wireless communication systems, GNSS real-time positioning devices and cartographic GIS engines along the last decade. Within the AAS system, the A-Guidance represents one of the major software components that is responsible for detecting safety hazards between moving vehicles. Such detection includes a continuous processing and validation of location-based data, correlated with other GIS techniques such as geographic localization, to determine either an alert should be triggered or not [7].

4.2.2 Architecture

The A-Guidance system is based on a modular solution providing location-based services that integrate the positioning data collected from moving objects with external systems containing information about flights, vehicles and worker tasks. The system was designed to collect real-time data from cooperative (e.g.

vehicles) and non-cooperative (e.g. aircrafts) mobiles, namely their geographic location, ID, category and current speed. Such information is acquired from the interaction between the components of the A-Guidance infrastructure, represented in Figure 4.2.

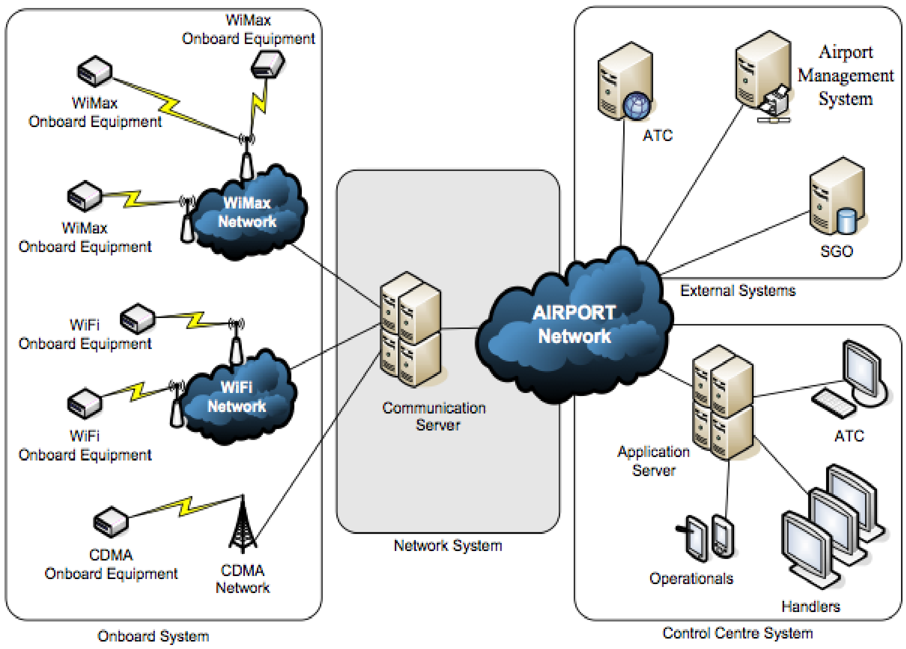


Figure 4.2: A-Guidance system global architecture [53].

The Onboard System represents the positioning equipment embedded on cooperative mobiles used to exchange data with the Communication Server. Each cooperative mobile is equipped with a PC board with a GPS/EGNOS receiver and a wireless network transponder. As represented in Figure 4.2, the Onboard Equipment can support different wireless technologies for transmitting the data obtained from the GPS/EGNOS receiver. For instance, WiFi and WiMax are the wireless network technologies offering a better quality of service with higher bit rate transmissions. On the contrary, public networks available on the airport such as CDMA and TETRA are only used as alternative communication technologies. On the other hand, non-cooperative mobiles are mainly detected with SMR and MLAT technologies. However, it is intended to improve them with ADS-B capabilities to detect non-cooperative objects.

The Communication Server within the Network System is responsible for performing the data fusion of the data transmitted from the the Onboard System. In fact, these two systems are connected through a bidirectional link that enables a continuous update of operational information. Such information is presented to the Application Server in a common interface with homogeneous data about every mobile positioning in real-time. The Control Centre System is then responsible for managing the data contained in the Application Server, providing each end-user (e.g. operationals, ATCO, handlers) with the appropriate monitoring and control tools.

External Systems gather data from several sources to be stored in the appropriate databases, which are accessible within the airport network to improve the situation awareness about ongoing tasks, flight schedules and movements. For instance, the ATC system stores the positioning data provided by the Communication Server. On the other hand, the Airport Management System has detailed information about each mobile and operational tasks (e.g. follow-me, surface clearance, bird control), as well as the SGO providing information about flight schedules [53].

4.2.3 Ground human machine interface

The GHMI is the graphical display used by the end-users to interact with the A-Guidance system (see Figure 4.3). Such interface represents an informational cockpit containing the business context adapted to each stakeholder's role, aiming to support the decision-making in high-risk situations. This business context is filled with a set of services [1], namely:

- **Monitoring:** Real-time positioning of moving objects in the geographic context of the airport, including its position, identification, category, direction, speed, operator and driver identification.

- **Control:** Detection of conflicts and safety infringements, namely the detection of collisions, unauthorized incursions and alerts.

- **Decision-support:** Panoramic view of the airport layout; dynamic operational information (e.g. visibility conditions, RWY accessibility); real-time interface with up-to-date traffic schedules; information about vehicles, drivers and assigned tasks; text messages sent to drivers with instructions; and log files with historical data.

The A-Guidance GHMI is managed by a GIS engine, which allows to organize the airport spatial context as a set of overlapped thematic layers. Such representation is presented in Figure 4.3, where each thematic layer is represented by a pre-defined polygon shape or line, representative of a specific operational area with an associated feature. In this case, all the layers are selected on the Map Features tab on the left side. For instance, TWY and stand guidance lines are represented by light tight lines within the movement area where aircrafts are taxiing as it is the case of TAP107, leaving the RWY on the top side of the airport layout. On the other hand, roadways are represented by double lines which are used by vehicles such as the case of SAFECD16 in the center. Each mobile is identified by a label with its identification and current speed, represented with a color code denoting the severity level for each hazard situation. A red label outlines a severe incursion and a yellow represents a less severe one. Furthermore, a green label indicates that the vehicle is operating normally, while the blue represents a vehicle that is stopped for more than 5 seconds.

In addition to color codes, end-users are provided with an Alert Viewer on the bottom side of the interface window, where any unauthorized incursion will automatically trigger a safety incursion alert message describing the intruder, the area affected and the time it occurred. This detection is performed by the Application Server that correlates the mobiles positioning against the protection polygons defining a restricted access area. Then, every time an alert is triggered, the controller is able to double click to zoom the current location

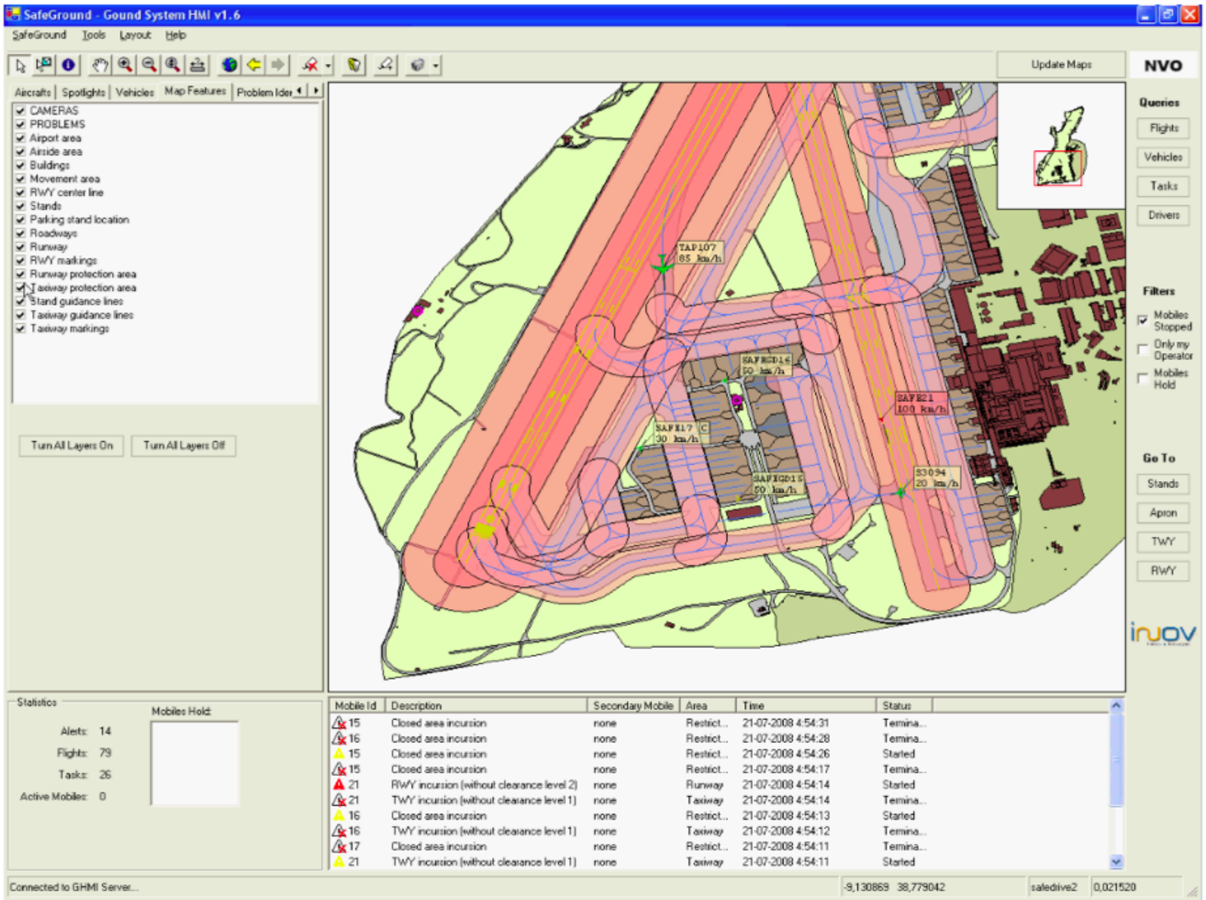


Figure 4.3: A-Guidance GHMI [53].

of the involved mobile. If necessary, the controller can also use radio communication or text messages to contact the vehicle driver.

Other functionalities of the A-Guidance GHMI are related to the possibility of activating and deactivating the vehicle's movement paths visualization. It allows to monitor driving habits, detect traffic rules infringements or even to identify traffic bottlenecks caused by routing or other operational inefficiencies. This functionality is improved by basic GIS functionalities such as making zoom or pan into the map layout or select a map feature to obtain more information.

The GIS engine enables then users at the control center to dynamically manage ongoing operations through a display with the airport layout as the background context. According to the compliance with the A-SMGCS requirements, the system only provides surveillance and control capabilities. Such level of implementation includes a collaborative decision support environment providing situational awareness about aircrafts and vehicles positioning in real-time, detecting safety-related issues by triggering an alert whenever an incursion, a business rule infringement or a collision between mobiles or obstacles is detected [53].

Nevertheless, the current version of A-Guidance requires a manual routing to vehicle and aircraft movements based on the traffic situation that can be seen from the control tower and the situational awareness obtained from the GHMI. Automated generation of route instructions is required to safely and efficiently coordinate every movement. This mechanism can be implemented based on the knowledge acquired from the airport spatial context and the operational information about flights schedule. Furthermore, the A-Guidance system allows to provide guidance support to vehicle drivers through the onboard embedded system installed on the vehicle. However, the lack of availability is a restraint that leads to the need of improved surface visual aids for automated guidance along assigned routes. Such guidance enables the detection of conflicts by continuously monitoring the compliance to the assigned route. In the case of a conflict, a resolution should be provided based on the traffic situation.

4.3 Implementation issues

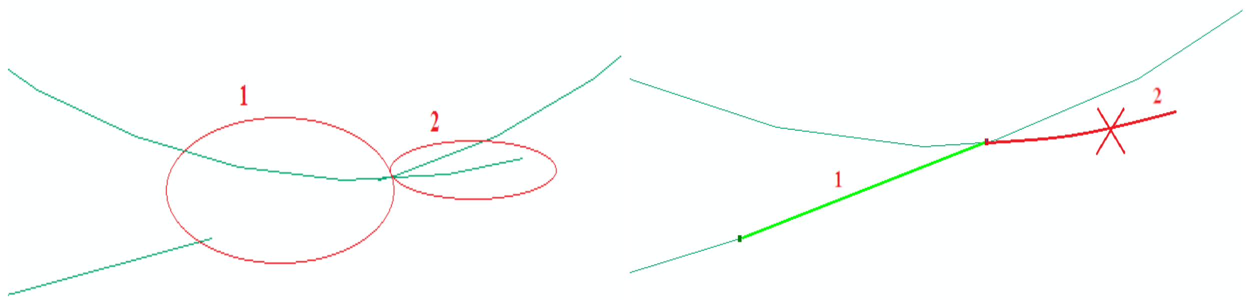
4.3.1 Metadata imperfections

The required extension of the A-Guidance system to levels III and IV of the A-SMGCS concept passes by implementing the proposed methodology described in the previous chapter. Theoretically, the spatial context together with real-time positioning of moving objects and operational business rules are enough to implement routing and guidance functionalities. In computation means, the knowledge about the airport cartographic representation requires the GIS capabilities to provide adequate and accurate geographic metadata. However, the computational representation of the real world usually contains a set of gaps that have to be adjusted according to the implementation requirements. In the case of the airport, such adjustments were mainly related to a set of cartographic imperfections (e.g. segments not linked), the business rules compliance (e.g. detection of tight turns) and other constraints such as the ability to detect which segment corresponds to a given pair of coordinates.

The XML file containing the metadata from the Lisbon airport cartography provided by the INESC development team had a set of imperfections that directly affect the default routing computation and consequently the expected behavior of the guidance model. The XML metadata was then modified using a GIS software called ArcGIS, version 9.3, from ESRI. The correspondent geodatabase feature class was loaded into the ArcCatalog, which is an application allowing the management of geodatabases data files. Such data files are represented on a map viewer included in the ArcMap, the sub-component of ArcGIS allowing the editing and drawing of shapes and features on a map layer (see Appendix A.7). The user is then able to manipulate the geospatial context, for instance by extending a line or modifying a shape.

The need to improve the cartographic accuracy of the geospatial data relates to the fact that the graph generation is not possible when the segments are not linked or an intersection is not detected. As a node in a graph represents an intersection between two arcs, every intersection must have at least two segments linked. Otherwise, these segments are considered independent and the intersection is not detected. The modifications made with the ArcMap software were then performed with the objective of obtaining a graph without errors. Such modifications are crucial to the routing algorithm performance since a non-detected intersection may force the algorithm to compute a longer route due to the absence of the required node.

Figure 4.4(a) outlines the most common imperfections detected in the XML metadata, namely two segments splitted without any link between them (1) and a too extensive segment that goes beyond the intersection (2). This lack of precision in the cartographic representation leads to the generation of unnecessary nodes in the routing graph. For instance, two splitted segments generate two independent nodes that are extremities instead of a single node linking two segments. These imperfections were rectified by joining the two segments (1) and by deleting the extra segment (2) (see Figure 4.4(b)).



(a) Splitted segments (1) and useless extra segments (2). (b) Extension (1) and deletion (2) of segments.

Figure 4.4: Cartographic imperfections resolution.

Another situation of unlinked segments that impedes the identification of a node in the graph is the example shown in Figure 4.5. Although the distance between the two represented segments is insignificant in a large scale, it is determinant when identifying linked segments. The algorithm considers that two segments are linked if one of their extremities are closer than 10 cm (see Section 3.4.2), so every single segment was analyzed in detail. In the case of the Figure 4.5, the extremity of the upper segment was adapted to be in contact with the bottom segment.

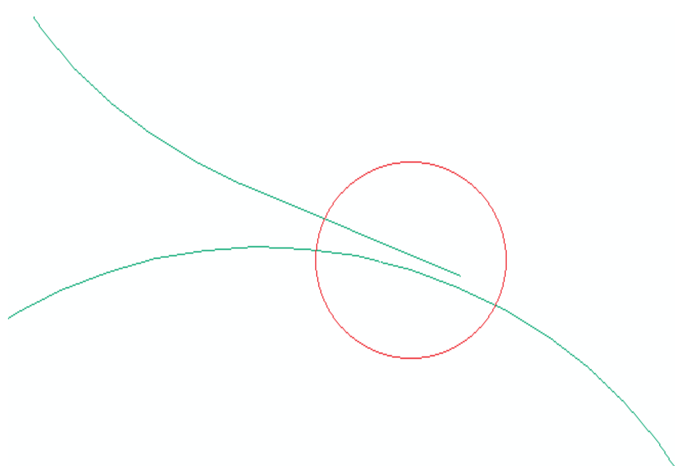


Figure 4.5: Unlinked segments.

Furthermore, the case represented in Figure 4.6 shows two linked segments that do not have a common point in their extremities. This is the typical example of adaptation that must be done to meet the specific implementation requirements, since the previous cartographic representation was created without considering such details. In this situation, the algorithm would not consider the intersection because the extremities of each segment are more distant than 10 cm from each other. The solution passes by splitting the bold segment in two pieces in the exact point where the intersection occurs. Thus, the algorithm will detect an intersection between the resulting three segments.

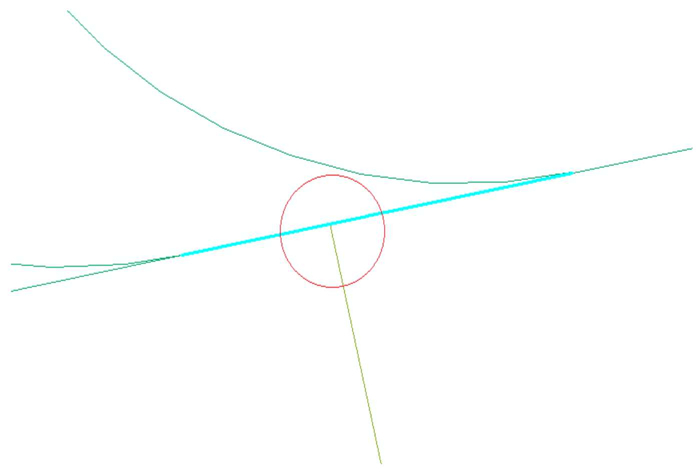
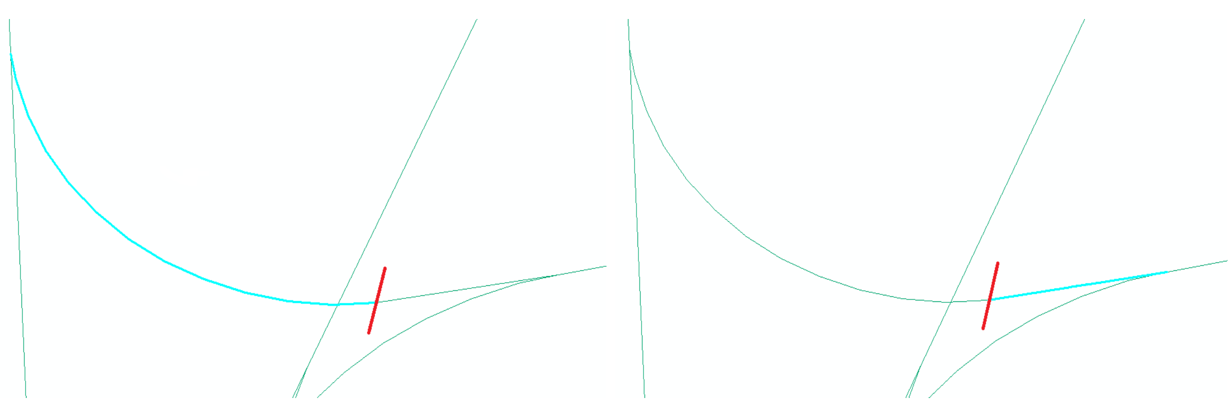


Figure 4.6: Linked segments without a common point.

On the contrary, there were also splitted segments that should be a single segment. As represented in Figure 4.7, the turn is splitted into two parts. This separation makes no sense and will increase the routing complexity because of the creation of unnecessary nodes in the graph. Thus, similar cases were resolved by joining the two segments.



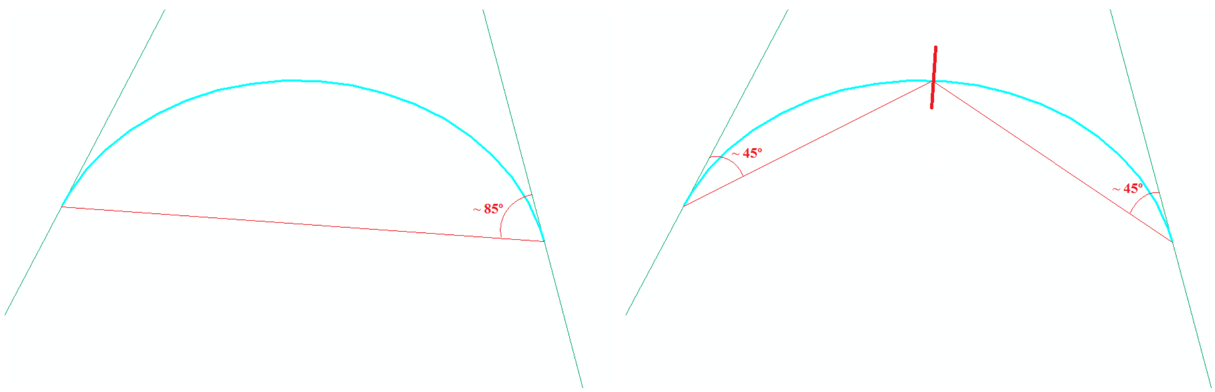
(a) Left part of the segment.

(b) Right part of the segment.

Figure 4.7: Unnecessary split of two segments.

4.3.2 Business rules compliance

The compliance with operational business rules requires the ability to detect tight turns from the geographic metadata. Nevertheless, several issues were detected during the implementation process. For instance, the scenario shown in Figure 4.8(a) represents an unexpected situation that was not considered while implementing the detection of tight turns. Since tight turns are detected by computing the angle between the extremities of the two segments, it can happen that one of the segments is so curved that it makes an angle between 0° and 100° such as is the case here. Thus, the system will mistakenly disable this turn, instead of allowing it. The solution passes by splitting the turn into two parts to let the system assume two normal turns with approximately 45° (see Figure 4.8(b)).



(a) Detection of a tight turn.

(b) Two normal turns by splitting segments.

Figure 4.8: Undetected turn resolution.

Moreover, business rules within the airport include specific priority rules between moving aircrafts, considering a set of characteristics or tasks associated with these particular targets. For instance, departing aircrafts have always higher priority within the movement area because they are releasing resources such as supporting vehicles and parking stands occupancy. The category of the aircraft is also considered when resolving conflicts because the larger the aircraft is, the more supporting vehicles are required. Thus, larger aircrafts have priority because they are carrying more passengers and they are releasing more resources.

4.3.3 Other constraints

During the implementation of the proposed methodology, a set of additional constraints were identified. For instance, it was difficult to associate a given pair of geographic coordinates to the correspondent segment. In other words, the association between a point in the map, called point A, and the closer segment to this point is not linear. Assuming a maximum distance (e.g. 1 m) between A and every segment in the map, there may be one segment that corresponds to the geographic pair of coordinates of A. The problem is that segments can be too close that it becomes difficult to understand which segment is closer to A. The solution passes by considering the distance between A and the midpoint of a given segment, called B. If A is inside the circle with center B and diameter being the length of the segment, then it is associated to this segment. In the case there are more than one segment close to A, then the nearest segment is chosen.

The association between a given geographic point and a segment is particularly hard when considering real data containing information about the positioning of aircrafts in real time. Such information is being transmitted under a large number of interferences, which causes a massive loss of data and affects the reliability and accuracy of the location data. Thus, it is often misleading to detect the real path followed by the pilot because each point in the path is hardly associated to the correspondent segment. In order to deal with this problem and simultaneously provide guidance to aircrafts, the position received every second from each aircraft is analyzed and converted into the correspondent segment. If the segment is not directly linked to the previous segment in the path, the system replaces it to the linked segment that points to the right direction (e.g. destination).

Furthermore, the scenario represented in Figure 4.9 illustrates a problematic situation requiring human intervention. In the figure, it is possible to notice that the smaller aircraft did not follow the assigned path, since the message "Wrong path." is presented in its label. Another aircraft is coming in its direction and it is impossible to stop the smaller aircraft to avoid the collision because there is not other alternative path or possible holding point. This leads to a situation that the system cannot resolve in an automated way, requiring human intervention. Although the function is not implemented due to time restraints, the system should trigger an alert notifying the collision, providing some additional decision-support information to the controller such as the nearest push-back in the surroundings. However, some segments are large enough to allow two aircrafts to cross each other in opposite directions. In this case, the system could verify if the involved aircrafts are allowed to cross each other in a particular segment. Such verification may be the comparison between the width of the segment and the sum of the length of the wings of each aircraft.

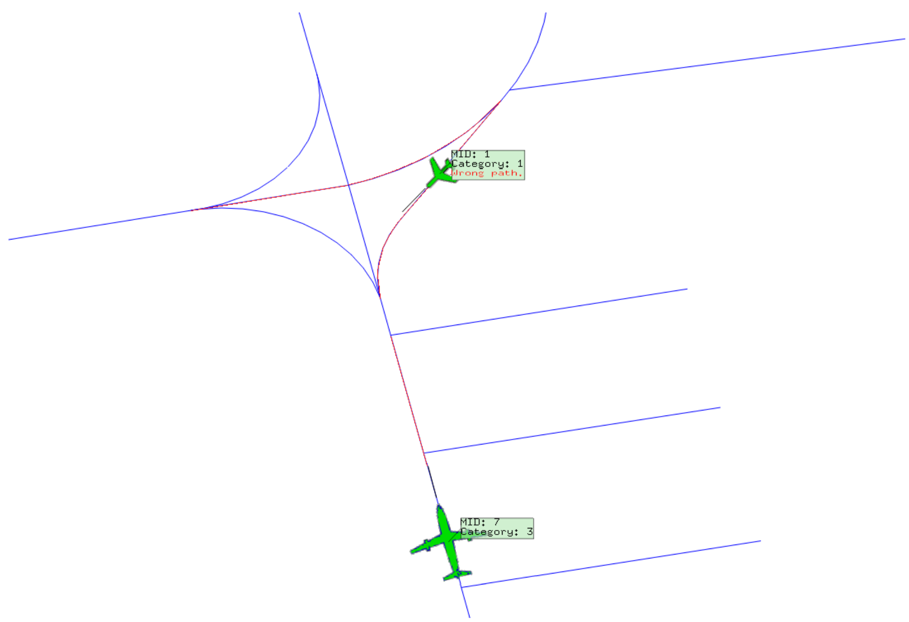


Figure 4.9: Frontal collision conflict requiring human intervention.

Moreover, the geospatial representation of the airport is the result of a merge between two layers, namely TWY guidance lines and stand guidance lines. The problem is that the XML contains metadata about a list of segments without distinguishing which segment belongs to each layer. So, segments representing a stand guidance line were explicitly marked on the XML by adding an attribute to each record, as previously explained in Section 3.4.1.

Chapter 5

Test and evaluation

The proposed methodology was evaluated in the Lisbon airport with the purpose of validating the compliance with A-SMGCS operational and performance requirements. Several tests were primarily performed in a simulation environment to validate how the system performs in conflict situations, how alternative paths are computed, how the guidance lighting system is activated and other related functionalities. A specific test scenario was designed to evaluate every single feature by analyzing its effectiveness and compliance with the required functionality. The implemented methodology was also tested with real operational data collected from historical logs, aiming to evaluate the system behavior when managing positioning data from a database in real-time. The main objective was to understand how the A-Guidance improvement contributes to the efficiency of ground movements when applied to a real scenario.

5.1 Testing environment

5.1.1 Test-bed: Lisbon airport

The Lisbon airport is composed by two RWY, 306 TWY segments and a large number of roadways within the movement area. Such configuration can be considered as a simple aerodrome since only one of the two RWY is operational and the airport layout has more than one TWY to the apron area. Furthermore, the traffic density may be categorized as medium, considering that typically there are registers between 20 and 35 total aerodrome movements in mean busy operational hours. These movements are mainly performed under sufficient visibility conditions to allow the pilot to taxi and avoid collisions by visual reference and insufficient visibility conditions to allow personnel of control units to monitor all movements based on visual surveillance. Such level of visibility corresponds to the visibility condition 2, according to the A-SMGCS categorization [5].

A visual perspective about the Lisbon airport layout is presented in Figure 5.1, which shows the transition from the satellite representation (a) to the correspondent layout with all thematic layers selected (b) and then to the representation of RWY, TWY, roadways and stands (c).

(a) Satellite representation (image from Google Maps).
(b) Thematic layers representation.
(c) RWY, TWY, stand and roadway guidance lines layers representation.

Figure 5.1: Lisbon airport layout.

The network composed by TWY and stand guidance lines, represented by the thinner lines in the Figure 5.1(c), was used to generate a graph where a routing algorithm can be applied. Such representation allowed to perform several routing tests, where a computed path corresponds to a list of segments that are uniquely identified by a number.

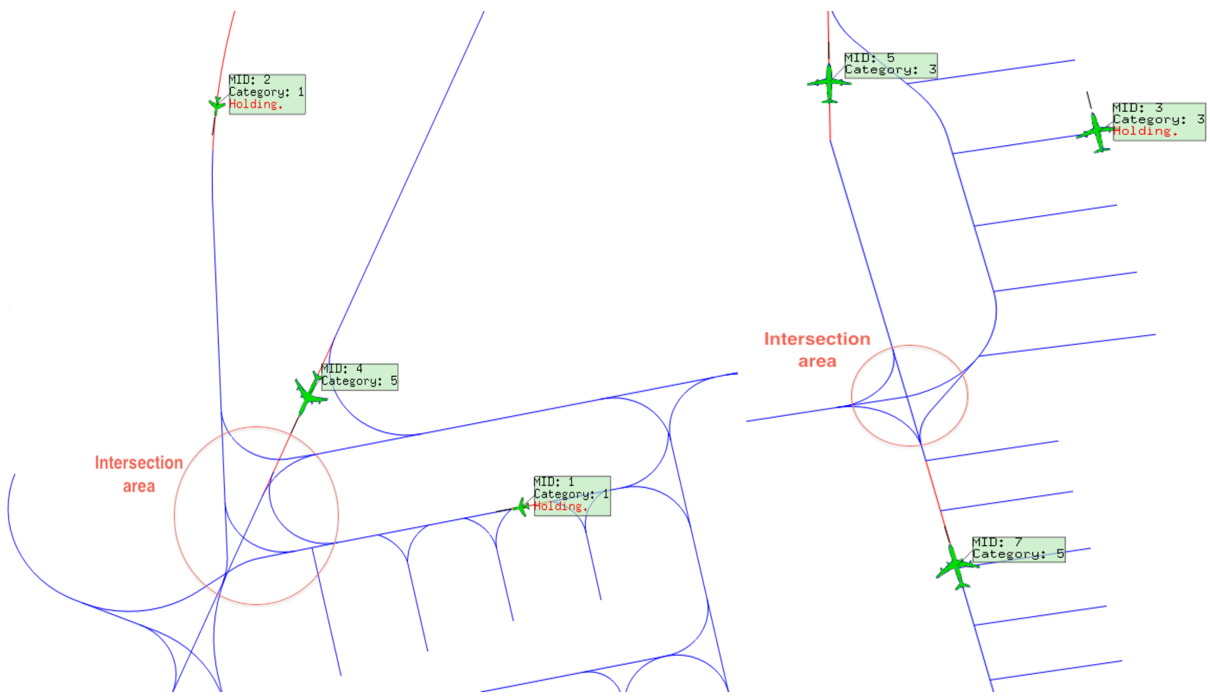
5.1.2 Test scenario

With the purpose of validating the implemented functionalities, a test scenario was designed in such a way that every possible situation can be tested and evaluated within a simulation environment. The test scenario includes seven aircrafts with different categories (small, medium or large), types (arriving or departing) and start times. All aircrafts move with a regular speed of 50 km/h and their origin and destination points were carefully assigned to purposely create conflict situations. The main objective of this test was to evaluate the system behavior under a dense flow of traffic, the correctness of conflicts resolution, the effectiveness of movements and the guidance lighting system activation. The following situations were tested:

- Conflicts resolution, including intersections, persecutions and frontal collisions.
- Shortest path computation.
- Guidance lighting system activating n+1 segments.
- Alternative path computation when the pilot does not follow the assigned path.
- Dynamic adaptation to path deviations.

Most of these situations are represented in Figure 5.2, where aircrafts are identified by a label with their identification (MID), category and optionally an alert message about their status (e.g. "Holding." or "Wrong path."). There are six aircrafts of the test scenario represented, the majority involved in a conflict.

Aircraft movements were simulated by constructing a text file for each aircraft with a list of geographic coordinates, representative of a real scenario with real-time positioning acquired from localization technologies. Such files allowed to update the position, every second, of each aircraft in the A-Guidance GHMI with the airport layout. Thus, it was possible to simulate a deviation from the assigned path by moving the aircraft into the wrong way, triggering an alert with the infraction. Such mechanism allowed also to provide guidance to each aircraft by comparing the position of each aircraft to the expected path.



(a) Larger aircraft with higher priority.

(b) First aircraft arriving at the intersection have higher priority.

Figure 5.2: Conflicts resolution in the test scenario.

Focusing on Figure 5.2(a), aircraft 4 has priority to cross the intersection area prior to aircrafts 1 and 2 because it is larger. For this reason, smaller aircrafts have to hold for a pre-defined period in a specified holding point, both defined by the system in order to maintain conflicts distant from the minimum configured time. Once the aircraft with MID 4 crosses the intersection, the system decided to authorize aircraft 1 to cross the intersection first, taking into account that it is departing and aircraft 2 is arriving.

On the other hand, Figure 5.2(b) outlines several situations that had to be handled by the system. For instance, aircrafts 5 and 7 were involved in a persecution conflict because their paths forced them to trail each other with a too reduced distance. The second aircraft, in this case the aircraft 7, had to wait for a pre-defined period. When arrived at the intersection, it forced the aircraft 3 to hold on the stand parking area until it crossed the intersection because it was the first arriving at the conflict point. Then, the aircraft 3 did not follow its assigned path when arriving at the intersection and went to the route where the aircraft 7 came from. Such deviation forced the system to compute an alternative path for this aircraft to the same destination, requiring a single coordination with another aircraft (not represented in the figure). However, this last aircraft was the one injured since the aircraft 3 had priority because, although they had the same category, it was departing and the other one was arriving.

Furthermore, another feature represented in Figure 5.2 is the guidance lighting system that automatically activates and deactivates the segment lights to provide assistance to pilots. For instance, aircrafts 4, 5 and 7 have the current segment and the segment immediately ahead turned on (represented with a different color). Such mechanism respects the n+1 policy, which provides clear instructions to pilots about the next segment to follow in the assigned path. On the contrary, aircrafts 1, 2 and 3 do not have any segment ahead turned on. This means that they have to wait at the end of the current segment until the lights are turned on, authorizing them to continue their path. In the case of the aircraft 3, the current segment is also turned off because it is not allowed to start moving.

Moreover, tests were also performed with operational data acquired from historical logs stored in a SQL database. Such data was provided by ANA-Aeroportos and is representative of the real movements captured in the beginning of 2011 in Lisbon. A sample of the positioning data of several aircrafts at the same instant is given in Appendix A.8, each row containing information about every aircraft once per second. For instance, each aircraft has associated an unique objectID, its identification number (MID[10]), its category (MCAT), the current speed, its geographic localization (X and Y WGS84 coordinates), a call sign identification string and the current time (Timestamp). This information is stored once per second for every aircraft, as it is possible to notice in the table. For instance, the flight TAP1817 is repeated five times, each for a different timestamp. Unlike the files with geographic positioning used to simulate aircraft movements, these tests accessed directly the real positioning data from the database.

Since the real data corresponds to historical registers, the system can designate a route for each aircraft but it can only verify it the pilot followed the same route or not. It is not possible to guide a pilot in real time because the available data for tests belongs to the past. However, these tests allowed to evaluate the system behavior when dealing with real movements, namely the ability to assign a route to every aircraft without causing any conflicts with other movements. The computed routes can then be compared to the real paths followed by the pilots in terms of distance and efficiency. Furthermore, the ability to dynamically adapt the flights schedule in case of a deviation from the assigned route could also be evaluated. The performance results are discussed in the next section.

[10]The MID is the same number every time the flight is reproduced, for instance daily.

5.2 Results evaluation

5.2.1 Simulation environment

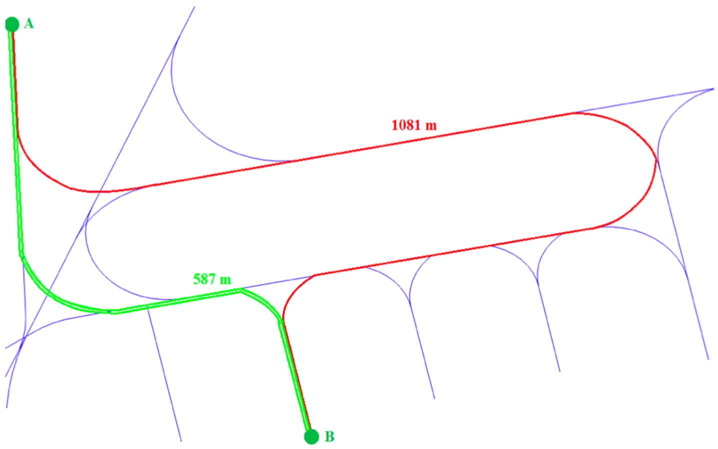
Table 5.1 presents the results obtained from the test scenario, measuring the taxi distance, the wait time and the number of conflicts for each aircraft. The taxi distance represents the length of the path followed by the aircraft and the wait time is the time spent in one or more holding points. Conflicts are the number of conflicts detected and resolved. As it is possible to notice, rows are ordered according to the start time in order to provide the evolution of the simulation.

Every aircraft represented in the table followed an optimal path. The taxi distance values correspond to shortest paths, scheduled without requiring the assignment of alternative paths to resolve conflicts. However, such movements were coordinated by forcing some aircrafts to wait in certain holding points, namely four aircrafts with less priority of the six involved. The main injured aircrafts were the aircrafts 1, 2 and 3 with a wait time of 18s, 20s and 19s respectively. On the contrary, aircrafts with higher priority (4, 5 and 7) were not affected. The system was then able to coordinate the movements efficiently, giving priority to the largest and departing aircrafts, while the smaller and arriving ones had to wait a few seconds.

Table 5.1: Test scenario results.

Aircraft	Category	Type	Start time	Taxi distance	Wait time	Conflicts
5	Medium	Departing	0:00:00	1390m	0s	0
1	Small	Departing	0:00:10	1732m	18s	1
7	Large	Departing	0:00:10	2167m	0s	1
3	Medium	Departing	0:00:30	2562m	19s	2
4	Large	Departing	0:01:20	1492m	0s	2
8	Small	Arriving	0:01:30	1385m	4s	1
2	Small	Arriving	0:01:35	1457m	20s	1

Another feature to be tested is the ability to compute alternative paths. As represented in Figure 5.3(a), the bold line represents the shortest path between A and B, while the dark line is the alternative path computed by the routing algorithm. Although it is a short distance, the difference between the shortest path (587m) and the alternative path (1081m) is significative since the second path is almost twice longer than the other. Other examples are presented in Table 5.3(b), where the first row is relative to the scenario shown in Figure 5.3(a). These values prove that some alternative paths are almost the double than the optimal paths, which is the case of the aircraft 1, 6 and 7. On the contrary, a short alternative path was found for aircrafts 2, 3, 4 and 5. This is particularly important when considering a deviation from the assigned path, allowing to find alternative paths with almost the same length than the optimal one.



(a) Optimal (bold) and alternative (dark) paths.

Aircraft	Taxi distance	
	Optimal	Alternative
1	587m	1081m
2	1454m	2223m
3	2113m	2562m
4	1020m	1134m
5	1952m	2002m
6	911m	1687m
7	545m	989m

(b) Optimal and alternative paths length.

Figure 5.3: Optimal versus alternative paths.

The routing function was also evaluated with respect to the execution time, depending on the number of segments of the path. In other words, the complexity of the algorithm was evaluated by measuring the execution times for paths with different sizes (number of segments). As expected, the execution time increases with the number of segments. However, as represented in Figure 5.4, the growth is not so significative considering that the difference is about 15ms for paths with 5 and 40 segments. For instance, paths until 20 segments spent approximately 20ms and paths with 35 segments only took 30ms to be computed. Such values are representative of a extremely fast and scalable algorithm that is able to compute paths with 1 to 42 segments in less than 30ms.

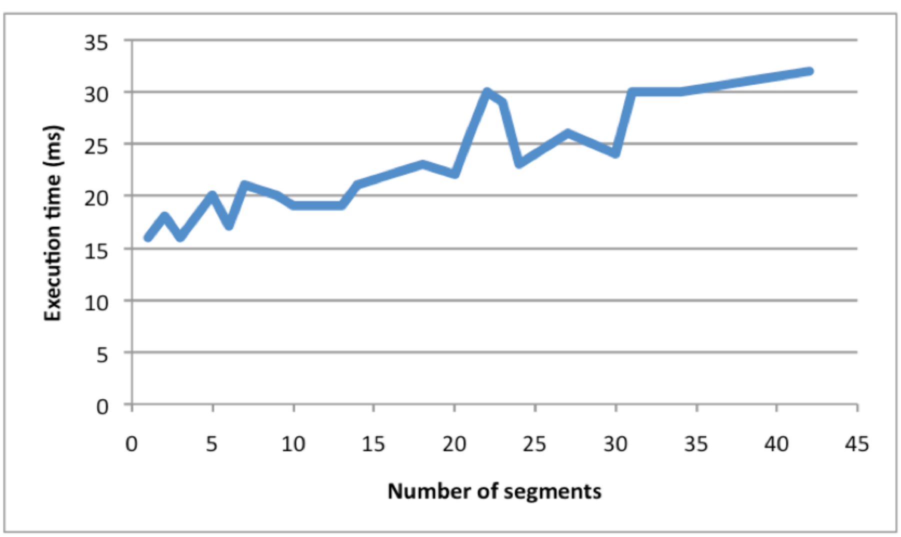


Figure 5.4: Execution times for paths of different lengths.

On the other hand, the resolution of conflicts should be handled within a very short period of time, considering that the involved movements are compromised and cannot proceed until the system provides a resolution. Such requirement was tested by measuring the execution time spent resolving conflicts, depending on the number of aircrafts and the number of conflicts. The results are presented in Table 5.2, that correspond to the conflicts resolution time for every new aircraft being introduced to the system. When there are no conflicts, the time spent searching for conflicts with the other movements is extremely low. For instance, with 1, 2, 5 and 7 aircrafts the execution times were 0ms, 4ms, 12ms and 26ms, respectively. The first aircraft entering the system does not require to search for conflicts since it is alone, but the complexity increases with the number of aircrafts. However, 26ms for searching conflicts with a traffic flow of 7 aircrafts is almost negligible. On the other hand, inserting aircrafts 3, 4 and 6 generated conflicts that had to be resolved, spending 28ms, 50ms and 38ms, respectively. These values are low considering that the system had to reschedule some movements, namely by holding certain aircrafts.

In the case of a deviation from the assigned path, the system has to recalculate an alternative path to be assigned to the infractor aircraft and must reorganize the movements schedule in real-time. In order to evaluate the ability of the system to deal with deviations in real-time, the execution time to respond to such situations was measured (see Table 5.3). In a scenario with 6 aircrafts, a deviation causing two conflicts spent 158ms to be resolved. On the other hand, a deviation causing a single conflict took 297ms to be handled in a scenario with 7 aircrafts. Although the second scenario was dealing with a single conflict, it spent more time to be resolved probably due to a higher difficulty coordinating all the movements. However, both scenarios were resolved in a very short period of time, when compared to the human scale (seconds).

Table 5.2: Conflicts resolution time in the case of a new aircraft entering the system.

Number of aircrafts	Generated conflicts	Resolution time
1	0	0ms
2	0	4ms
3	1	28ms
4	4	50ms
5	0	12ms
6	1	38ms
7	0	26ms

Table 5.3: Conflicts resolution time in the case of a deviation from the assigned path.

Number of aircrafts	Generated conflicts	Resolution time
6	2	158ms
7	1	297ms

Routing and guidance initialization times were also measured in order to evaluate the system response time in case of unexpected situations (e.g. lack of energy, natural incidents) that force to restart the system. As mentioned previously in Section 3.4.4, the routing information is saved in a auxiliary file that aims to speed up the initial computation time. If the routing network never changes, the initialization process only spends approximately 700ms. However, if an operational change (e.g. closing a route for maintenance) occurs, the system has to recompute the routing data which spends around 15s. This value is high but reasonable, considering that it corresponds to static routing information that is computed only once and does not affect directly the efficiency and safety of ground movements. Finally, the initialization of the guidance mechanism spends approximately 800ms, for the specified test scenario with 7 aircrafts. This value includes the insertion of the aircrafts and the conflicts resolution time. It is also an acceptable value, corresponding to less than 1s in the human scale which is insignificant.

5.2.2 Operational environment

The operational environment comprises the historical data collected from the Lisbon airport. This data contains several gaps caused by interferences or other communication difficulties, causing the defective transmission of positions out of the TWY guidance lines boundaries. Such lack of precision forced to implement a function that determines the real sequence of segments followed by the pilot, in order to enhance the guidance ability to detect conflicts and provide clear instructions to the pilots. This function included primarily detecting the set of segments corresponding to the positions registered in the database, then correcting these segments by constructing a feasible path. However, about only 35% of the historical logs were profitable in terms of correctness of the path. This means that it was possible to reconstruct and test approximately one third of the positioning data relative to one operational day in a real airport environment.

Most of the proposed optimal paths by A-Guidance were similar to the ground movements registered in the past. Thus, almost all the pilots followed the shortest route by receiving guidance instructions from the controllers on the control tower. However, the improved version of A-Guidance was able to find some shortest paths. The results are presented in Table 5.4, where the values represent the length of the path for each aircraft. The first column (Real data) corresponds to the path followed by the pilot in the past and the A-Guidance to the shorter path proposed by the system. The difference is particularly significative for TAP741 and KLM1692, estimated at 1099m and 477m respectively. These values are the proof that the A-Guidance would improve the movements efficiency by assigning shorter and more efficient routes that save large amounts of time.

Table 5.4: Length of paths computed by A-Guidance, comparing to real movements in the Lisbon airport.

Aircraft	Taxi distance	
	Real data	A-Guidance
TAP741	2380m	1281m
TAP668	1625m	1601m
KLM1692	2069m	1592m
IBE31EW	1898m	1625m

The execution time accessing SQL data was also measured in order to evaluate the ability and rapidity to interact with a database in real-time. So, two different scenarios were evaluated by measuring the execution time spent to insert one aircraft and two aircrafts, spending 4.8s and 19.5s respectively. Inserting an aircraft includes the query to the database to obtain the path followed by the pilot, the routing computation and the conflicts resolution. These values are high, considering that the system has to access data in real-time. However, the implementation method was not adequate because it did not consider the best method to perform queries. For instance, the data about the path followed by the pilot was requested with a single query, since it was already stored in the historical logs. In a real situation, this is not feasible because the aircraft sends the position periodically and according to the displacement, instead of sending the data relative to the entire route. Then, the correct way to implement it was to read row by row, instead of reading the set of rows relative to that flight. Another lack of efficiency is related to the fact that the sample of data used to perform tests is relative to one entire operational day, containing more than one million rows. Thus, executing queries to such a large database spends much more time than a smaller database. To resolve this problem, a more efficient method could be used such as reading smaller amounts of rows at the same time or simply by having a database with less registers, only relative to some hours. Unfortunately, these problems were not resolved due to lack of time.

5.3 Compliance with the A-SMGCS requirements

This section outlines the main outcomes obtained from the evaluation made to the implemented solution. Such assessment consists in validating the A-Guidance compliance with the A-SMGCS requirements (see Section 3.1), classifying each requirement with one of two possible status: "Yes" if the functionality was implemented and the requirement achieved, "No" if the functionality was not demonstrated or implemented. Furthermore, the symbol "*" in the "Yes" status represents an innovation (e.g. creation or enhancement of a functionality) made to the original version of the A-Guidance.

Table 5.3 sums up which operational requirements were achieved, providing a brief description of the implemented functionalities. In terms of surveillance, the previous version of the A-Guidance was already equipped with accurate location technologies that are able to provide the continuous positioning of static and moving objects within the movement area (S1, S2 and S3) [53]. On the other hand, the ability of the control function to detect and resolve conflicts was improved (C3). Instead of relying on visual monitoring, the system is now able to automatically detect conflicts in real-time and provide a resolution that will not affect the other movements. However, the maximum authorized capacity of the airport was not tested due to the complexity related to the guidance of several tens of aircrafts at the same time (C2).

The main innovation made to the A-Guidance focuses on routing and guidance functionalities. For instance, the system is now able to designate a optimal route for each aircraft (R1), while minimizing the taxi distance (R6) and conflicts with the other movements (R7). Once every aircraft has an assigned path, the pilot is assisted with a guidance lighting system in the centre line of the TWY providing instructions about the path to follow (G1 and G2), triggering alerts whenever the pilot deviates from the path (G6). Such automation decreases the workload of the stakeholders (e.g. users at the control center), allowing to cope with large flows of traffic at complex aerodromes (R4).

Table 5.5: Compliance with the A-SMGCS operational requirements [53].

Function	A-Guidance compliance
Surveillance	• S1: Provide accurate positioning about all moving objects within the monitored area. YES: GPS/EGNOS receivers and IP-based wireless communication links to detect vehicles and aircrafts positioning. • S2: Cope either with moving and static objects. YES: Surveillance is independent of objects state of motion. • S3: Update moving objects' position along the time. YES: The position of every object is continuously updated in the GHMI.
Control	• C1: Have the capacity for planning the requested movements within a period of up to one hour (static capacity). YES: External systems provide updated information about operational business data. • C2: Have the capacity for supporting the maximum authorized movement rate at any time (dynamic capacity). NO: Field tests were only performed with vehicles (maximum of 25 cooperative vehicles). • C3: Detect conflicts and provide resolutions. YES*: Safety alerts are triggered to both vehicles and aircrafts and the conflicts are resolved.
Routing	• R1: Be able to compute a route for each authorized moving object. YES*: Optimal routes are assigned to each aircraft. • R2: Allow for a change of destination at any time. NO: A route to another destination can be computed at any time, but the explicit change of destination during the movement was not implemented. • R3: Allow for a change of a route to the same destination at any time. NO: An alternative route to the same destination can be computed at any time, but the explicit change of the route during the movement was not implemented. • R4: Cope with large flows of traffic at complex aerodromes. YES*: GHMI functionalities together with routing and guidance enhancements decrease the workload of stakeholders. • R6: Minimize the length of computed paths. YES*: The routing function was designed to compute shortest paths. • R7: Minimize the conflicts. YES*: Conflicts are detected and resolved before start taxiing and during the movement.

	• R8: Ease of adaptation to operational changes (e.g. routes closed for maintenance, temporary hazards or obstacles). YES*: The routing algorithm only considers active taxiways, even if it requires an explicit update of the file with routing data to reflect operational changes. • R9: Use standard terms and symbols. YES: The airport layout is in conformity with ED-119 recommendations. • R10: Be capable of validating routes. YES*: Routes with linked segments and without unauthorized turns are valid.
Guidance	• G1: Provide guidance for every authorized moving object, for any assigned route. YES*: Aircrafts are provided with the guidance lighting system in the centre line of the taxiway, while vehicle drivers have a map-based cockpit with visual aids. • G2: Provide clear instructions to pilots to help them following their path. YES*: Segments are activated/deactivated according to the aircraft movement, indicating explicitly the current and next segments belonging to its assigned path. • G3: All pilots should be continuously aware about their position on their assigned routes. NO: Pilots are aware about the next segment on the path, not their positioning. • G4: Allow for a change of a route at any time. NO: The system is able to find an alternative path in case of a deviation, but the option to change a route was not implemented. • G5: The system should detect routes and areas that are restricted or not available for use. NO: The modification of the operational configuration must be explicitly updated. • G6: Allow monitoring the operational status of all guidance aids. YES*: The operational status is updated on a label respective to each aircraft in the GHMI.

Several requirements were not met because they are not required to satisfy the proposed goals of this thesis. It is the case of changing the destination (R2) or the route (R3) at any time, which corresponds to the computation of an alternative path. However, the routing mechanism is already implemented to provide support to R2 and R3. Another requirement missing in A-Guidance is the automatic detection and adaptation to operational changes (G5), requiring a manual update of the file concerning the operational configuration. However, this functionality can be implemented by providing tools to enable and disable segments, which would automatically generate a XML reflecting the changes.

On the other hand, Table 5.6 addresses the A-SMGCS performance requirements, using the same symbology as the previous table. Such requirements were already satisfied in the previous version of A-Guidance in terms of surveillance and control. For instance, existing location technologies are able to provide precise information about every moving object positioning (S1) every second (S2), allowing the implementation of routing and guidance functionalities [53]. However, several enhancements are required, namely related to the transition from outdoor to indoor environments or loss of signal.

Table 5.6: Compliance with the A-SMGCS performance requirements [53].

Function	A-Guidance compliance
Surveillance	• S1: Be capable of detecting an aircraft within a radius of 7.5 m. YES: The operational location technologies have an accuracy better than 7.5m, even if the signal is not good enough for positioning precision in some places. • S2: The position and identification of a moving object should be updated at least once per second. YES: The positioning of moving objects is performed every second.
Control	• C1: The probability of detection of an alert should be greater than 99.9 %, whereas a false alert should be triggered with a probability less than 10^{-3}. YES: All alerts were detected. • C2: Be capable of responding within 0.5 second. YES*: The detection and resolution of conflicts spent a maximum of 0.3s in performed tests.
Routing	• R1: The initial route should be computed in less than 10 seconds. YES*: Routes were computed in less than 0.3s, for considerably complex paths. • R2: Recompute the path for a moving object should not exceed 1s. YES*: The recalculation of an alternative path for a moving aircraft took less than 0.3s. • R3: The optimal routes should be processed with a taxi distance resolution better than 10m and a timing better than 1s. YES*: Taxi distances are measured with WGS84 coordinates, achieving a resolution of some centimeters. The timing depends on the taxi speed, computed with a resolution better than 1s.
Guidance	• G1: The guidance function should initialize within a maximum of 2 seconds. YES*: The guidance function initializes in approximately 0.8s. • G2: The reversion time should not exceed 0.5 second. YES*: The reversion time did not exceed 0.3s in operational tests.

According to the results presented in this chapter, the system is now able to compute a route in few milliseconds, instead of the 10 seconds required by the A-SMGCS (R1). This is also true when computing an alternative path that should not exceed 1 second (R2). Such values are the result of an extremely fast algorithm that can be applied to any operational configuration, assuring a good routing performance.

The guidance function was also improved in terms of performance, initializing in less than the half required by the A-SMGCS (G1). This function is able to deal with deviations from assigned paths in less than 0.3s, computing an alternative path to the infractor aircraft and rescheduling other affected movements (G2). Such mechanism is extremely fast in the human scale, allowing to reschedule several movements in real-time while being unnoticed by the pilots.

Chapter 6

Conclusions

6.1 Overview

The growth of air traffic caused an increased complexity of airport surface movements, as well as operational resources became exhausted, leading in turn to an increase of the stakeholders workload. Relying on the "see and be seen" principle is no longer feasible, especially at rush hours when many operations must be managed simultaneously, sometimes under bad visibility conditions. The need of improving the safety and efficiency of such operations led to the implementation of A-SMGCS surveillance and control services in main airports in Europe. However, controllers are still not capable to deal with high flows of traffic and automated mechanisms are required to enhance safety management procedures.

On the one hand, the implementation of levels III and IV of A-SMGCS requires a reliable surveillance function and an accurate control function. Only predicted to be implemented on 2015, the routing and guidance functionalities depend on the quality of the positioning data provided by the location technologies. For this purpose, a survey about these technologies allowed to conclude about which technology best captures the location of a moving object in real-time, taking into account the environmental difficulties and other communication constraints. In the airport, ADS-B is the most promising one for the detection of aircrafts, while vehicles are mainly tracked with GPS solutions.

On the other hand, the state-of-the-art about routing algorithms resolving the shortest path problem contributed to decide which algorithm is more suitable to determine the optimal path between two points within the movement area of an airport in a very short period. Floyd has the higher runtime complexity, but it only spends time computing the initial routing information. This information is stored and is always the same until there is an operational change in the network configuration. So, a path is determined by a single read of the routing information, instead of computing the path when it is required. This feature allows to comply with real-time requirements, computing the shortest path in few milliseconds. When the path includes unauthorized turns, an alternative mechanism was designed based on some algorithms resolving the k shortest path problem. This mechanism allows to compute a route without unauthorized turns and was inspired on K* and A*, supported by an heuristic function that considers the closest node to the destination to determine the sequence of nodes in the path.

The static assignment of routes to aircrafts was improved with a dynamic function that was able to detect conflicts between each movement and provide a resolution such as finding an alternative route or holding the aircraft for a pre-defined period. This function was based on the MILP model to provide guidance assistance to pilots while moving along their assigned paths. This model allows to schedule several movements along the time, resolving conflicts in the case of a deviation from the assigned route. However, it does not adapt each movement dynamically to avoid congestions or other operational requirements.

6.2 Main contributions

This thesis proposed a methodology based on a LBS infrastructure supported by the A-Guidance system that copes with levels I and II of A-SMGCS. The main contribution was to extend the existing platform with routing and guidance functionalities, corresponding to levels III and IV of A-SMGCS. The management of the traffic flow was based on the optimization of the TWY occupation by scheduling the available resources in a continuous time manner.

The business case used to successfully test the proposed methodology proved the compliance with the operational and performance A-SMGCS requirements, enabling the routing function to assign a path to every aircraft while minimizing the taxi distance as well as minimizing the risk of conflicts with other moving objects. Furthermore, the guidance function copes with dynamic changes to routing, enabling, for instance, to interact with the lighting system to guide the pilot from the current position to the assigned stand or runway. The performance goals were also achieved since the routes are computed extremely fast and the system responds accurately to emergency situations.

So, the proposed goals were successfully accomplished since the airport capacity and efficiency were improved by avoiding delays and minimizing conflicts within the movement area of the airport. Such improvement contributed to the optimization of turnaround times, while releasing the workload of stakeholders.

6.3 Future work

The proposed functionalities were successfully implemented, even if there are some imperfections to be enhanced in the future. For instance, a frontal collision between two aircrafts caused by a deviation from the assigned path was not resolved in the case that both aircrafts are moving forward each other without any alternative route. Usually, there are some bidirectional TWY that are large enough to enable the simultaneous passage of two aircrafts in opposite directions. The problem of the frontal collision can then be resolved by comparing the width of the TWY with the sum of the length of the wings of the involved aircrafts, plus a margin of error. This comparison must be performed as soon as the problem is detected, in order to avoid the approximation between the aircrafts. If the aircrafts are too large to fit in the TWY, a manual intervention is required and an alert should be triggered. Otherwise, any conflict is detected and the system proceeds its execution normally.

Another feature not implemented was the Floyd reconfiguration of the graph network whenever an operational change occurs. The presented methodology assumed that, periodically, the operational conditions were verified in order to adapt the routing information to the new network configuration in case a route is closed for maintenance, for instance. However, this functionality was not implemented due to time restraints and is required to be added in the near future. For this purpose, it is intended to restart the Floyd matrices whenever an operational change occurs. This process was tested and spent around 15s, which is acceptable in the human scale.

Moreover, the implemented methodology has some limitations in terms of the capacity allowed in the airport. Although the system is responsive to complex traffic flows in a aerodrome such as Lisbon airport, it was not tested in more complex airport configurations in extreme conditions. The management of a dozen of simultaneous movements in a simple aerodrome, with perfect meteorological conditions, is completely different to the traffic flow registered in Frankfurt Main, for instance. Although the case study was centered in the Lisbon airport, it is intended to turn the system more scalable and compatible with any configuration and traffic flow. Then, it is required to test the implemented solution with more complex movements in order to evaluate its behavior in all possible scenarios.

As discussed in the evaluation of the implemented solution, the system was tested in a simulated environment. However, the real operational data served to evaluate how the system performs in a real environment. Several issues were detected, namely the difficulty to capture the real path followed by each pilot due to the interferences and other communication inefficiencies. The methodology was designed to provide routing and guidance functionalities, assuming that everything works as predicted. In a simulation environment, every movement is performed exactly as expected and there are no delays and unpredictable situations. On the contrary, the real world introduces a large set of problems that cannot be predicted. For instance, a pilot can commit a mistake due to bad visibility conditions, wrong voice instructions received from the control tower or simply by human error. It is then intended to update the current version of A-Guidance in Lisbon, in order to perform additional tests related to the dynamic management of unpredictable movements in a real environment.

The management of real operational data, including the queries made to the database, was not efficient in terms of execution time. As mentioned in the evaluation chapter, the implementation method to access data in real-time was not adequate because the aircraft sends its position periodically and according to the displacement, instead of sending the data concerning the entire route. So, the information shall be read periodically, row by row, instead of reading the entire set of rows concerning that flight. Another inefficiency is that the sample of data used to perform tests is relative to one entire operational day, containing more than one million rows. Thus, executing queries to such a large database spends much more time than a smaller database. To resolve this problem, a more efficient method could be used such as reading smaller amounts of rows at the same time or simply by having a database with less registers, only relative to some hours.

Finally, the main goal of the future work focus on extending the proposed methodology to provide guidance assistance to airport vehicles, together with the aircrafts. In this case the routing algorithm becomes more complex because vehicle drivers can have unpredictable behaviors. Such behaviors are extremely difficult to predict and introduce additional variables to the algorithm that might compromise its performance. Research is being done to respond to those challenges, namely to consider both forward and backward vehicle movements, tight turns, traffic rules and circulation priorities based on the type of vehicles as well as between vehicles and aircrafts. In this sense, an hierarchical Voronoi approach seems to be a promising solution to integrate both vehicles and aircrafts in a common network, with different hierarchical levels. Such approach divides the road network into adjacent levels of sub-graphs, each one with a different class of road. The distinction of classes allow to define different business rules to each level, while considering the entire network as the basis. With this configuration, it is possible to manage both movements independently, while detecting conflicts between them [54].

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Appendix A

A.1: Segments layer metadata.

This is the XML representation of the segment 39, belonging to the TWY guidance lines layer of the movement area configuration of the Lisbon airport. The metadata provided corresponds to the line segment geometry, defined with WGS84 geographic coordinates.


```
- <Record xsi:type="esri:Record">
  - <Values xsi:type="esri:ArrayOfValue">
      <Value xsi:type="xs:int">39</Value>
    - <Value xsi:type="esri:PolylineN">
      - <Extent xsi:type="esri:EnvelopeN">
          <XMin>-9.13565686499993</XMin>
          <YMin>38.7864645640001</YMin>
          <XMax>-9.13435716999993</XMax>
          <YMax>38.7889045310001</YMax>
        </Extent>
      - <PathArray xsi:type="esri:ArrayOfPath">
        - <Path xsi:type="esri:Path">
          - <PointArray xsi:type="esri:ArrayOfPoint">
            - <Point xsi:type="esri:PointN">
                <X>-9.13565686499993</X>
                <Y>38.7864645640001</Y>
              </Point>
            - <Point xsi:type="esri:PointN">
                <X>-9.13565573899996</X>
                <Y>38.7864676470001</Y>
              </Point>
            - <Point xsi:type="esri:PointN">
                <X>-9.13561598099994</X>
                <Y>38.786550059</Y>
              </Point>
            - <Point xsi:type="esri:PointN">
                <X>-9.13435716999993</X>
                <Y>38.7889045310001</Y>
              </Point>
            </PointArray>
          </Path>
        </PathArray>
      </Value>
      <Value xsi:type="xs:double">2.76464154277826E-03</Value>
      <Value xsi:nil="true" />
      <Value xsi:type="xs:string">stand</Value>
    </Values>
  </Record>
- <Record xsi:type="esri:Record">
    ...
  </Record>
```

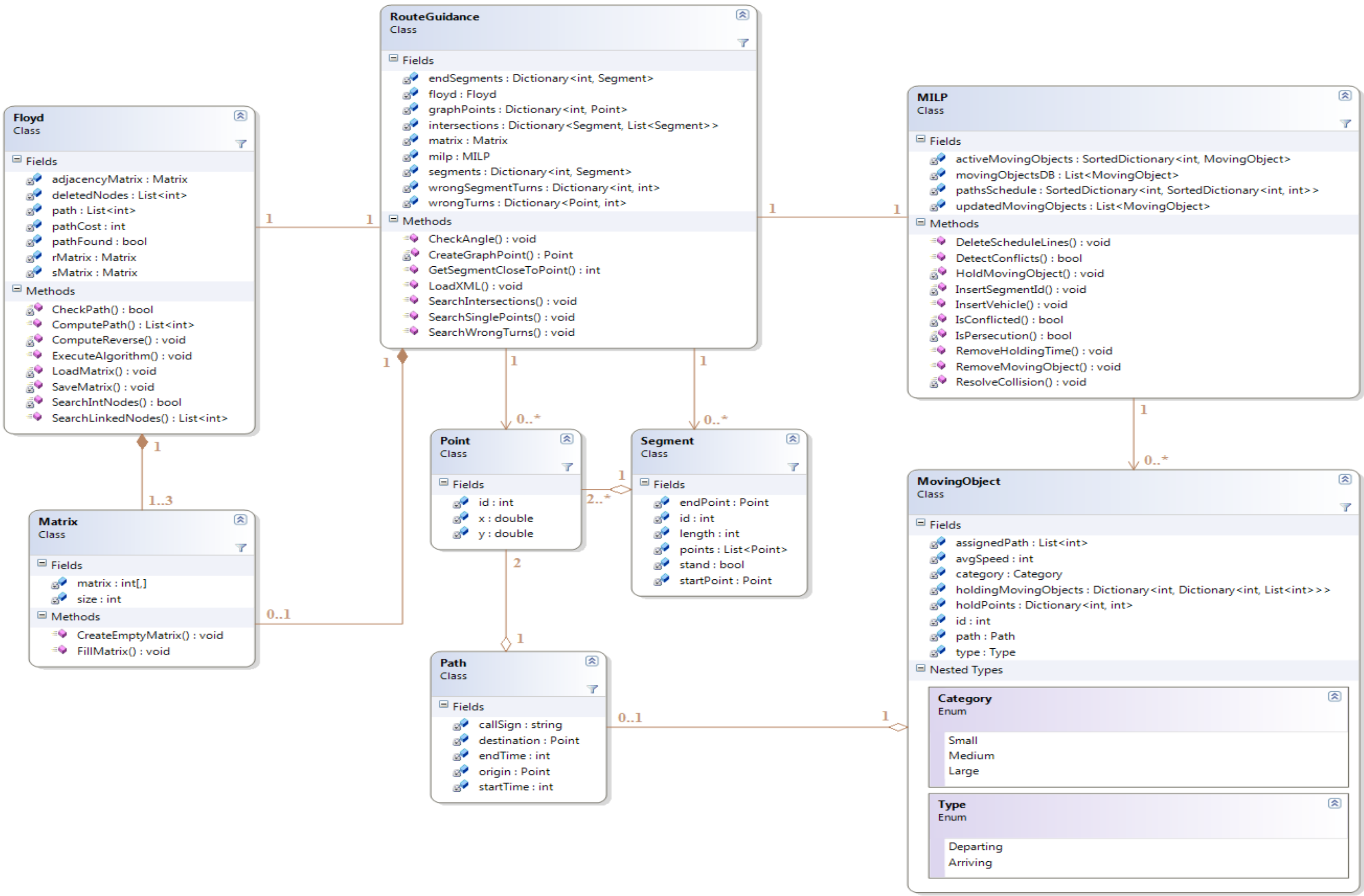
A.2: XML reader code.

The code presented shows an example of the XML reading, where the points constituting a segment are collected. This code is executed for each segment of the map, aiming to obtain a list of segments with their respective characteristics.

```
// Read the components of each Value
while (true)
{
    // Read the next node of the stream
    reader.Read();

    // Get the list of points of the segment
    if (reader.Name.Equals("Point") && reader.GetAttribute(0).Equals("esri:PointN"))
    {
        // Read the next node of the stream
        reader.Read();

        // Get the coordinates
        if (reader.Name.Equals("X"))
            x = reader.ReadElementContentAsDouble();
        if (reader.Name.Equals("Y"))
            y = reader.ReadElementContentAsDouble();

        // Add to the list of points of that segment
        segmentPoints.Add(new Point(id++, x, y));
    }
}
```

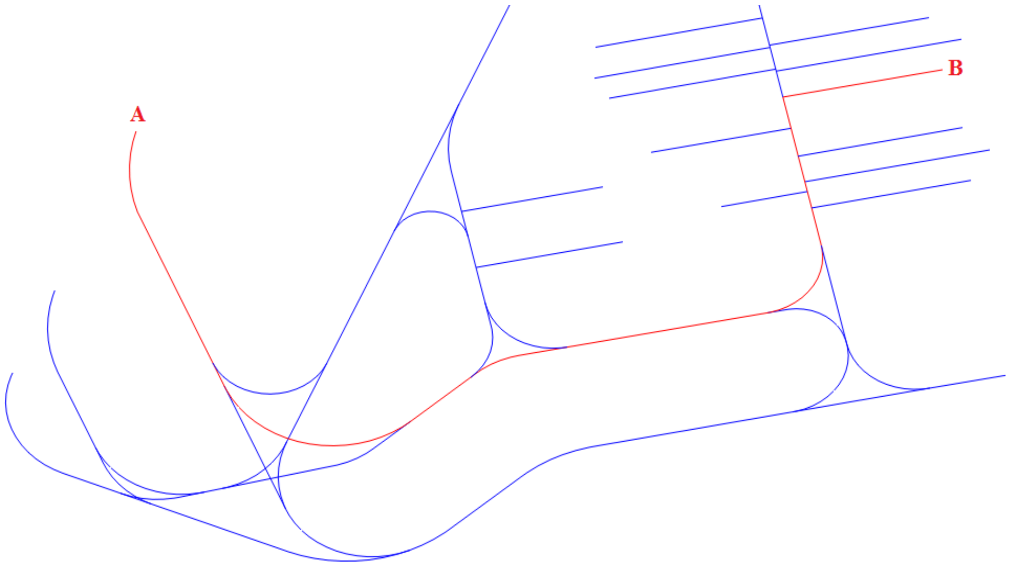
A.3: UML data structure.

The UML represents the domain model of the implemented system, where is represented the data structure organization and the objects' interaction.



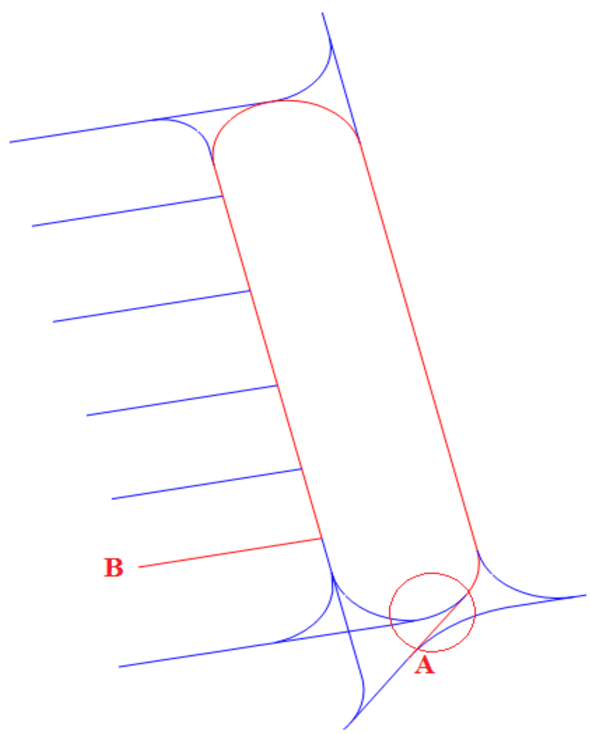
A.4: Route computed by Floyd.

The highlighted path represents the shortest path between A and B.



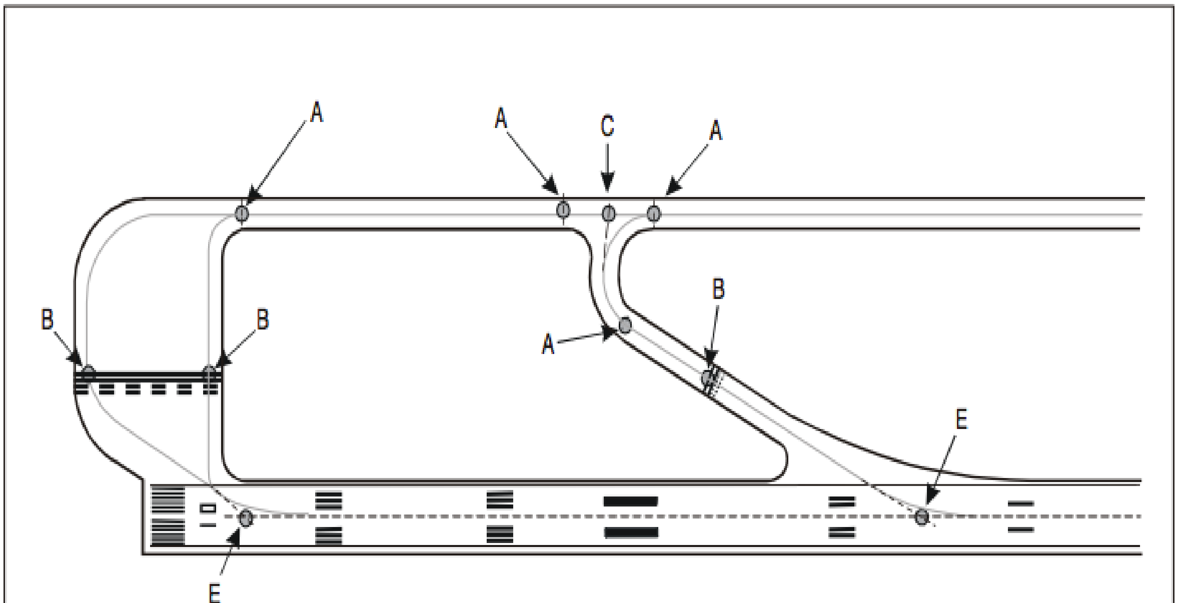
A.5: Alternative route to avoid a tight turn.

Instead of using the tight turn (represented with a circle), the shortest path between A and B takes a longer route.



A.6: Taxiway guidance lines topography points.

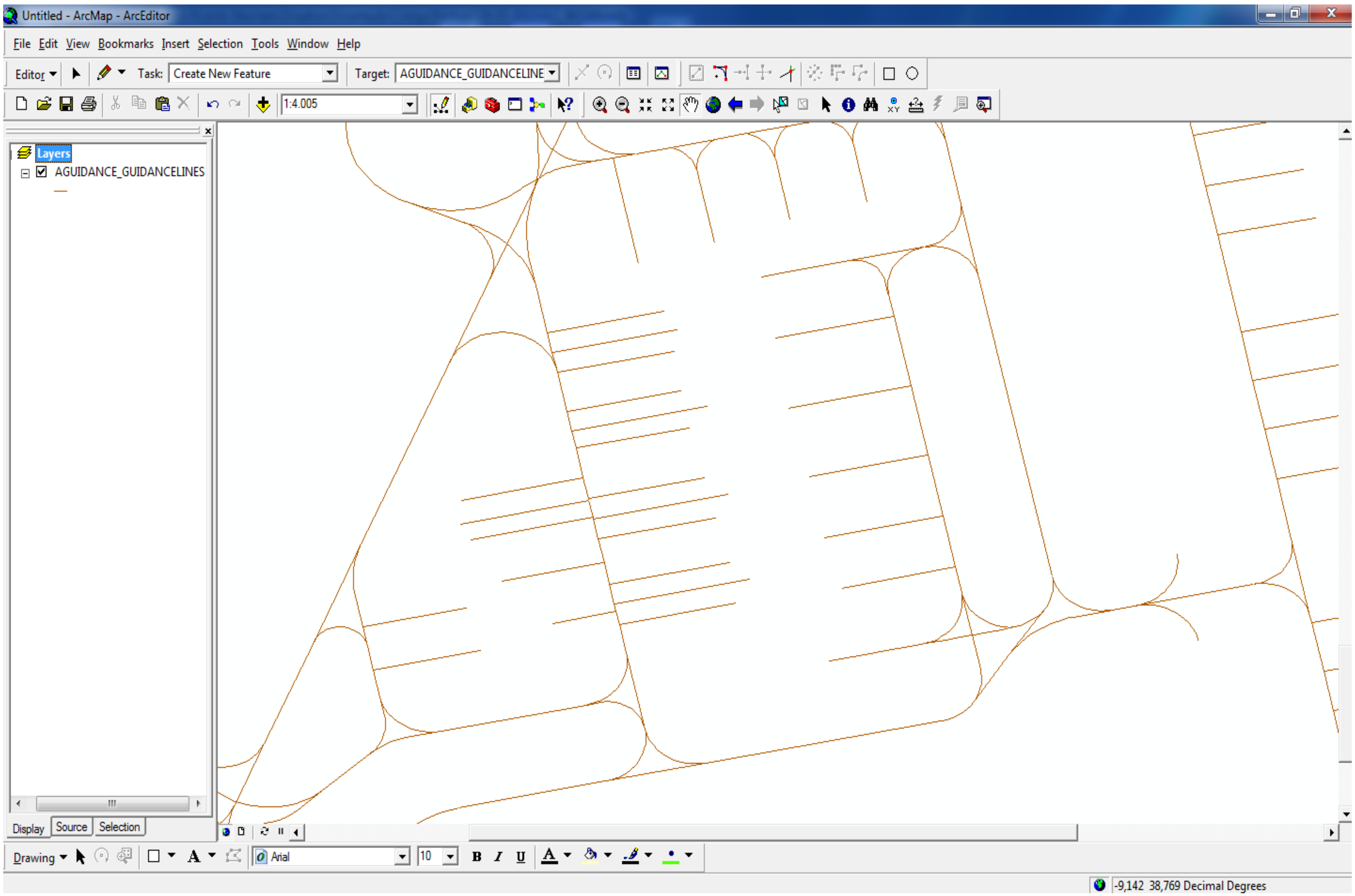
Representation of the taxiway intersections, runway exits and holding points within the movement area of an airport [5].



Runway holding points (B), runway exits (E), taxiway intersections (C) and intersection limits (A)

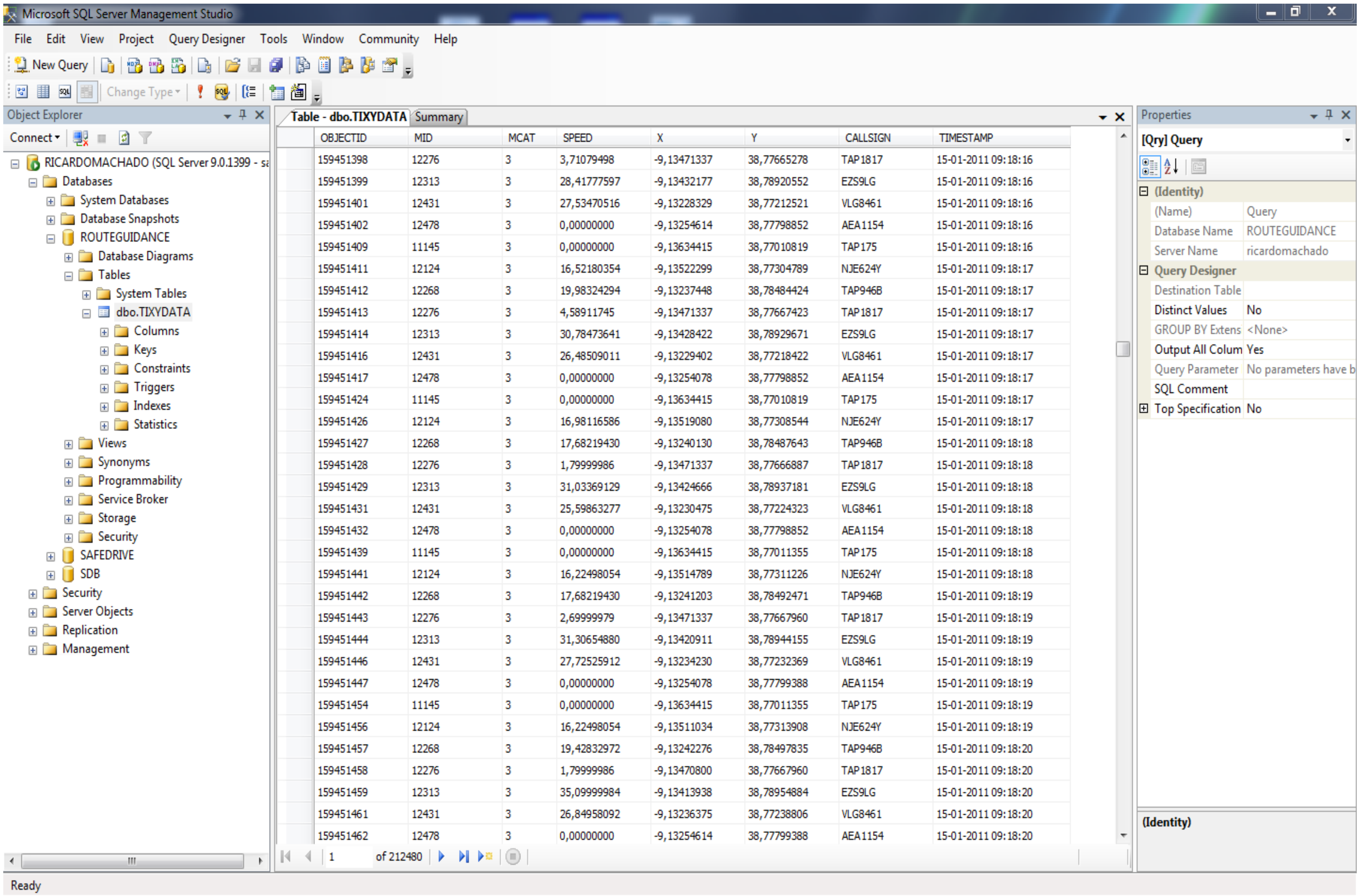
A.7: ArcMap - ArcEditor interface

Editing of the layer representative of the Lisbon airport taxiway guidance lines, used to repair a set of imperfections presented on the map.



A.8: SQL database with operational data.

SQL table with positioning data stored in historical logs from January 2011 about ground movements in the Lisbon airport.



OBJECTID	MID	MCAT	SPEED	X	Y	CALLSIGN	TIMESTAMP
159451398	12276	3	3,71079498	-9,13471337	38,77665278	TAP1817	15-01-2011 09:18:16
159451399	12313	3	28,41777597	-9,13432177	38,78920552	EZS9LG	15-01-2011 09:18:16
159451401	12431	3	27,53470516	-9,13228329	38,77212521	VLG8461	15-01-2011 09:18:16
159451402	12478	3	0,00000000	-9,13254614	38,77798852	AEA1154	15-01-2011 09:18:16
159451409	11145	3	0,00000000	-9,13634415	38,77010819	TAP175	15-01-2011 09:18:16
159451411	12124	3	16,52180354	-9,13522299	38,77304789	NJE624Y	15-01-2011 09:18:17
159451412	12268	3	19,98324294	-9,13237448	38,78484424	TAP946B	15-01-2011 09:18:17
159451413	12276	3	4,58911745	-9,13471337	38,77667423	TAP1817	15-01-2011 09:18:17
159451414	12313	3	30,78473641	-9,13428422	38,78929671	EZS9LG	15-01-2011 09:18:17
159451416	12431	3	26,48509011	-9,13229402	38,77218422	VLG8461	15-01-2011 09:18:17
159451417	12478	3	0,00000000	-9,13254078	38,77798852	AEA1154	15-01-2011 09:18:17
159451424	11145	3	0,00000000	-9,13634415	38,77010819	TAP175	15-01-2011 09:18:17
159451426	12124	3	16,98116586	-9,13519080	38,77308544	NJE624Y	15-01-2011 09:18:17
159451427	12268	3	17,68219430	-9,13240130	38,78487643	TAP946B	15-01-2011 09:18:18
159451428	12276	3	1,79999986	-9,13471337	38,77666887	TAP1817	15-01-2011 09:18:18
159451429	12313	3	31,03369129	-9,13424666	38,78937181	EZS9LG	15-01-2011 09:18:18
159451431	12431	3	25,59863277	-9,13230475	38,77224323	VLG8461	15-01-2011 09:18:18
159451432	12478	3	0,00000000	-9,13254078	38,77798852	AEA1154	15-01-2011 09:18:18
159451439	11145	3	0,00000000	-9,13634415	38,77011355	TAP175	15-01-2011 09:18:18
159451441	12124	3	16,22498054	-9,13514789	38,77311226	NJE624Y	15-01-2011 09:18:18
159451442	12268	3	17,68219430	-9,13241203	38,78492471	TAP946B	15-01-2011 09:18:19
159451443	12276	3	2,69999979	-9,13471337	38,77667960	TAP1817	15-01-2011 09:18:19
159451444	12313	3	31,30654880	-9,13420911	38,78944155	EZS9LG	15-01-2011 09:18:19
159451446	12431	3	27,72525912	-9,13234230	38,77232369	VLG8461	15-01-2011 09:18:19
159451447	12478	3	0,00000000	-9,13254078	38,77799388	AEA1154	15-01-2011 09:18:19
159451454	11145	3	0,00000000	-9,13634415	38,77011355	TAP175	15-01-2011 09:18:19
159451456	12124	3	16,22498054	-9,13511034	38,77313908	NJE624Y	15-01-2011 09:18:19
159451457	12268	3	19,42832972	-9,13242276	38,78497835	TAP946B	15-01-2011 09:18:20
159451458	12276	3	1,79999986	-9,13470800	38,77667960	TAP1817	15-01-2011 09:18:20
159451459	12313	3	35,09999984	-9,13413938	38,78954884	EZS9LG	15-01-2011 09:18:20
159451461	12431	3	26,84958092	-9,13236375	38,77238806	VLG8461	15-01-2011 09:18:20
159451462	12478	3	0,00000000	-9,13254614	38,77799388	AEA1154	15-01-2011 09:18:20