Politecnico di Milano
School of Industrial and Information Engineering
Department of Aerospace Science and Technologies
Master of Science in Aeronautical Engineering

An integrated solution for the optimization of the departures, surface and arrivals management at Milano Linate airport

Advisor: Professor Alberto L. M. Rolando
Co-Advisor: Professor Maurizio Bruglieri

Author: Giovanni Pavese 823565

Academic Year 2016/2017

ACKNOWLEDGMENTS

I would like to thank Professor Alberto Rolando for giving me the opportunity to work at this thesis: although the algorithm design has not been easy, this experience allowed me to overcome complex challenges every day, giving me the chance to improve my academic knowledge and to work with people of great personal and professional qualities. In particular, I would like to thank him for always believing, sometimes more than myself, in this project, and for his leadership during these months.

My thanks go to Professor Maurizio Bruglieri for his support in the algorithm design and its cordial availability in offering his help whenever it was needed.

My thanks also go to Roberto Careri (ENAV) which from the first day has given me valuable advices on how to model the complex and fascinating world of air traffic control.

My thanks, then, go to Paolo Sordi, Riccardo Conti and Anna Maria Francinelli (SEA) that, with their availability and courtesy, have provided to me information and data necessary to develop and apply the algorithm to a real context.

Special thanks go to my classmates and to all friends, for having laughed and, sometimes, cried together during this unforgettable adventure.

My sincere gratitude goes to my girlfriend and companion Denise for having been by my side in this years, with her cheerfulness, gentleness and patience, sharing with me the happy moments and encouraging me in difficult times.

Finally, my heartfelt thanks go to my family and especially to my parents who, with their sacrifices and support, have allowed me to become who I am today. I hope you're proud of me as I am of you.

RINGRAZIAMENTI

Vorrei ringraziare il Professor Alberto Rolando per avermi dato la possibilità di lavorare a questa tesi: sebbene il progetto dell'algoritmo non sia stato semplice, questa esperienza mi ha permesso di superare ogni giorno sfide complesse, dandomi la possibilità di migliorare le mie conoscenze accademiche e di collaborare con persone di grande qualità personale e professionale. In particolare, vorrei ringraziarlo per aver sempre creduto, a volte più di me stesso, in questo progetto, e per la sua guida durante questi mesi.

Il mio ringraziamento va al Professor Maurizio Bruglieri per il suo supporto nel progetto dell'algoritmo e la sua cordiale disponibilità nell'offrirmi il suo aiuto ogni qualvolta fosse stato necessario.

La mia riconoscenza va, inoltre, a Roberto Careri (ENAV), che fin dal primo giorno mi ha fornito preziosi consigli su come modellare al meglio il complesso ed affascinante mondo del controllo del traffico aereo.

I miei ringraziamenti vanno, poi, a Paolo Sordi, Riccardo Conti ed Anna Maria Francinelli (SEA) che, con la loro disponibilità e cortesia, mi hanno fornito le informazioni ed i dati necessari per sviluppare ed applicare l'algoritmo ad un contesto reale.

Un ringraziamento va ai miei compagni di università ed in generale agli amici, per aver riso e, a volte, pianto insieme durante questa indimenticabile avventura.

La mia gratitudine più sincera va alla mia ragazza e compagna Denise per essermi stata accanto, in tutti questi anni, con la sua allegria, dolcezza e pazienza, condividendo con me le gioie e supportandomi nei momenti difficili.

Infine, il mio più sentito ringraziamento va alla mia famiglia e soprattutto ai miei genitori che, con i loro sacrifici e sostegno, mi hanno permesso di diventare ciò che sono oggi. Spero siate orgogliosi di me come io lo sono di voi.

ABSTRACT

In recent decades the global air traffic has reached considerable levels and performance so that, nowadays, thousands of flights and millions of passengers are handled every day, safely and efficiently. It is expected, however, that their numbers will grow in the near future even twice, so preventive actions must be taken today to ensure a sustainable development of aviation.

Focusing on airports, departing and arriving aeroplanes have to be scheduled and routed through the taxiways and at the runways in a smooth and safe traffic flow, a complex task that normally is obtained seeking to achieve the best result in each single problem. One of the most interesting challenge is to consider the Departure, Surface and Arrival Management Problems as a unique integrated problem, considering the specific tasks of the stakeholders that operate around the aircraft (Airport Operator, Ground Handlers, Air Traffic Controllers, Aircraft Operators) and trying to improve the global efficiency of the airport system.

Taking inspiration from the Single European Sky ATM Research (SESAR) Solutions, then, in this thesis are presented the design and the validation of an optimization algorithm having the purpose of implementing an integrated Departure - Surface - Arrival Manager at Linate airport (Milan, Italy). With specific tools of the Operational Research, the integrated problem DMAN-SMAN-AMAN has been heuristically decomposed in three linked sub-problems in order to have real-time computations and adhere as much as possible to the operative procedures and constraints, and to the objectives of the airport stakeholders.

Obtained results show that the algorithm can significantly contribute to the reduction of delay, of taxi time and of fuel consumption of the aircraft operating at Linate, contributing to reach a more sustainable and performing aviation.

In chapter 1 is given an introduction to the thesis work, while in chapter 2 are described the ATM improvement problem, the European context, the common challenges and the SESAR Solutions. In chapter 3 is specified the Italian situation and given an historical, statistical and topological description of Milano Linate airport. In chapter 4 are illustrated the Operational Research tools and their application in the literature to ATM improvement. In chapters 5 and 6 are described the algorithm design and the results analysis, while in chapter 7 are reported the conclusions and possible future developments. Last, in Appendix A, are given some hints at the implementation of the algorithm at other airports, in particular at Milano Malpensa.

Keywords: Air Traffic Management, SESAR, DMAN, SMAN, AMAN, A-CDM, Operational Research.

SOMMARIO

Negli ultimi decenni il traffico aereo mondiale ha raggiunto livelli e prestazioni considerevoli tanto che, al giorno d'oggi, migliaia di voli e milioni di passeggeri sono gestiti, ogni giorno, in maniera sicura ed efficiente. Si prevede, però, che nel prossimo futuro il loro numero aumenti anche del doppio, pertanto delle azioni preventive devono essere prese già oggi al fine di garantire uno sviluppo sostenibile dell'aviazione.

Guardando nello specifico agli aeroporti, gli aerei in partenza ed arrivo devono essere schedulati ed instradati lungo le vie di rullaggio e sulle piste in un flusso di traffico scorrevole e sicuro, un compito complesso che normalmente è ottenuto cercando di raggiungere il miglior risultato possibile per ogni singolo problema. Una delle sfide più interessanti è considerare la gestione delle partenze, degli arrivi e della movimentazione al suolo in un unico problema integrato, considerando i compiti specifici di tutti i soggetti interessati nella gestione del velivolo (gestore aeroportuale, aziende di assistenza a terra, controllori del traffico aereo e compagnie aeree) e cercando di migliorare l'efficienza globale del sistema aeroportuale.

Traendo ispirazione dagli studi di SESAR, quindi, in questa tesi vengono presentati il progetto e la validazione di un algoritmo avente lo scopo di ottimizzare la gestione integrata delle partenze, degli arrivi e della movimentazione di superficie dei velivoli all'aeroporto di Milano Linate (Italia). Utilizzando gli strumenti della Ricerca Operativa, il problema è suddiviso euristicamente in tre sotto-problemi interconnessi tra loro, in modo da ottenere i risultati in tempo reale e rispettare il più possibile le procedure aeroportuali, oltre che soddisfare gli obiettivi delle parti interessate.

I risultati ottenuti dimostrano che l'algoritmo può contribuire in modo significativo a ridurre il ritardo, il tempo di rullaggio ed il consumo di combustibile dei velivoli operanti a Linate, contribuendo a raggiungere un'aviazione più sostenibile e performante.

Nel capitolo 1 è introdotto il lavoro di tesi, mentre nel capitolo 2 sono descritti il problema del miglioramento della gestione del traffico aereo, il contesto europeo, le sfide comuni e le soluzioni implementative di SESAR. Nel capitolo 3 è riportata un'analisi del contesto italiano, con una descrizione storico-statistico-topologica dell'aeroporto di Linate. Nel capitolo 4 sono illustrate le tecniche della Ricerca Operativa e la loro applicazione nella letteratura al problema di interesse. Nei capitoli 5 e 6 sono descritti il progetto dell'algoritmo e l'analisi dei risultati, mentre nel capitolo 7 sono riportate le conclusioni ed i possibili sviluppi futuri. Infine, in appendice A, vengono forniti dei cenni all'implementazione dell'algoritmo in altri aeroporti, in particolare in quello di Milano Malpensa.

Parole chiave: Gestione del Traffico Aereo, SESAR, Cielo Unico Europeo, DMAN, SMAN, AMAN, A-CDM, Ricerca Operativa.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

A-CDM	Airport Collaborative Decision Making
AFI	Arrival Free Interval
AGHT	Actual Ground Handling Time
AIBT	Actual In-Block Time
ALDT	Actual LanDing time
ALP	Aircraft Landing Problem
AMAN	Arrival MANager
ANS	Air Navigation Services
ANSP	Air Navigation Services Provider
AO	Aircraft Operator
AOBT	Actual Off-Block Time
ARDT	Actual Ready Time
ASAT	Actual Start Up Approval Time
A-SMGCS	Advanced Surface Movement Guidance and Control System
ASRT	Actual Start Up Request Time
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATCS	Air Traffic Control Service
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
ATOT	Actual Take-Off Time
ATP	Aircraft Take-Off Problem
ATW	Arrival Tolerance Window
BIP	Bynary Integer Programming
CFMU	Central Flow Management Unit
CONOPS	CONcept of OPerationS
CONUS	CONtiguous United States

CPS	Constrained Position Shifting
CTOT	Calculated Take-Off Time
DFS	Deutsche Flugsicherung
DMAN	Departure MANager
DSNA	Direction des Services de la Navigation Aérienne
DTW	Departure Tolerance Window
ECAC	European Civil Aviation Conference
EIBT	Estimated In-Block Time
ELDT	Estimated LanDing Time
ELRP	Estimated Line-up and Roll to airborne Period
ENAC	Ente Nazionale per l'Aviazione Civile
ENAIRE	Aeropuertos Españoles y Navegación Aérea
ENAV	Ente Nazionale per l'Assistenza al Volo
EOBT	Estimated Off-Block Time
ERBP	Expected Runway Delay Buffer
ERWP	Estimated Runway Hold Waiting Period
ESWP	Estimated Stand Waiting Period
ETOT	Estimated Take-Off Time
EU	European Union
EWP	Expected Waiting Period
EXIP	Estimated Inbound Taxi Period
EXIT	Estimated Taxi-In Time
EXOP	Estimated Outbound Taxi Period
EXOT	Estimated Taxi-Out Time
FAA	Federal Aviation Administration
FCFS	First Come First Served
FDPS	Flight Data Processing System
FIR	Flight Information Region
FPL	Flight PLan
GA	General Aviation

GH	Ground Handler
GS	Ground Air Speed
IAS	Indicated Air Speed
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILP	Integer Linear Programming
LP	Linear Programming
LSSIP	Local Single Sky ImPlementation
MDI	Minimum Departure Interval
MILP	Mixed Integer Linear Programming
MPS	Maximum Position Shifting
MTTT	Minimum Turn-round Time
NATS	National Air Traffic Services
NLP	Non Linear Programming
NMOC	Network Manager Operations Centre
OI	Operational Improvement
OR	Operational Research
PCP	Pilot Common Project
PKB	Parking Position or Stand
RDPS	Radar Data Processing System
RPS	Relative Position Shifting
RWY	Runway
SEA	Società Esercizi Aeroportuali
SES	Single European Sky
SESAR	Single European Sky ATM Research
SESAR-JU	SESAR Joint Undertaking

SIBT	Scheduled In-Block Time
SID	Standard Instrument Departure
SMAN	Surface MANager
SOBT	Scheduled Off-Block Time
STAR	Standard Instrument Arrival
STW	Slot Tolerance Window
TIBT	Target In-Block Time
TLDT	Target LanDing Time
TMA	TerMinal Control Area
TOBT	Target Off-Block Time
TSAT	Target Start Up Approval Time
TSP	Traveller Salesman Problem
TTG	Time To Gain
TTL	Time To Lose
TTOT	Target Take-Off Time
TWY	Taxyway
VFR	Visual Flight Rules
VTT	Variable Taxi Time

GLOSSARY

In the following glossary are reported some definitions useful to readers to understand the principal terms used in the thesis work. They can be found, with many others, in the EUROCONTROL ATM lexicon site [20]. Consider, for a general comprehension, *target* times calculated by a computer system, *scheduled* times provided by airlines and/or airport services provider, *estimated* times provided by Air Traffic Control authority and/or airlines, *actual* times recorded by airport and/or tower control personnel, *calculated* times provided by European offices (like NMOC).

A-CDM	A process in which decisions related to Air Traffic Flow and Capacity Management (ATFCM) at airports are made based on interaction between operational stakeholders and other actors involved in ATFCM and which aims at reducing delays, improving the predictability of events and optimising the utilisation of resources.
AIBT	The actual date and time when the parking brakes have been engaged at the parking position.
ALDT	The actual date and time when the aircraft has landed (touch down).
AMAN	A planning system to improve arrival flows at one or more airports by calculating the optimised approach / landing sequence and Target Landing Times (TLDT) and, where needed, times for specific fixes for each flight, taking multiple constraints and preferences into account.
AOBT	The time the aircraft pushes back / vacates the parking position.
ASAT	Time that an aircraft receives its start up approval.
ATM	The aggregation of the airborne and ground-based functions (air traffic services, airspace management and air traffic flow management) required to ensure the safe and efficient movement of aircraft during all phases of operations.
ATOT	The time that an aircraft takes off from the runway (Equivalent to ATC ATD–Actual Time of Departure.)
CTOT	A time calculated and issued by the Network Manager Operations Centre (NMOC), as a result of tactical slot allocation, at which a flight is expected to become airborne.

DMAN	A planning system to improve departure flows at one or more airports by calculating the Target Take-Off Time (TTOT) and Target Start Up Approval Time (TSAT) for each flight, taking multiple constraints and preferences into account.

EIBT	The estimated time that an aircraft will arrive in-block.
ELDT	The estimated time that an aircraft will touchdown on the runway. (Equivalent to ATC ETA – Estimated Time of Arrival = landing).
EOBT	The estimated time at which the aircraft will commence movement associated with departure. It is indicated in the flight plan by the pilot.
ETOT	Forecast of time when aircraft will become airborne taking into account the EOBT plus EXOT.
EXIT	The estimated taxi time between landing and in-block.
EXOT	The estimated time between off-block and take-off. This estimate includes any delay buffer time at the holding point or remote de-icing prior to take-off.

SIBT	The time that an aircraft is scheduled to arrive at its first parking position.
SMAN	An ATM tool that determines optimal surface movement plans (such as taxi route plans) involving the calculation and sequencing of movement events and optimising of resource usage (e.g. de-icing facilities).
SOBT	The time that an aircraft is scheduled to depart from its parking position.

TIBT	The targeted in-block time, computed from the Arrival management process, taking taxiway sequence and constraints into account. Note: this term is defined and used only in this document to reference to the time calculated from the optimization algorithm.
TLDT	Targeted Time from the Arrival management process at the threshold, taking runway sequence and constraints into account. It is not a constraint but a progressively refined planning time used to coordinate between arrival and departure management processes.
TOBT	The time that an aircraft operator / handling agent estimates that an aircraft will be ready, all doors closed, boarding bridge removed, push back vehicle present, ready to start up / push back immediately upon reception of clearance from the TWR.

TSAT	The time provided by ATC taking into account TOBT, CTOT and/or the traffic situation that an aircraft can expect to receive start up/push back approval.
TTOT	An ATM computed take-off time, which takes into account the TOBT/TSAT and the EXOT. It is used to define the departure airport sequencing and optimization of runway throughput. Each TTOT on one runway is separated from other TTOT or TLDT to represent vortex and/or SID separation between aircraft.

LIST OF SYMBOLS

Sign	Description	Unit
δ_d	Target departure time (ETOT or CTOT).	[h]
τ_{fg}	Separation time between flight f and flight g at the runway.	[h]
λ_l	Target arrival time (ELDT).	[h]
A	Set of arcs of the airport graph.	[-]
D	Set of departing flights (departures).	[-]
d	Departing flight.	[-]
F	Set of all flights.	[-]
H	Time horizon of the flights that have to be scheduled at the runway.	[h]
H_d	Tolerance window of a departure (DTW or STW).	[h]
H_l	Tolerance window of an arrival (ATW).	[h]
HP	Set of nodes indicating holding points.	[-]
$k^{\nu}_{f,f}$	Boolean variable for disjunctive constraints in Step 3.	[-]
L	Set of landing flights (arrivals).	[-]
l	Arriving (or landing) flight.	[-]
l^a_f	Running time for flight f through arc a.	[h]
$\dot{m}$	Fuel flow associated at each engine of the aircraft f.	$[kg/s]$

Sign	Description	Unit
N_e	Number of engines of the aircraft f.	[-]
p^v	Waiting time at holding point.	[h]
PKB	Set of nodes indicating parking positions.	[-]
pkb_f	Parking position of flight f.	[-]
Q	Set of nodes indicating release points for push-back procedures.	[-]
R	Set of airport roads or paths.	[-]
r_f	Route assigned to flight f.	[-]
t	Schedule time at the runway (Step 2) or at nodes and arcs (Step 3) or day time.	[h]
TX_f	Minimum time necessary to f to run the assigned route r_f.	[h]
u_f^a	Binary variable of Step 1 associated to the usage of arc a by flight f.	[-]
V	Set of nodes of the airport graph.	[-]
w_d	Cost associated to a dropped flight.	[-]
x_{ft}	Binary variable of Step 2 associated to take-off and landing times.	[-]
y_d	Binary variable of Step 2 associated to a dropped departure d.	[-]

1

INTRODUCTION

Since the invention of the airship and of the aeroplane in the early 1900s, men understood that it was possible to go faster and farther from a point to another like never before. With the development of aviation the objective became more strict, wanting to go even faster and farther than before, and at the same time it was felt the need of more safety related to air transportation. Nowadays global aviation has achieved performances that were not even thinkable a few decades ago but, as happened in the past, new challenges have to be faced and won, especially for future generations of air travellers and world citizens.

Today air traffic involves thousand flights and millions passengers that are managed efficiently and in safety but, in the future, is expected a growth of them. With the actual deployment of infrastructures and services, however, will be impossible to accommodate all the flights, so some measures have to be implemented from now. The objectives, then, not only include an increase in capacity and safety, but also in environmental and economical sustainability. These new problems are complex and the solutions have to be implemented with a new idea of cooperative optimization. First of all, the services and operations involving air traffic have to be seen as a unique process (called Air Traffic Management), that has to be shared among all the interested stakeholders in order to achieve better global results. Then, technical improvements have to be studied with the purpose to design more efficient aeroplanes, and to manage them in the best possible way.

In this context, therefore, it fits this thesis work, which looks at the Air Traffic Management improvement and aims to design an optimization algorithm for computing the best possible solution to the integrated problem of departures, surface and arrivals management at Milano Linate airport located in Italy.

Figure 1.1: Visualisation of air traffic flow over Europe. [https://goo.gl/3tuuGX]

2

AIR TRAFFIC MANAGEMENT: BACKGROUND AND FUTURE CHALLENGES

The Air Traffic Management (ATM) is the aggregation of the airborne and ground-based functions (air traffic services, airspace management and air traffic flow management) required to ensure the safe and efficient movement of aircraft during all phases of operations [20]. With the *gate-to-gate* concept, in fact, a flight is considered and managed as a continuous event, from planning, through execution, to the post-flight activities. Some operations can start many months ahead of the date of the flight, other are related to daily activities. Looking at figure 2.1 there can be seen the principal phases associated to a flight, which comprise push-back at the gate, taxiing between the gate and the runway, take-off and initial climb following Standard Instrument Departure (SID) procedures, cruise, final descent following a Standard Instrument Arrival (STAR) route, landing on the runway and taxiing to the gate. For a global performance of the ATM system, these activities should be optimized and considered at the same time for all the interested flights: gate assignment, ground routing and scheduling, take-off and landing times decision or the choose of an appropriate air route are only few example of ATM work. Everything means that the ATM system is highly complex, handles a huge number of flights and involves many actors (airlines, Air Navigation Services Providers (ANSPs), airports, national and international regulatory authorities, etc.) each of which has specific objectives to satisfy.

The ATM, then, acts in such a dynamic environment, in which the safety and efficiency are the most important keys. However, it does not look only at the present situation, but tries to anticipate the future improving itself day by day, in order to develop a sustainable air traffic for future generations.

In the world many studies and efforts have been done in the ATM field, developing specific programs like NextGen for USA or Single European Sky (SES) for Europe. This latter, which will be described in the following sections and taken as reference for the present thesis work, deals with the improvement of ATM between the European States, maybe representing the best example of cooperation between different Nations in order to achieve a common objective.

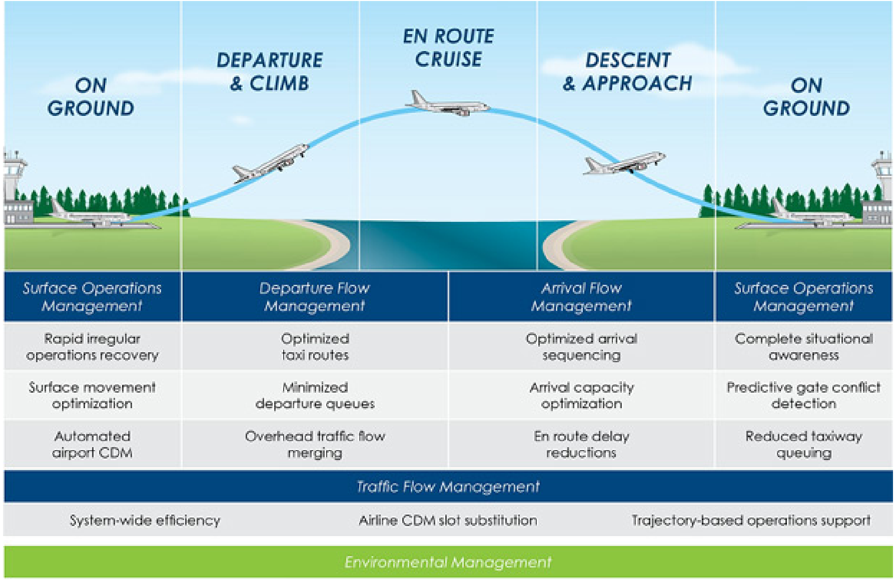


Figure 2.1: Gate-to-gate concept in Air Traffic Management. [`https://goo.gl/UQf9mz`]

2.1 EUROPEAN CONTEXT

Since 1999 the European Union underlined the importance of taking measures for the improvement of ATM. In particular, it was felt the need of a common vision, within the states, regarding the smoothness and punctuality of the flights, and the management of the capacity of the whole air space [19]. Therefore, in 2004, with the aim to achieve a "more sustainable and high-performing aviation", was born the Single European Sky (SES) (Package I, revised and extended in 2009 with the SES II Package), with whom the Commission wanted to highlight how aviation is an important driver of economic growth, jobs and trade, with a major impact on the life and mobility of European Union (EU) citizens.

In 2005, the Commission stated its political vision and set high-level goals for the SES to be met by 2020 and beyond. It should:

- enable a 3-fold increase in capacity which will also reduce delays both on the ground and in the air;
- improve safety by a factor of 10;
- enable a 10 % reduction in the effects that flights have on the environment;
- provide ATM services to the airspace users at a cost of at least 50 % less.

These objectives are fundamental to manage the huge quantity of flights and the complexity of the European air space. The following are some background statistics useful to contextualize the problem:

- In 2016, the European ATM system controlled 10.197 millions flights, that are about $27,900$ flights on an average daily basis. [21]
- As a result of the SES policy, average delays for en-route air traffic flow management are now close to 0.5 min per flight, which is a remarkable achievement compared to the heavy delays that occurred in the 1990s and 2000s. [15]
- On average each flight is 49 km longer than the direct flight. [15]
- The European airspace extension is 11.5 million km^2 with 37 operating ANSPs. Five biggest ANSPs (DFS for Germany, DSNA for France, ENAIRE for Spain, ENAV for Italy and NATS for the UK) bear 60% of total European gate-to-gate service provision costs and operate 54% of European traffic. The total staff is composed of $56,300$ units, of which $17,370$ are Air Traffic Controllers (ATCOs). [15, 28]

  Estimated costs of fragmentation of airspace amounts to € 4 bn a year.[15]
- Making a comparison with the USA, it appears that the CONUS airspace has one ANSP (FAA), it is 10% smaller than European airspace, 57% more flights (operating under Instrument Flight Rules (IFR)) were controlled by 24% fewer air traffic controllers than in Europe in 2015. On average, US airspace is denser and its airports larger than European ones. In addition, over the past 15 years, European traffic has grown by 15%, whereas traffic levels in the US have decreased by 14%.[28]
- According to the most-likely scenario, the traffic growth within the EU will lead to 11.6 millions flights in 2023 and 14.4 millions flights in 2035. Compared to the values of 2000 (8 millions) and 2016 (10.197 millions), in 2023 will be 45% more than 2000, and 14% more flights respect to 2016. Looking at long term forecast, in 2035 will be 80% more flights respect to 2000, and 40% more than the actual flights (2016/2017).[17, 21]
- It is estimated that cost savings and the value of all performance benefits deriving from the implementation of the SES would amount to annual recurring benefits ranging potentially from € 8 billion to € 15 billion per year in 2035, compared to a scenario where SES would not be deployed.[17]

To satisfy the high-level goals, in 2004 was launched the Single European Sky ATM Research (SESAR) programme. Its role is to define, develop and deploy what is needed to increase ATM performance and build Europe's intelligent air transport system. Established in 2007 as a public-private partnership, the SESAR Joint Undertaking (SESAR-JU) is responsible for the modernisation of the European Air Traffic Management (ATM) system by coordinating and concentrating all ATM relevant research and innovation efforts in the EU (SESAR Solutions) [44].

During the SESAR Definition Phase (2005-2008) was determined the CONcept of OPerationS (CONOPS), that is a specific application of the International Civil Aviation Organization (ICAO) Global Air Traffic Management Operational Concept, adapted and interpreted for Europe with due regard to the need for global interoperability. The CONOPS (or target concept) describes the *Trajectory Based Operations*, where all partners in the ATM network will share trajectory information in real time, resulting in a more efficient flight management [10]. However, to reach the complete development of the CONOPS at the higher level, three Concept Steps have been defined [16]:

- Time Based Operations (Step 1): is the building block for the implementation of the SESAR Concept and is focused on flight efficiency, predictability and environment. Initial trajectory-based operations are deployed through the use of airborne trajectories (by the ground systems), and a controlled time of arrival (to sequence traffic and manage queues) (see also [48]).
- Trajectory Based Operations (Step 2): is focused on flight efficiency, predictability, environment and capacity, which becomes an important target. The sharing of 4D trajectory (longitude, latitude, flight level and time) information is the most important key of success.
- Performance Based Operations (Step 3): will achieve the high performance required to satisfy the SESAR target concept through integrated, network-centric, collaborative and seamless air/ground ATM system.

SESAR has concluded the first phase SESAR-1 (2008-2016) in 2016 [50] and has just entered in the SESAR-2020 phase (2014-2024) within the Development Phase (2008-2024). In addition to this, the Deployment Baseline (2015-2035) goes on through Step 1 (officially approved in 2012 [45]) with a look at Step 2 (the time progress depends on what Operational Changes have been implemented) [17, 44]. See figure 2.2 for the timeline of the SESAR phases.

The Development and Deployment phases are detailed in the Master Plan [46], which is composed of three levels: the Executive View (level 1), the Planning and Architecture View (level 2) and the Implementation view (level 3). In the Executive View [17] are defined four Key Features, that are strategic orientations to achieve the CONOPS:

- Optimised ATM network services;
- Advanced air traffic services;
- High-performing airport operations;
- Enabling aviation infrastructure.

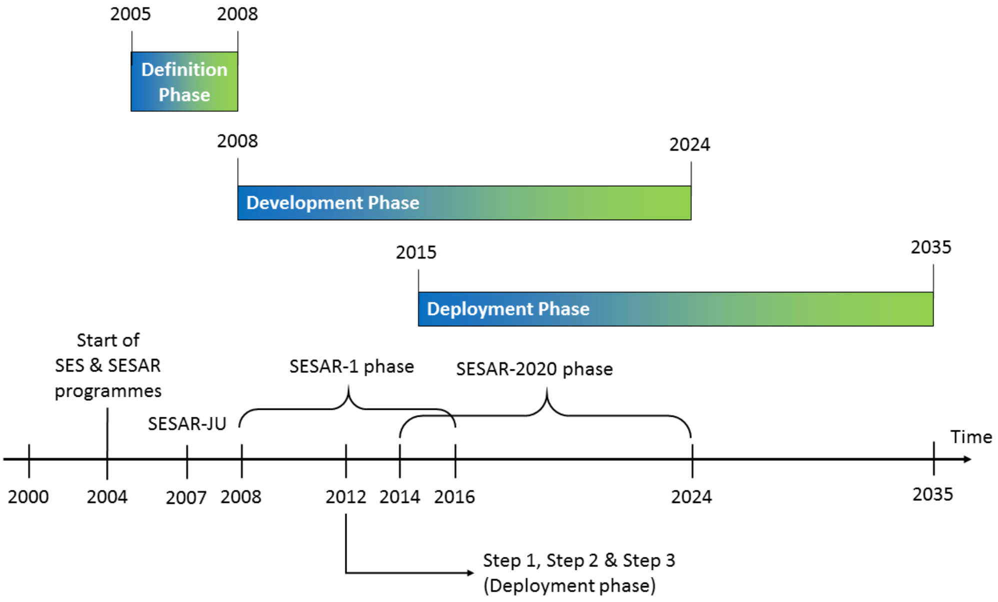


Figure 2.2: SESAR phases timeline.

In the Master Plan the Operational Changes are also defined, which provide performance benefits to one or more of the four types of operating environment, i. e. airport, en-route, TerMinal Control Area (TMA) and network. Each of the Operational Changes supports the Key Performance Ambitions (that are Cost efficiency, Operational efficiency, Capacity, Environment, Safety and Security) identified for one operating environment or more, within the ambient of the four Key Features [1].

2.2 SESAR SOLUTIONS FOR ATM IMPROVEMENT

The "High performing airport operations" Key Feature considers the airports as full integrated nodes in the ATM system. This implies enhanced airport operations, ensuring a seamless process through the A-CDM, in normal conditions, and through the further development of collaborative recovery procedures in adverse conditions. This Key Feature, then, addresses the enhancement of runway throughput, integrated surface management, airport safety nets and total airport management. The levers with which these objectives can be reached are delivered by SESAR and are named SESAR Solutions ([44, Solutions]) and are, among all, the DMAN, AMAN, SMAN and their optimal integration. In order to improve the ATM at Linate airport, then, in this thesis

---

[1] See the ATM Master Plan portal ([46]) for insights on the relationships among the Operational Changes, Operating Environment, Performance Ambitions and Key Features.

the indications given by SESAR for the design of these Solutions have been followed, adapting them to the specific local context.

2.2.1 *Departure Manager*

The Departure MANager (DMAN) is a planning system to improve departure flows at one or more airports [20]. The need of a Departure Manager arises from the fact that within the ATCO the First Come First Served (FCFS) principle is the most applied, that is to authorize the aircraft to start up and taxi to the runway as soon as the ground handling operations are concluded. In this way the traffic flow is not smooth and aircraft have to wait at holding points near the runway many minutes before the take-off clearance, creating queues that cause unnecessary fuel burning, delays, unpredictability and frustration for passengers. The idea of DMAN, on the contrary, is based on a general optimization vision, taking into account the scheduled departure times, slot constraints, runway constraints and airport factors. In doing so, it improves traffic predictability, cost efficiency and environmental sustainability, as well as safety. The DMAN is composed of two elements [47]:

- Pre-departure management, with the objective of metering the departure flow to a runway by managing Off-block-Times via Start up-Times. In combination with the Airport Collaborative Decision Making (A-CDM), Pre-departure management aims thus at reducing taxi times, increasing Network Manager Operations Centre (NMOC)[2] slots compliance and increasing predictability of departure times for all linked processes.
- Departure management, with the objective of maximising traffic flow on the runway by setting up a sequence with minimum separations.

The DMAN uses the Target Off-Block Time (TOBT) provided by the A-CDM process as input for elaborating both pre-departure sequence (with Target Start Up Approval Time (TSAT)) and departure sequence (with Target Take-Off Time (TTOT)). Another input is the Estimated Outbound Taxi Period (EXOP), which is the estimated time between off-block and take-off without delays. The EXOP is derived from static tables in the basic version [47], or from the Routing and Planning service (i. e. the Surface MANager (SMAN)) in the newest versions [49]. If the tables consider accurately how stand areas locations, traffic density and weather influence the taxi time, the improvement provided by routing and planning is not so evident. On the other hand, the more complex the taxiway layout is, the more improvement is expected by taxi times provided by routing and planning.

For each flight, then, the DMAN firstly defines the aircraft rank in the take-off sequence computing the TTOT as the sum of TOBT and taxi time, taking into account

---

[2] NMOC was previously called Central Flow Management Unit (CFMU).

possible delays at the runway or at the parking position. Then the departure manager computes the TSAT backwards, from the runway to the parking stand, in order to define the pre-departure sequence[3]. For a clearer meaning of the DMAN milestones, see figure 2.3.

When elaborating departure sequence the DMAN takes into account:

- existing NMOC slots (Calculated Take-Off Time (CTOT)), which have to be respected as much as possible;
- Variable Taxi Times (including remote de-icing times when needed);
- runway constraints such as capacity, runway pressure, departure rate, others;
- Aircraft Wake Vortex separations;
- SID and Minimum Departure Interval (MDI).

All of these items will be discussed in the chapter relative to the algorithm implementation, focusing on what are the specific needs of the local context.

2.2.2 *Arrival Manager*

The Arrival MANager (AMAN) is a planning system to improve arrival flows at one or more airports by calculating the optimised approach / landing sequence and Target Landing Times (TLDT) and, where needed, times for specific fixes for each flight, taking multiple constraints and preferences into account [20]. Its main aims are to assist the controller to optimise the runway capacity (sequence) and/or to regulate (or manage or meter) the flow of aircraft entering the airspace, such as a TMA. It also aims to provide predictability for its users (both ground and air) and at the same time minimise the impact on the environment, by reduced holding and low-level vectoring [24].

The main input sources of the Arrival Manager are the flight plan data retrieved from a Flight Data Processing System (FDPS) and the radar data from a Radar Data Processing System (RDPS), which is then correlated to flight plan data. The system utilises an aircraft performance model and it is also fed with known airspace/flight constraints, such as speed restrictions to be used in the calculation of predicted times and aircraft trajectories. Wake Turbulence Category and weather information are also taken into consideration.

Manual inputs to the AMAN include insertion of the landing rate or separation on final and/or the cadence of landing for a runway, or “slots” to block a runway for a specified length of time.

---

[3] See reference [49, Appendix B] for the equations.

An AMAN system may also take into consideration prescribed optimisation criteria.

The outputs of the system generally comprise an optimised sequence, a time-line, time-information and delay management advisories, which are provided on a screen for the AMAN supervisor. These advisories can include Time To Lose (TTL) or Time To Gain (TTG) indications, speed advisories or turn advisories, which are computed comparing a constrained and an unconstrained sequence of the arriving aircraft.

The Extended AMAN is expected to extend its range of operations beyond its current "normal" use, that is within the TMA, and by including its use in En Route airspace, to begin the Arrival Management process much earlier in the flight.

According to Local Single Sky ImPlementation (LSSIP) reporting of 2015, 17 airports in the European Civil Aviation Conference (ECAC) area have implemented basic AMAN functionality [18]. These are represented in figure 2.4. Many of them have implemented also the integration with the DMAN [23]. The two Italian Pilot Common Project (PCP) airports (Roma Fiumicino and Milano Malpensa) have indicated no plans to implement basic AMAN, as it will be comprised in the implementation of Extended AMAN [27].

2.2.3 *Surface Manager*

The Surface MANager is an ATM tool that determines optimal surface movement plans (such as taxi route plans) involving the calculation and sequencing of movement events and optimising of resource usage (e.g. de-icing facilities) [20].

With the increase of air traffic, the complexity of airports and the more stringent constraints the need of such a system has become important. Optimum management of surface traffic flows will not only increase efficiency and predictability during the ground movement phase but will also have a positive impact on the environment. The planning of surface routes may consider constraints imposed by the need to minimise the environmental impact, especially surface holding or the need to avoid braking or changes in engine thrust levels as the aircraft moves from the runway to the stand or vice versa.

Predicting the taxi times and routing of inbound and outbound traffic, the SMAN can provide stable and reliable planning (target) times and is a prerequisite for pre-departure sequencing and an optimised usage of the departure runway(s). Integration of the SMAN tool with the arrival and departure management tools (AMAN/DMAN) is a necessity to gain the full benefit of these tools [10].

The SMAN is the Planning function in the Advanced Surface Movement Guidance and Control System (A-SMGCS), that is a system useful to improve the situational

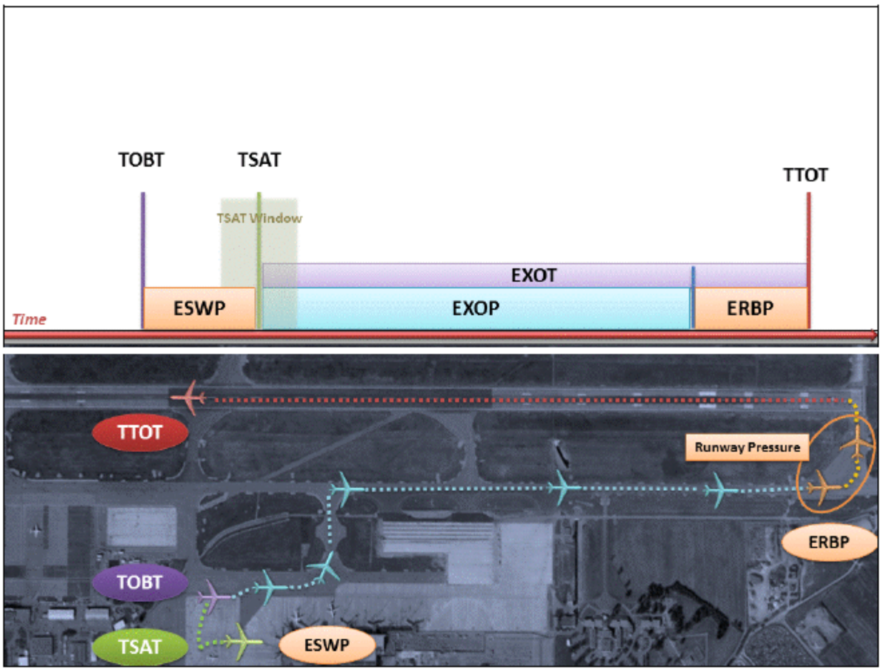


Figure 2.3: Basic DMAN milestones [47]

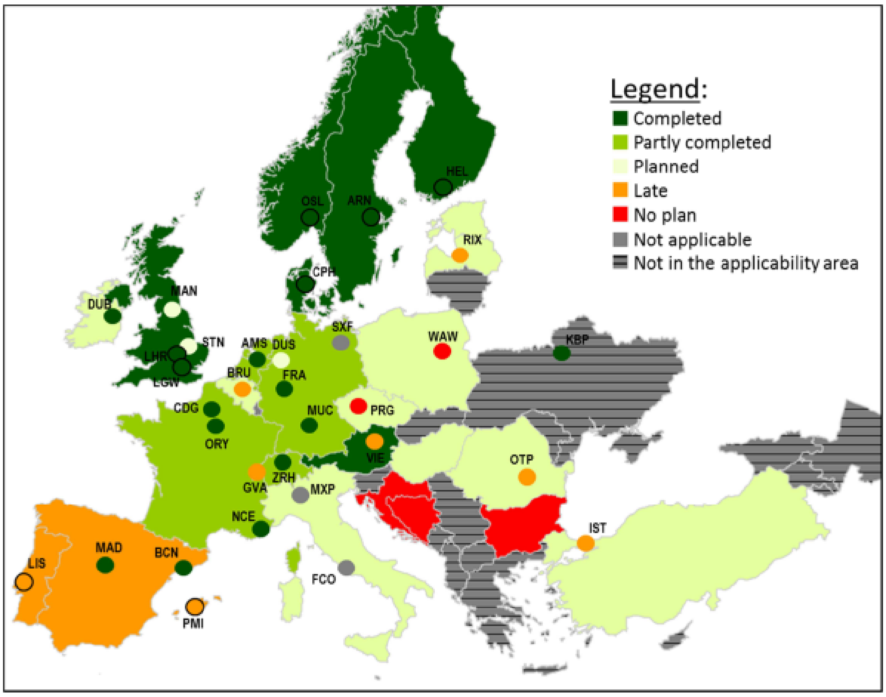


Figure 2.4: Basic AMAN (airports) and Extended AMAN (States) - Status of implementation as reported in LSSIP 2015 and in [18].

awareness both for the controller, aircrew and vehicle drivers, including conflict detection and warning systems. It is also the key to enhance airports surface safety and capacity.

2.2.4 *Airport Collaborative Decision Making*

The Airport Collaborative Decision Making is the concept which aims at improving Air Traffic Flow and Capacity Management (ATFCM) at airports by reducing delays, improving the predictability of events and optimising the utilisation of resources [20]. Implementation of Airport CDM allows each Airport CDM Partner to optimise their decisions in collaboration with other Airport CDM Partners, knowing their preferences and constraints and the actual and predicted situation. The decision making by the Airport CDM Partners is facilitated by the sharing of accurate and timely information and by adapted procedures, mechanisms and tools [26].

The Airport CDM concept is divided in the following elements:

- Information Sharing: connects all the stakeholders (airport, airlines, ATCOs, ground handling) at the same data processing system, being in fact the “glue” that ties the partners together in their aim to efficiently coordinate airport activities;
- Milestone Approach: The main objective of the Milestone Approach is to improve the common situational awareness of all partners when the flight is inbound and in the turn-round flight phases. The progress of a flight is tracked in the A-CDM Platform by a continuous sequence of different events and rules for updating downstream information and the target accuracy of the estimates are defined. Different A-CDM Partners can be responsible for different milestones, with the aim of integrating all of the milestones into a common seamless process for the flight. See figure 2.6.
- Variable Taxi Time: the estimated time that an aircraft spends taxiing between its parking stand and the runway or vice versa. Variable Taxi Time is the common name for inbound (Estimated Taxi-In Time (EXIT)) and outbound (Estimated Taxi-Out Time (EXOT)) taxi times, used for calculation of TTOT or TSAT, and the more is precise, the more the calculation is reliable.
- Pre-departure Sequencing: allows Air Traffic Control (ATC) to handle the Target Off-Block Times (TOBTs) obtained from the turn-round process in a way that flights can depart from their stands in a more efficient and optimal order.
- Adverse Conditions: the Adverse Conditions Element aims to enable the management of reduced capacity in the most optimal manner possible and to facilitate a swift return to normal capacity once adverse conditions no longer prevail. In particular, if de-icing procedure is necessary, also the time required by it has to be considered, in order to create an efficient pre-departure sequence.

- Collaborative Management of Flight Updates: integrates Airport CDM into the core of the flow and capacity management process. By establishing information exchange with the Network Operations systems (that is at European level), Collaborative Management of Flight Updates is re-conciliating the network view with Airport operations, closing the loop between en route / arrival constraints and departure planning.

One of the most important key of success of A-CDM is the information sharing between airports and its related activities. In reference [22] have been explained the objective for the principal airport stakeholders of Copenhagen (Denmark) and Stockholm Arlanda (Sweden) airports, focussing on the distribution of information between them. The informations collected in the document can be useful in other airport contexts, and are summarized in the following points:

- Air Traffic Control: ATCOs' primary concern is to optimize the arrival flow while guaranteeing safety. Their mindset is "speed and distance"-oriented and not "time"-oriented as for the other parties. In general, they build up the sequence according to the FCFS principle and taking account of aircraft type (wake vortex category, speed) and other restrictions. ATC mainly has data on arrivals and only very limited information on departures. The most important parameter is Estimated Off-Block Time (EOBT) (or TOBT) for the departure sequence, and the availability of parking stands. They furnish Estimated LanDing Time (ELDT) and TSAT.

- Airport service provider: it is the link between passengers and airlines. The main objective of the airlines is to realise their flight schedule maintaining punctuality, the direct interest of the airport with regards to passengers is information. To fully satisfy these task, the airport needs reliable information especially concerning EOBT and Estimated In-Block Time (EIBT), because they trigger different events: baggage belt, door opening, parking fees (billing, statistics), gate allocation, taxi time computation.

- Airlines: as said before, the main objective of the airlines is to realise their flight schedule maintaining punctuality. A precondition for that is a full use of the capacity of the whole airport system (e.g. runways, taxiways, aprons, stand/gates, terminal, baggage system and the whole landside access). For optimized aircraft usage short turnaround times are required. In contrast to the airport authorities who like to stick to the original timetables, the airlines prefer their aicraft to arrive earlier than planned to assist turnaround time and lessen fuel consumption. They would like to obtain accurate ELDT. They furnish EOBT. Finally, airlines seem not to trust confidentially of data management systems.

- Ground handling companies: they supervise the necessary tasks of an aicraft's turnaround process, including loading/unloading, catering, cabin cleaning, fuelling, check-in and boarding. They are airlines' clients: ground handlers do not reveal confidential delay information without the airlines' prior approval. They would like to receive ELDT updates after FIR entry and taxi time estimates at peak hours and under adverse condition. They furnish Actual Off-Block Time (AOBT) and Actual In-Block Time (AIBT), and EOBT updated to TOBT.

To meet the demands of the airport stakeholders two sort of information are clearly the most important: EOBT, which is decisive for all processes related to departing aircraft, and for create suitable gaps in the arrival stream time (DMAN and AMAN integration), and EIBT that triggers most processes related to an arriving aircraft. These two parameters are also the most difficult to get and share among the stakeholders. For this reason, the A-CDM concept is fundamental for the whole airport system, in which the parties should furnish reliable data in order to achieve a global optimality.

2.2.5 *Integration between the solutions*

All the solutions and technical tools described in the previous sections, in the idea to obtain the maximum results in terms of capacity, safety, environmental sustainability and traffic flow improvements, have to be integrated.

The first integration concerns the DMAN and the SMAN: in the pre-departure and departure sequence the calculation of the TSAT and the TTOT takes into account many constraints deriving from airport topology and its utilization. The SMAN can compute optimal routes for the departing aircraft with accurate taxi times, helping DMAN in the departure sequencing, but also the best rout to arriving aeroplanes to the gate.

In this work the SMAN will compute optimal routes for each of the scheduled flight, so as to collaborate to the optimal departure sequence.

The coupled AMAN/DMAN primarily aims at increasing predictability and reducing or at least better manage delay. Apart from this a small increase in runway throughput and reduction of fuel consumption can be realised. The coordination is also between approach and tower, as they pro-actively agree on a defined sequence pattern and Arrival Free Interval (AFI)-size based on an integrated traffic picture for the respective runway. AMAN and DMAN will be coupled in this solution and provide the operators with an integrated view on the planned runway sequence. In general, the AMAN acts as master, and is in charge of calculating the arrival sequence. The time period between two successive Target LanDing Times (TLDTs) corresponds with an AFI, and the DMAN has to allocate departures within this time window. The solution described is defined as "flow-based" integration since it aims to optimize traffic flows [49].

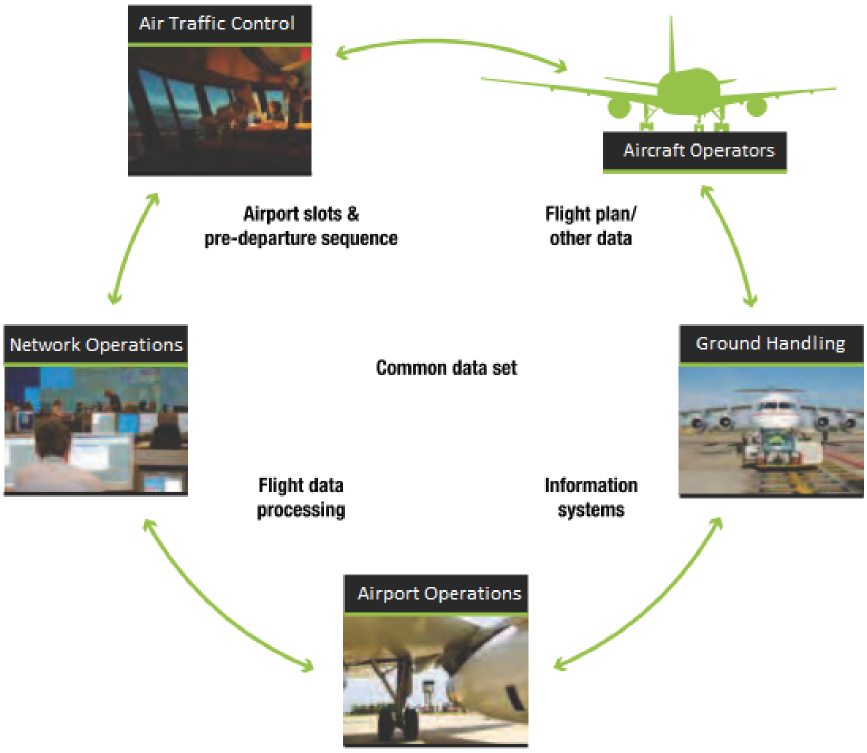


Figure 2.5: A-CDM concept [26].

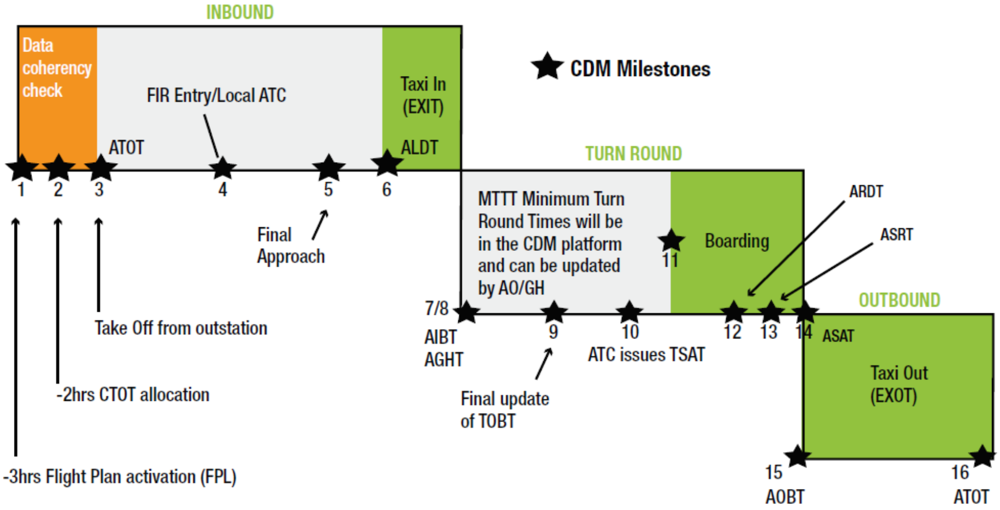


Figure 2.6: A-CDM milestones [26].

The sequence pattern agreed between approach and tower describes the sequence of arrivals and departures on the runway following a pattern that is continuously repeated for a certain time period. With 'A' for an arrival and 'D' for a departure, with the last character in the pattern just indicating the beginning of the new pattern, a pattern might look like:

- ADA results in (ADADADADADA . . .);
- ADDA results in (ADDADDADDA . . .).

There might be different implementations on how to plan the sequence pattern. The following strategies might be applied:

1. Based on the rationale that DMAN is the expert in providing TTOTs, DMAN can sequence as many departures as possible between two TLDTs (regardless of the pattern, i.e. DMAN does not care whether it received an "ADDA" pattern or an "ADA" pattern). DMAN is free to optimise departures, subject to ensuring that they do not conflict with the arrival TLDTs.
2. Based on the rationale that DMAN plans a traffic flow rather than an exact runway sequence, DMAN fills up the pattern as closely as possible.

In the present work will be followed the first method, as will be explained in the chapter relative to the implemented algorithm.

Finally, the last integration regards the A-CDM: as seen before, it is the conjunction ring between all the stakeholders acting at the airport and on the aircraft. Without, in fact, a platform in which information are collected and shared among the stakeholders and the different systems, the global vision of the ATM can not be reached. The A-CDM, connected with the departure, arrival and surface managers, can be the key for the optimization of the airport processes.

The aim of this thesis is to design an algorithm able to improve the ATM in a local context, using data coming from the A-CDM platform. For everything said before, it have been considered local constraints and specific objective of airport stakeholders, possibly meeting the objectives described in the following Operational Changes with the corresponding Operational Improvement (OI):

- DMAN synchronised with pre-departure sequencing:
  - Basic Departure Management (Pre-departure Management) (TS-0201): Pre-Departure management has the objective of delivering an optimal traffic flow to the runway considering multiple constraints (TSAT and TTOT calculation). The Tower Runway Controllers are not expected to follow the TTOT order.

  - Pre-Departure Sequencing supported by Route Planning (TS-0202): in order to achieve the optimal sequence, accurate taxi time forecasts provided by route planning are taken into account for TSAT calculation before off-block.
  - Collaborative Pre-departure Sequencing (AO-0602): Pre-departure sequences are established collaboratively with the A-CDM partners.
- DMAN integrating Surface Management Constraints:
  - Departure Management supported by Route Planning and Monitoring (TS-0203): Departure management aims at providing an optimized departure sequence (runway sequence) with optimization focusing on predictability or runway throughput. In addition to pre-departure sequencing performed by following TSAT, controllers will also follow TTOT as closely as possible (within the TTOT tolerance window).
- Automated Assistance to Controller for Surface Movement Planning and Routing:
  - Automated Assistance to Controller for Surface Movement Planning and Routing (AO-0205): the system provides the controller with the most suitable taxi route calculated by minimising the delay according to planning, ground rules, and potential conflicting situations with other mobiles.
- Approach & Departure Separations:
  - Optimised Separation Delivery for Departure (AO-0329): the ATCO is helped by an algorithm, able to consider wake separation, aircraft type, departure procedures in place (SID) and other constraints, to efficiently deliver airborne separation.
- AMAN/DMAN Integration Including Multiple Airports:
  - Flow based Integration of Arrival and Departure Management (TS-0308): integrated Arrival MANager and Departure MANager aims at increasing throughput and predictability at an airport.

3

ITALIAN CONTEXT AND LOCAL ATM IMPROVEMENT

Italy is one of the founding member of European Union and member of EUROCONTROL since 1996. Italy is actively participating to the development of the Single European Sky through its Civil Aviation Authority ENAC, and its Air Navigation Services Provider ENAV. In particular, ENAV is considered one of the "big five" European ANSPs in terms of operative performances and technological innovation.

The Italian airspace is divided in three Flight Information Regions (FIRs), in which are provided the Flight Information Service (FIS) and the ALarm Service (ALS): Milano, Roma and Brindisi. In addition to them, there are four Terminal Control Areas (TMAs), in which is provided the Air Traffic Control Service (ATCS) with the aim to prevent collisions between aicrafts and obstacles and to guarantee an expedite and ordered traffic flux: Milano, Padova, Roma and Brindisi.

Moreover, Italy is part of the BLUE-MED Functional Airpace Block (FAB), which is a part of European airspace (in particular the Mediterranean one) in which the provision of air navigation services and related functions are performance-driven and optimised [27].

In terms of air traffic volume, in 2016 the Italian organizations managed almost 1,734,800 flights. The EUROCONTROL Seven-Year Forecast of February 2017 [21] predicts an average annual increase between 0.1% and 4%, with a baseline growth of 1.9% for Italy during the planning cycle 2017-2023 (figure 3.1).

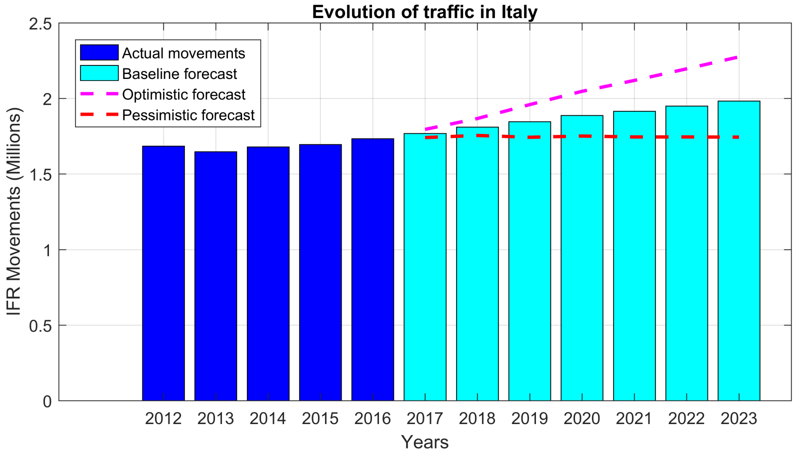


Figure 3.1: Seven-year traffic forecast for Italy updated at February 2017.

The air traffic volume can be seen at airports level in terms of aircraft movements, number of passenger managed by the airport and tons of cargo transported through the airport. The aircraft movement is defined as an aircraft take-off or landing: for airport traffic purposes one arrival and one departure is counted as two movements. Looking at the statistics related to the Italian airports, taken from [5, Assaeroporti], they can be done some considerations. The tables 3.1 to 3.4 report the traffic data of the first 13 major airports of each year from 2013 to 2016. The airports have been reordered looking at movements, passengers and cargo traffic in tables 3.5 to 3.7.

Table 3.5 shows the ranking of the airports from year 2013 to 2016 in terms of aircraft movements: it can be noticed that, in general, the airports maintained their position, with the exceptions of Napoli and Catania airports in positions 7 and 8. The major Italian airport is Roma Fiumicino, followed by Milano Malpensa and Milano Linate. In order to understand visually the relationships between the principal airports, in figure 3.2 have been showed the values of the aircraft movements for the first five airports for the last four years. Fiumicino airport has the double of movements respect to Milano Malpensa, and in general it can be seen that the number of aircraft movements in all airports slowly increases with the years, in line with the national growth.

The same considerations can be done looking at table 3.6 and figure 3.3 in which have been showed the passenger ranking and traffic. The first airport is still Roma Fiumicino from years 2013 to 2016, followed again by Milano Malpensa. The third and fourth position are exchanged between Milano Linate and Bergamo airports, as some others in the ranking.

Finally, looking at cargo traffic in table 3.7 and figure 3.4, it can be seen that the first Italian airport is Milano Malpensa, which has almost the triple cargo tons managed respect to Roma Fiumicino.

From an international point of view, Roma Fiumicino airport is positioned around the 40th place in the global ranking of aircraft movements [51] and passenger traffic [52], and 8th in European ranking in terms of passengers in 2015 [29]. Milano Malpensa was the 9th biggest European airport in terms of cargo traffic in 2015, while Roma Fiumicino was 18th [29]. Looking again at the European ranking, in 2016 Fiumicino was 10th in terms of passenger traffic, Malpensa 29th, Bergamo 50th and Linate 54th [53].

In order to satisfy the expected air traffic growth and contribute to reach the SES high-level goals, Italy is implementing many projects that involve all the levels of ATM [27]. Most of them affect the biggest Italian airports: Roma Fiumicino, Milano Malpensa, Bergamo, Milano Linate, Venezia and Napoli. In particular, for Fiumicino and Malpensa airports (which are PCP airports) are planned the development of the Time Based Separation concept and the implementation of AMAN tools and procedures (Extended AMAN). As explained in the previous chapter, however, an integrated approach to the management of the flights can be useful for the whole airport system and for reach the SES objectives. In particular, an integration between DMAN, SMAN, AMAN and the A-CDM platform can help air traffic controllers and the airport stakeholders to reach specific and global aims. In order to demonstrate this, in this thesis has been designed an algorithm applied to Milano Linate airport which, as seen before, is one of the most important airports in Italy and, thanks to its topology, well fits to such a kind of study.

3.1 MILANO LINATE AIRPORT

Milano Linate airport, dedicated to Enrico Forlanini (one of the first pioneer of Italian aviation), is situated in the municipality of Peschiera Borromeo, near the locality Linate, far only 8 km from Milano city centre, in south-east direction. It is considered Milano city airport: from 1937 it serves the citizens of Milano with its short and medium range routes, with national, European and international destinations. As seen before, Linate airport is one of the busiest airports in Italy, being on the top of Italian ranking from four years and more. Looking at the values of 2016, Linate has been the 3th Italian airport for aircraft movements (118,535), the 4th for passenger traffic (9.7 million) and the 8th for cargo traffic (15 ktons). In addition to this, the airport is situated in the richest catchment area in Italy (produces nearly 1/3 of Italy's GDP) and Europe (see figure 3.5), in which are situated 14.2 million companies (24% of the total number in Italy). Nearly 40% of Italy's import/export market is based in this region, meaning that it has a strategic position, connected to the heart of Europe [43, SEA - Company profile]. The historical data for Milano Linate airport, relative to the last ten years, are reported in figure 3.6. It can be seen that, in 2009 and 2012, the traffic has two breakdowns, due to the economic recession experienced by all States, and in particular by Italy: this trend, then, respects the national one. In 2015 the traffic in terms of aircraft movements and passenger has an increase due to the organization of the World Exposition *EXPO Milano 2015*, which brought many tourists and business people to the city. In general, cargo traffic decreases because of the decision, taken by SEA, to concentrate it in Malpensa airport. A forecast for future years could be extrapolated by this figure: looking at the trend of most recent years , it could be expected an increase at Linate airport in terms of passengers and movements. This forecast, however, could be less or more exact according to the national and international economic growth, the airlines economic status (in particular that of Alitalia company), tourism trends, geopolitical variations and many other aspects. For these reasons, further analysis are left to specific studies.

Società Esercizi Aeroportuali (SEA) is the group responsible for managing Milano Malpensa and Milano Linate airports. It is one of the ten biggest airport operators in Europe for goods and passenger traffic, while it is the second-biggest in Italy for the number of passengers handled and the biggest in the country for goods transported [43, SEA - Company profile].

Airport (ICAO code)	Movements [-]	Passengers [-]	Cargo [tons]
Bergamo (LIME)	71,742	8,964,376	116,112
Bologna (LIPE)	65,392	6,193,783	44,150
Brescia (LIPO)	7,125	10,311	39,431
Catania (LICC)	54,406	6,400,127	6,123
Roma Ciampino (LIRA)	46,365	4,749,251	16,436
Roma Fiumicino (LIRF)	298,233	36,166,345	141,911
Milano Linate (LIML)	113,321	9,034,373	19,614
Milano Malpensa (LIMC)	164,745	17,955,075	430,343
Napoli (LIRN)	55,940	5,444,422	7,515
Palermo (LICJ)	40,244	4,349,672	1,533
Pisa (LIRP)	38,961	4,479,690	2,422
Torino (LIMF)	43,655	3,160,285	9,689
Venezia (LIPZ)	80,999	8,403,790	45,662

Table 3.1: Traffic data relative to major Italian airports (2013). [5]

Airport (ICAO code)	Movements [-]	Passengers [-]	Cargo [tons]
Bergamo (LIME)	67,674	8,774,256	123,206
Bologna (LIPE)	65,058	6,580,389	41,789
Brescia (LIPO)	7,520	13,528	40,573
Catania (LICC)	59,926	7,304,012	6,206
Roma Ciampino (LIRA)	47,376	5,018,289	15,668
Roma Fiumicino (LIRF)	308,144	38,506,908	143,088
Milano Linate (LIML)	113,249	9,025,978	17,458
Milano Malpensa (LIMC)	166,749	18,853,203	469,657
Napoli (LIRN)	58,681	5,960,035	9,950
Palermo (LICJ)	41,321	4,569,550	1,507
Pisa (LIRP)	38,868	4,683,811	8,210
Torino (LIMF)	42,463	3,431,986	7,037
Venezia (LIPZ)	77,732	8,475,188	44,426

Table 3.2: Traffic data relative to major Italian airports (2014). [5]

Airport (ICAO code)	Movements [-]	Passengers [-]	Cargo [tons]
Bergamo (LIME)	76,078	10,404,625	121,045
Bologna (LIPE)	64,571	6,889,742	40,998
Brescia (LIPO)	8,239	372,963	29,903
Catania (LICC)	54,988	6,163,188	6,220
Roma Ciampino (LIRA)	53,153	5,834,201	15,756
Roma Fiumicino (LIRF)	315,217	40,463,208	145,017
Milano Linate (LIML)	118,650	9,689,635	15,714
Milano Malpensa (LIMC)	160,484	18,582,043	511,191
Napoli (LIRN)	60,261	6,163,188	10,727
Palermo (LICJ)	42,407	4,804,812	1,186
Pisa (LIRP)	39,515	3,972,105	8,697
Torino (LIMF)	44,261	4,910,791	6,047
Venezia (LIPZ)	81,946	8,751,028	50,961

Table 3.3: Traffic data relative to major Italian airports (2015). [5]

Airport (ICAO code)	Movements [-]	Passengers [-]	Cargo [tons]
Bergamo (LIME)	79,953	11,159,631	117,765
Bologna (LIPE)	69,697	7,680,992	47,708
Brescia (LIPO)	8,506	19,239	24,416
Catania (LICC)	61,080	7,914,117	6,379
Roma Ciampino (LIRA)	48,252	5,395,699	15,796
Roma Fiumicino (LIRF)	314,167	41,744,769	160,904
Milano Linate (LIML)	118,535	9,682,264	15,365
Milano Malpensa (LIMC)	166,842	19,420,690	548,767
Napoli (LIRN)	63,935	6,775,988	10,724
Palermo (LICJ)	44,122	5,325,559	407
Pisa (LIRP)	40,601	4,989,496	10,283
Torino (LIMF)	46,472	3,950,908	6,346
Venezia (LIPZ)	90,084	9,624,748	57,973

Table 3.4: Traffic data relative to major Italian airports (2016). [5]

Ranking	2013	2014	2015	2016
1	Fiumicino	Fiumicino	Fiumicino	Fiumicino
2	Malpensa	Malpensa	Malpensa	Malpensa
3	Linate	Linate	Linate	Linate
4	Venezia	Venezia	Venezia	Venezia
5	Bergamo	Bergamo	Bergamo	Bergamo
6	Bologna	Bologna	Bologna	Bologna
7	Napoli	Catania	Napoli	Napoli
8	Catania	Napoli	Catania	Catania
9	Ciampino	Ciampino	Ciampino	Ciampino
10	Torino	Torino	Torino	Torino
11	Palermo	Palermo	Palermo	Palermo
12	Pisa	Pisa	Pisa	Pisa
13	Brescia	Brescia	Brescia	Brescia

Table 3.5: Ranking of the major Italian airports in terms of aircraft movements. [5]

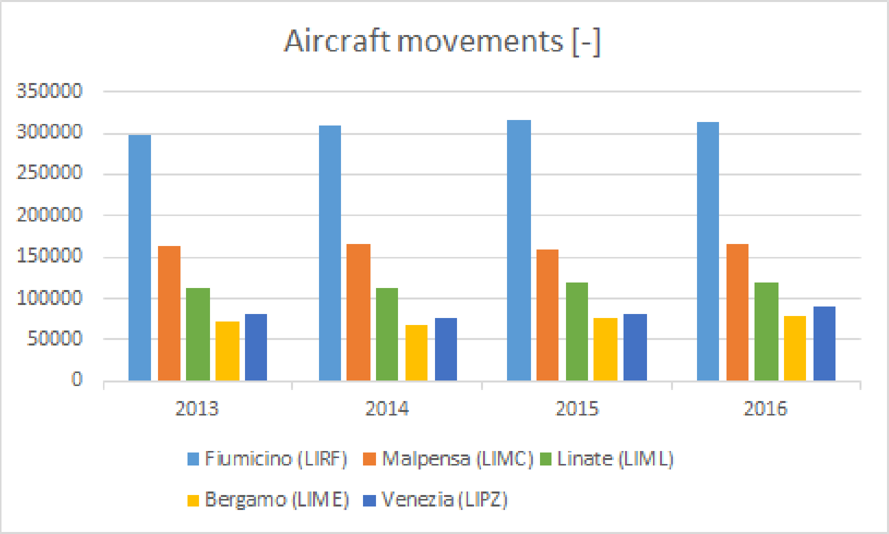


Figure 3.2: Aicraft movements of the five major italian airports.

Ranking	2013	2014	2015	2016
1	Fiumicino	Fiumicino	Fiumicino	Fiumicino
2	Malpensa	Malpensa	Malpensa	Malpensa
3	Linate	Linate	Bergamo	Bergamo
4	Bergamo	Bergamo	Linate	Linate
5	Venezia	Venezia	Venezia	Venezia
6	Catania	Catania	Bologna	Catania
7	Bologna	Bologna	Catania	Bologna
8	Napoli	Napoli	Napoli	Napoli
9	Ciampino	Ciampino	Ciampino	Ciampino
10	Pisa	Pisa	Torino	Palermo
11	Palermo	Palermo	Palermo	Pisa
12	Torino	Torino	Pisa	Torino
13	Brescia	Brescia	Brescia	Brescia

Table 3.6: Ranking of the major Italian airports in terms of passenger traffic. [5]

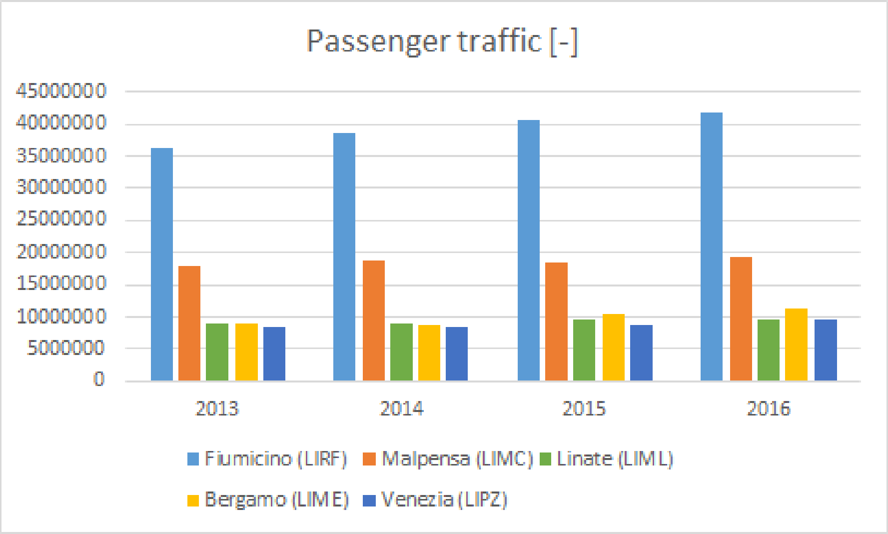


Figure 3.3: Passenger traffic of the five major italian airports.

Ranking	2013	2014	2015	2016
1	Malpensa	Malpensa	Malpensa	Malpensa
2	Fiumicino	Fiumicino	Fiumicino	Fiumicino
3	Bergamo	Bergamo	Bergamo	Bergamo
4	Venezia	Venezia	Venezia	Venezia
5	Bologna	Bologna	Bologna	Bologna
6	Brescia	Brescia	Brescia	Brescia
7	Linate	Linate	Ciampino	Ciampino
8	Ciampino	Ciampino	Linate	Linate
9	Torino	Napoli	Napoli	Napoli
10	Napoli	Pisa	Pisa	Pisa
11	Catania	Torino	Catania	Catania
12	Pisa	Catania	Torino	Torino
13	Palermo	Palermo	Palermo	Palermo

Table 3.7: Ranking of the major Italian airports in terms of cargo traffic. [5]

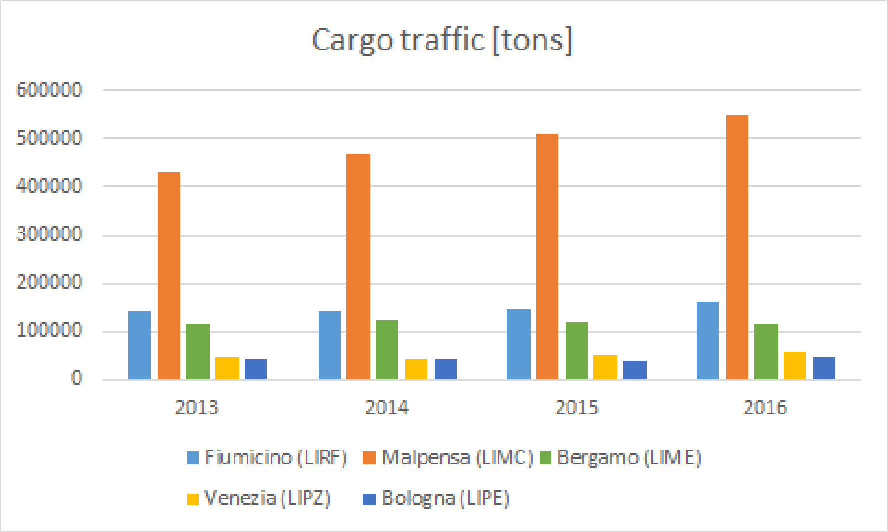


Figure 3.4: Cargo traffic of the five major italian airports.

Linate airport has one main runway, long $2,442$ meters, which is generally used for departures and arrivals (RWY 36-18), and a second parallel one that can be (but rarely is) used by general aviation (RWY 35-17). Parallel to the main runway there is a main taxiway that goes from the north apron to the holding position near the runway threshold. In general, without strong wind or particular circumstances, the aeroplanes take-off and land using the RWY 36, heading to north (see figure 3.7). In order to achieve the holding position of RWY 36, the general aviation must travel the taxiway situated at north of the runway and go through the main taxiway, which is travelled by the commercial flights too. Because of the single main taxiway, then, there can be bottlenecks that could be eliminated using an optimization algorithm for the aircraft ground sequence. In addition to this, the need to utilize one single runway in mixed mode (departures and arrivals) is challenging for an algorithm that have to schedule the flights in the optimal way. Finally, such kind of study has never been done focused on Linate airport and, if the algorithm proves to be efficient, it could be replicated also in other operative contexts.

The mean delay variation in year 2016 is showed in figure 3.8, calculated for each month at the parking position as:

- $\frac{1}{L_m}\sum_{f=1}^{L_m}|SIBT_{mf} - AIBT_{mf}|\ \forall m \in$ months, where L indicates the number of arriving flights; or
- $\frac{1}{D_m}\sum_{f=1}^{D_m}|SOBT_{mf} - AOBT_{mf}|\ \forall m \in$ months, where D indicates the number of departing flights.

It can be noticed that the departures delay is less than arrivals delay: this behaviour is due to the fact that arrivals target times are more difficult to respect than departing times, since that the departures delay at the parking position depends only by airport procedures, while arrivals delay depends also on the delay accumulated at the departure airport and en-route delay. Moreover, it can be seen that the values are comprised between 26 and 44 minutes, with three peaks in June, September and December.

Figure 3.9 reports the mean taxi time variation in year 2016, calculated for each month as:

- $\frac{1}{L_m}\sum_{f=1}^{L_m}|ALDT_{mf} - AIBT_{mf}|\ \forall m \in$ months, where L indicates the number of arriving flights; or
- $\frac{1}{D_m}\sum_{f=1}^{D_m}|ATOT_{mf} - AOBT_{mf}|\ \forall m \in$ months, where D indicates the number of departing flights.

It can be noticed that the taxi time of departure flights is the triple respect to the arrivals' because of the shorter path: this is clear looking at figure 3.7 and remembering that the usual runway is RWY 36. The mean annual value is about 10 minutes for arrivals and 32 for departing flights, with the highest value in July for departures: thinking at the more traffic through the taxiways and at the runway in that month, the higher value could be associated to holding position delays (queue delays).

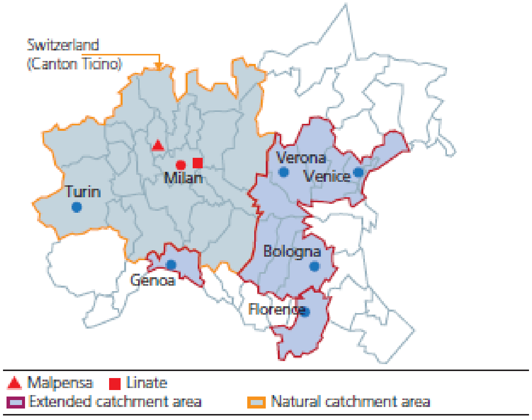


Figure 3.5: Catchment area of the Milano airport system. [`https://goo.gl/aK1gRG`]

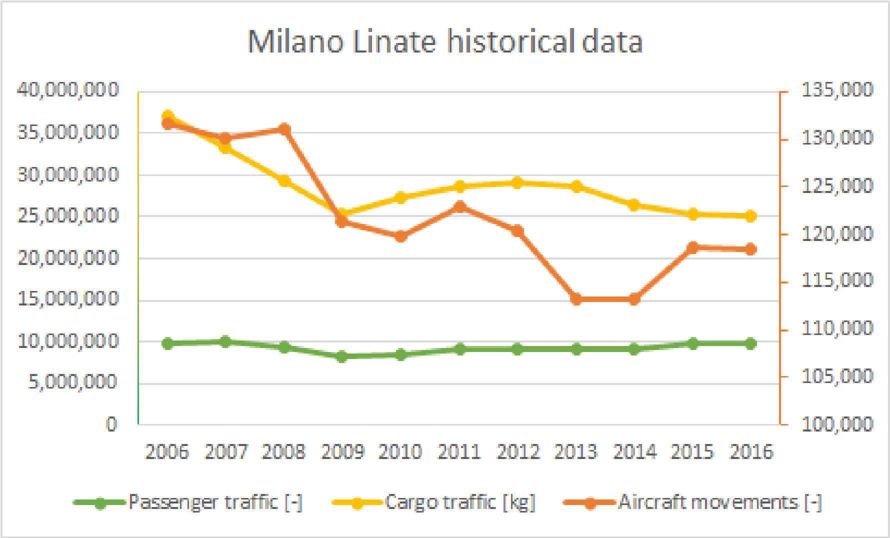


Figure 3.6: Milano Linate historical data. [5]

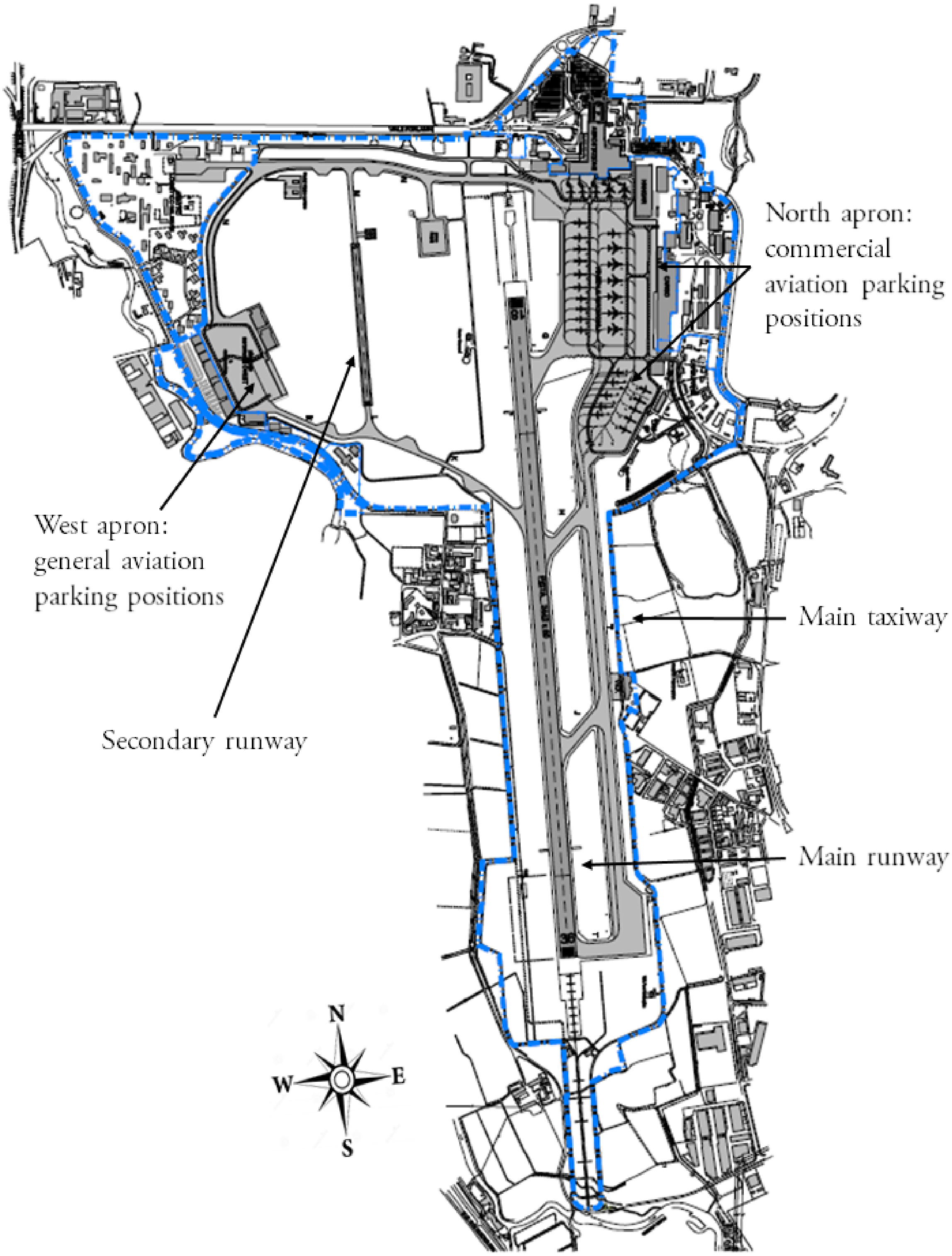


Figure 3.7: Map of Linate airport. [https://goo.gl/G8uqYN] (See ADPML2-1 in reference [13] for a detailed updated map.)

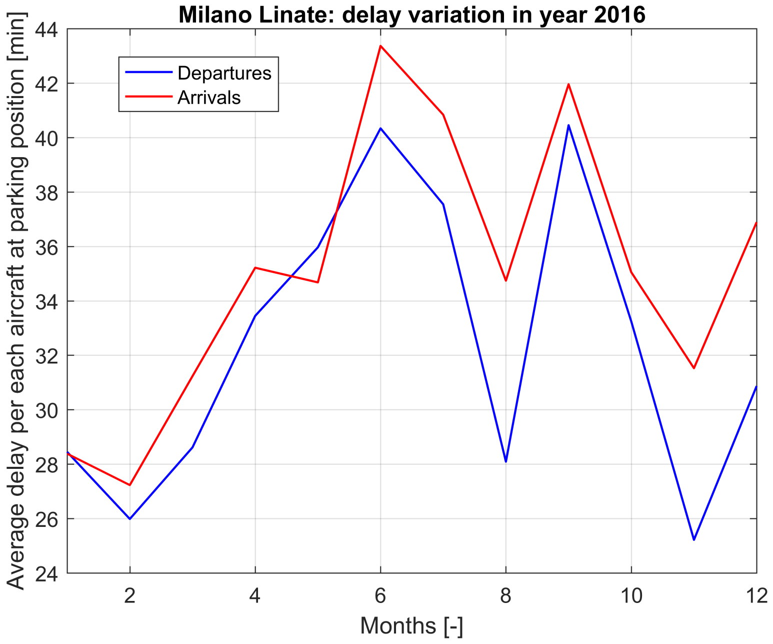


Figure 3.8: Linate airport: monthly variation of the mean delay at parking position (year 2016).

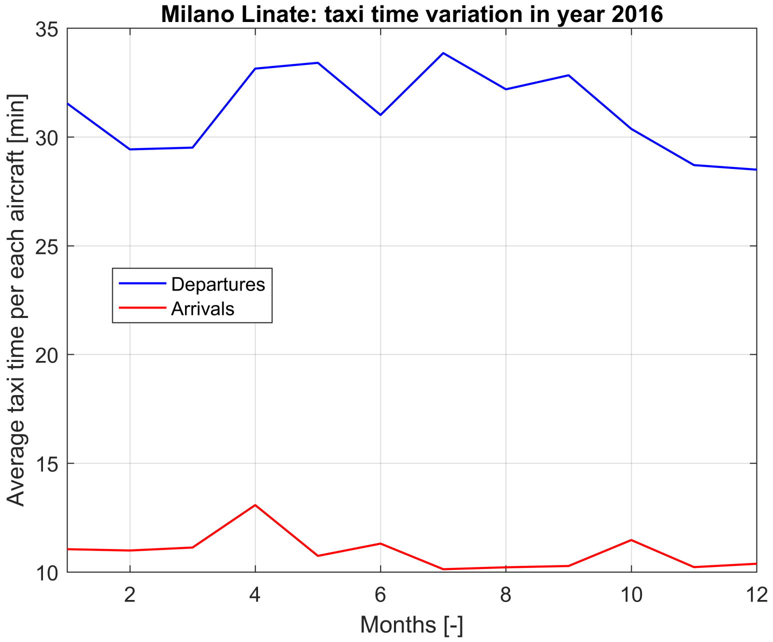


Figure 3.9: Linate airport: monthly variation of the mean taxi time (year 2016).

4

OPERATIONAL RESEARCH APPLIED TO AIR TRAFFIC MANAGEMENT

4.1 BACKGROUND

The Operational Research (OR), or Operations Research in American English, is a branch of engineering, mathematics and economics sciences which deals with the search of the best way to conduct operations. As a discipline, operational research originated in the efforts of military planners during World War II. In particular in 1940, P.H.Blackett, a professor at the University of Manchester, gathered a group of experts (called "Blackett circus" for the heterogeneity of the members) to organize the study of radar interception for protection from air attacks. Successively also the American army started to think "mathematically" to war problems, as did professor Ellis Johnson (who would later become a name very famous in the field of Operations Research) concerning bombing problems.

Operational Research does not, however, arises only in engineering: another great contribution comes from the sectors of the economy and mathematics. Between the two world wars, in fact, in the URSS many studies were conducted in linear programming applied to production management and in mathematics applied to economics. In the decades after, mathematics theories, some of them rewarded with Nobel prizes (e.g. Kantorovich and Koopmans in 1975, or John Nash in 1994) played a fundamental role in the expansion of OR to business, industry and society problems.

The motivations of Operational Research development are of two types. The first derives from the theoretical impulse that there has been in mathematical modelling sectors. The second reason is connected with the advent of computers that have helped it to grow from small size problems to average or even large size problems, so as to allow the application of its techniques to real cases.

The development methodologies are essentially two: "for problems" and "for methods". The first looks at the OR as a set of techniques useful to solve different applied problems, and it's more an economic vision. The second method looks more mathematically at the OR, deriving from general mathematical analysis conditions (for example, necessary and sufficient conditions of the first or second order) the solution algorithms. Within the engineering field it can be found a synthesis between the two methodologies. (For insights see [8, Bruglieri and Colorni])

Nowadays the OR is well consolidated and applied into all contexts characterized by high dynamicity and complexity, where the decision-making process has to face objectives, constraints and logics that are difficult to manage manually, without the use of algorithms and computers. These fields can comprise all the aspect of real world as project planning, network optimizations (telecommunications, public transport), routing (shortest or fastest path), scheduling, computational biology and others. Also the aeronautical field, obviously, uses the OR methodologies to improve its processes and help decision-makers to reach the best possible results. In this thesis the Operational Research strategies have been applied to a real case study, in order to improve the ATM and help the airport stakeholders to make the best possible decisions.

4.2 DECISION PROBLEMS

As mentioned before, the Operational Research is useful whenever a process or operation has to be improved or optimized. Following [8, Bruglieri and Colorni], a *decision problem* or *optimization problem* arises when:

- exists many (admissible) solution to the problem;
- it's possible to define at least one evaluation criteria or objective that permits to compare the solutions.

A decision process can be decomposed in five phases, as showed in figure 4.1:

1. Problem individuation: it requires a dialogue period with the customer, in order to understand if the problem is a real decision problem, which are the elements that can change and which can not, the constraints and the objective preferences. In addition, some data have to be collected to feed the model, and these can be accessible or not, certain or estimated.
2. Model definition: it represents the most delicate phase, in which the real problem is modelled mathematically. The decision aspects are represented by variables, the customer desires are modelled with objective functions and, through the use of constraints, the variables are mathematically obliged to be compatible with the real aspects of the problem.
3. Algorithm choice and definition: an algorithm is a computational process composed of finite instructions capable to elaborate the input data and provide the solution of the problem. The chosen algorithm has to be implemented in some programming language, in order to obtain a code that can be fed to a computer. There can be different types of algorithms:
    - *exact algorithm*: it is capable to compute an admissible solution (meaning that it respects the imposed constraints) and reach the best solution in order to satisfy the objective function.

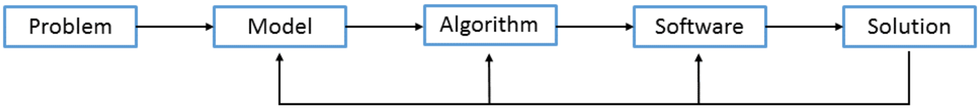


Figure 4.1: Decision process flowchart.

  - *approximated algorithm*: the algorithm can not provide an optimal solution but can guarantee that the admissible solution is "close enough" to the optimal one. In fact, even if it is not known the optimal value, it can be often derived a lower bound on the optimal value for a minimization problem (or, in the case of maximization problems, an upper bound). If it can be showed that the algorithm always produces a solution whose value is far from the lower bound of a small factor, then the algorithm solution is also within the same factor from the optimal one.
  - *heuristic algorithm*: the algorithm can not provide an optimal solution, and can not guarantee on the quality of the admissible sub-optimal solution that has found. However, in general, this approach permits to have low computational time and good solution of the problems.
  - *meta-heuristic algorithm*: the algorithm provides a sub-optimal solution without quality information, but tries to improve the admissible solution in order to reach the optimal one, often implying high computational time.

4. Use of a solution software with a graphical interface that makes the program usable even by those who did not implemented the algorithm code.

5. Analysis of the solution in terms of consistency with the reality and accuracy of the code or software. If the results are unsatisfying, an iteration within the previous steps has to be considered.

The decision process can be applied whenever a decision problem should be solved, and this was also done within this thesis work. In the following paragraphs are reported some theoretical discussions about points 2 and 3, in order to achieve a better comprehension of the general mathematical context.

MODELS The mathematical model is an abstraction that allows to describe in "mathematical" terms the relevant features of the problem that it want to study and solve. A decision problem (or optimizing problem) can be classified as:

- *simulating problem*, that is generally employed when the reality in question is very complex and the data necessary to study the problem are not known with certainty, but influenced by a large variability;

- *analytical problem*, in which the system is described by means of mathematical (or logical) relations (or constraints) between decision variables that represent its elements, while the selection criteria which must be maximized or minimized are expressed by means of mathematical functions, called objective functions.

The simplest analytical problem is called *Mathematical Program* and is obtained when there is one single decision maker, one single objective function and certain (or deterministic) data.

The modelling of a generic Mathematical Problem assumes the following aspect:

$$\min\ f(x), \quad \text{with}\ \ x \in X \tag{4.1}$$

where $f(x)$ is the objective function, x is the vector of decision variables and $X \subseteq \mathbb{R}^n$ is the admissible (or feasible) region which represents the set of solutions that satisfies the constraints of the problem. Note that a maximization problem can be written as a minimization problem since that $\max\{f(x) : x \in X\} = -\min\{-f(x) : x \in X\}$. A Mathematical Problem is called *infeasible* if $X = \emptyset$, *unbounded* if $f(x)$ has no limits. Solve the problem 4.1 means to find, if exists, an *optimal solution*, that is an admissible solution such that

$$x^* \in \mathbb{X} : f(x^*) \leqslant f(x), \forall x \in X. \tag{4.2}$$

The models of Mathematical Programming can be classified in:

- Linear Programming (LP): models with linear objective function, constraints defined by linear inequalities and continuous decision variables. A generic LP problem can be written as follows:

$$\begin{aligned} \min c^T x \\ Ax \geqslant b \\ x \geqslant 0 \end{aligned} \tag{4.3}$$

  where c and $x \in \mathbb{R}^n$ ($\mathbb{R}^n$ is the set of n-dimensional vectors of real numbers), $A \in \mathbb{R}^{mxn}, b \in \mathbb{R}^m$.

- Integer Linear Programming (ILP): models with linear objective function and constraints, but integer variables. The generic formulation is:

$$\begin{aligned} \min c^T x \\ Ax \geqslant b \\ x \in \mathbb{Z}_+^n \end{aligned} \tag{4.4}$$

  where $\mathbb{Z}_+^n$ is the set of n-dimensional vectors of integer numbers, $c \in \mathbb{R}^n, A \in \mathbb{R}^{mxn}, b \in \mathbb{R}^m$. A particular case of ILP is the Bynary Integer Programming (BIP), in which the variables can assume only the values 0 or 1.

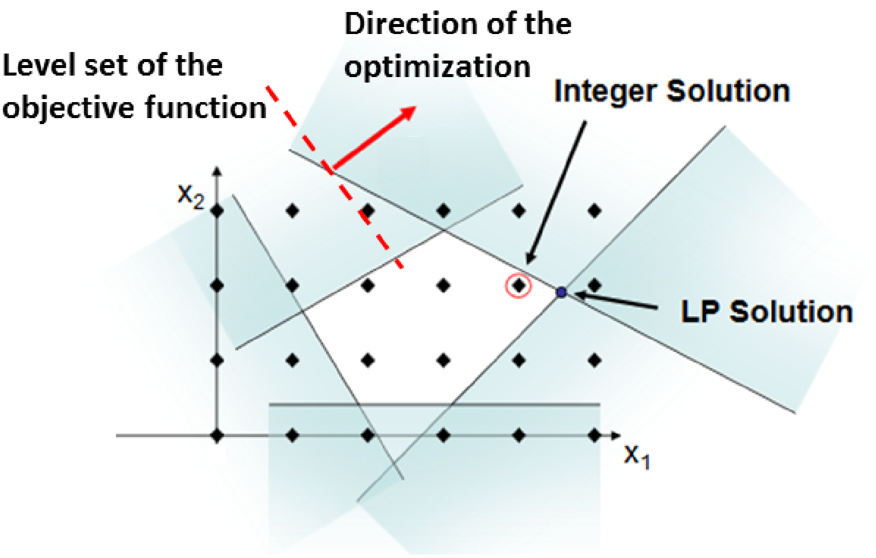


Figure 4.2: Pictorial representation of a two variable LP and ILP. [`https://goo.gl/P7Ge9H`]

- Mixed Integer Linear Programming (MILP): involves models in which only some of the variables are constrained to be integers, while other variables are allowed to be non-integers. A generic formulation is of the form:

$$\begin{aligned} \min c^T x + d^T y \\ Ax + Dy \geqslant b \\ x \in \mathbb{R}^p_+, y \in \mathbb{Z}^n_+ \end{aligned} \tag{4.5}$$

  with $A \in \mathbb{R}^{m \times n}, D \in \mathbb{R}^{m \times p}, b \in \mathbb{R}^m, c \in \mathbb{R}^n, d \in \mathbb{R}^p$.

- Non Linear Programming (NLP): models in which the objective function and/or some of the constraints is not linear in the variables.

In general the ILP, MILP and NLP are problems that are difficult to solve: if the real problem permit it, the LP formulation should be preferred respect to these ones, because the algorithm complexity can be high, as explained in the following paragraph.

ALGORITHMS COMPLEXITY AND PROBLEMS CLASSES After that a real problem has been modelled, it should be implemented in an algorithm that can provide a solution because, in general, for models describing a complex real problem it is difficult to obtain a solution manually. As seen before, an algorithm can be exact, approximated, heuristic or meta-heuristic, based on the type of solution, optimal or sub-optimal, that it returns at the end of the computational analysis. Saying that an the algorithm can not provide an optimal solution signifies that it can not provide an optimal solution

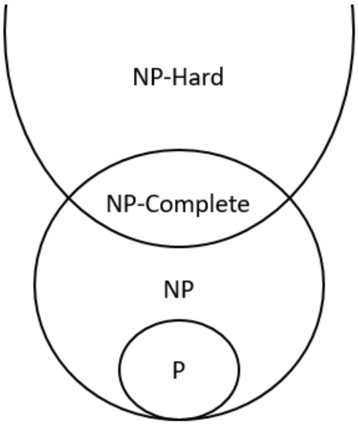


Figure 4.3: Problems divided in complexity classes. [`https://goo.gl/Pxsmqs`]

in an efficient manner. The efficiency of an algorithm is defined taking into consideration the *memory complexity*, that is the memory needed for data processing, and the *computational complexity*, based on the number of elementary operations (additions-subtractions, multiplications, divisions, comparings) needed to obtain the solution. In practice, instead of determining the exact number of necessary elementary operations, it is more useful to know their rapidity of growth as a function of the instance[1] size: it is the asymptotic complexity. If the asymptotic complexity is polynomial, then the algorithm is efficient (respect to the computational time) and the decision problem that generated the algorithm is defined *tractable*.

In computational complexity theory the problems are divided in different complexity classes, according to the efficiency of the best (known) algorithm capable to solve that specific problem (see figure 4.3). Following the informatics definition, the problems P, NP[2] and NP-Complete are *decision problems* (their solution is a YES-NO answer) while NP-Hard are *optimization problems* (the solution is a minimum or a maximum of an objective function): they are strictly connected because an optimization problem can be seen as a decision problem, and vice-versa. NP-Complete are decision problems for which are not known (and maybe never will be) solution algorithms with polynomial complexity. NP-Complete problems are connected to NP-Hard: it can be demonstrated that, if a NP-Hard can be solved efficiently with an algorithm, then that algorithm can solve also the NP-Complete, NP and P problems.

Unfortunately many real problems are, for their nature, NP-Hard (as ILP, NLP and TSP) so, if the instances of the problem are too many, the computational complexity would be too high for an exact algorithm, so approximated, heuristic or meta-heuristic algorithms have to be considered (See ref. [8] for insights).

---

[1] A problem instance represents a specific case of the problem, that is a value assignment to its input data.

[2] The abbreviation NP refers to "nondeterministic polynomial time" problems.

4.3 LITERATURE REVIEW

In chapter 2 it has been seen that, since the early 2000s, the European attention was focused on the improvement of Air Traffic Management, especially considering that an increase of the air traffic equal to 14.4 million flights is expected by 2035, that is the 80% more than 2000, and the 40 % more than today. Due to significant improvements which have already been achieved in enhancing en-route traffic capacity (for example thanks to the NMOC in Brussels which provides the Air Traffic Flow and Capacity Management), the air traffic bottleneck is shifting from en-route segments to airport capacity (and hence runways, gates and TMA). Air Traffic Control in the busy terminal area is becoming one of the main challenges confronting air traffic controllers. Since building new airports or extending existing ones causes many serious economical, political, geographical and environmental problems, there is a great interest in improving and optimizing airport capacity.

In recent years, several researchers have carried out studies in developing optimization models and algorithms to increase airport capacity, but also punctuality, safety and environmental sustainability. [40]

4.3.1 *Separated problems*

The term "separated problems" describes decision problems that are solved independently from each other.

AIRCRAFT LANDING AND TAKE-OFF PROBLEMS The Aircraft Landing Problem (ALP) and the Aircraft Take-Off Problem (ATP) tries to determine the sequence of aircraft landing, or taking-off, on the available runways at airports in order to optimize given objectives, subject to a variety of operational constraints. Following [40, Bennel et Al.], which collects the studies done in ATM field until 2009, the ALP and ATP can be formulated in different manners, like machine scheduling problem, Traveller Salesman Problem (TSP) or queueing system. Thinking about the ALP as a machine scheduling problem, it can be found that each job corresponds to a landing operation of the aircraft; each machine with capacity one represents a runway; the ready time (release time) of the job corresponds to the ELDT of the aircraft; the starting time of the job represents the Actual LanDing time (ALDT) of the aircraft; the completion time of the job corresponds to the time the aircraft frees the runway; and the sequence-dependent processing time between jobs represents the separation between aircraft.

The single-runway ALP can be represented as a time-dependent TSP where each city corresponds to an aircraft; intercity distances represent the separation between aircraft; and the time windows for visiting each city be the landing time windows. The multiple-runway case may also be modelled as multiple-TSP.

The ATP is seen more as dynamic programming problem or as a queueing problem. Between the examples reported in [40], a special mention should be done for [6, Atkin]: in his study he presented a meta-heuristic algorithm (Tabu search) for the sequencing and the scheduling problem at London Heathrow airport (United Kingdom), joined with a heuristic for the path assignment through the holding points. The results show a reduction of the CTOT slots missed and of the delay at the holding point near the runway.

In general, the ALP and ATP problem have been solved with both exact and heuristic methods, but many algorithms that are proposed in the literature take far too long to be run for the operating needs of Air Traffic Controllers, who are interested in algorithms which can quickly find (in a matter of seconds) a good solution (near-optimal) rather than an optimal solution achieved after a lengthy computation.

SURFACE ROUTING PROBLEM In the airport surface routing problem , the goal is to assign a strategic taxi route to each aircraft and to plan when aircraft should move along this route, in order to maximize the efficiency and predictability of the airport surface operations. In general, this kind of problem is affected by numerous uncertainties, like departure times, taxi speeds, circulation rules and operative procedures, and meteorological dependencies. However, some studies have been carried on this problem, as stated in reference [12, Durand et Al.], an updated review to 2016 of meta-heuristics applied to ATM. Some of them involves MILP formulations and have been applied to Amsterdam Airport Schiphol (Netherlands) and Detroit Metropolitan Airport (USA), in which binary variables describe when each aircraft will travel each portion of taxiway and the constraints ensure that each aircraft will be assigned a feasible route with conflicts resolutions.

In [1, Adacher et Al.], local heuristics were applied to have an optimal ground scheduling in order to reduce the pollution at Milano Malpensa airport (Italy). Three objective function were examined in different lexicographical order: (i) the maximization of the number of on time aircraft; (ii) the maximization of the safety; (iii) the minimization of pollution and noise. The problem was modelled as a job-shop scheduling problem based on the alternative graph formulation, that is a generalization of the disjunctive graph [38, 39]. In [2, Adacher and Flamini] the authors develop their previous work with a routing optimization, in order to minimize the total tardiness of the aircraft at Malpensa airport.

The surface routing problem has been also applied at Roma Fiumicino airport (Italy), where a methodology for supporting the decision-makers involved in both the apron design and management phases was designed [9, Confessore et Al.]. The problem was modelled as a Shortest Path Problem over a weighted undirected graph, and the computational results showed a reduction in aircraft flowtime and a relevant decrease in aircraft ground flows.

Meta-heuristics can also be applied to surface routing problem, in order to deal with some more detailed and more flexible problem formulations. Following [12], a genetic algoritm has been applied, for example, to Madrid-Barajas (Spain) and Roissy-CDG (France) airports obtaining reductions in taxi times.

OTHER PROBLEMS Following the reference [12] there can be found many applications of OR to ATM, in order to improve all the aspect of air traffic. Some of them include air route optimization, airspace design and departure slot allocation, for which have been studied geometric, evolutionary, ant colony and neural algorithms. This thesis deals only with airport optimizations, but for future works could be useful take into consideration also the above mentioned problems with the relative algorithms.

4.3.2 *Integrated problems*

Although the "separated" problems offer good solutions to ATM improvement, in general they can be applied only in few particular circumstances, for example the ALP and ATP problems can be seen separated only if the airport has two (or more) runways that operate in segregated mode, that is one runway is dedicated to departing flights and the other to arrivals. This vision, however, does not consider the relations between them, for example the need to solve the conflicts on taxiways. For this reason some decisions have to be taken not for optimizing the single result, but for the global efficiency of the airport system, looking more at the "integrated" problems instead of the "separated" ones.

RUNWAY SCHEDULING PROBLEM The runway scheduling problem consists in finding an optimal sequence for arriving and departing aircraft. Airport runways are an important source of traffic congestion because of the separations (in time and distance) that are required between each operation (take-off or landing), that come from aerodynamic effects (wake vortices due to the creation of lift by aeroplanes), operative restrictions applied by controllers for safety reasons or general procedures, other constraints coming from higher levels (for example the respect of CTOT emitted by NMOC).

Some studies have been conducted utilizing meta-heuristics algorithms [12], dynamic programming and heuristics [40].

In [7, Bianco et Al.] a no-wait job-shop scheduling model was designed in order to optimize the air traffic scheduling in the TMA of Milano Malpensa and Roma Fiumicino airports (Italy). Since that this type of problem is NP-Hard, in which the dynamics of the scenario are high, the authors applied an heuristic algorithm. In order to reduce the controllers' and pilots' workload, two Constrained Position Shifting (CPS) concepts have been considered: the Maximum Position Shifting (MPS) which is introduced to prevent an aircraft from being excessively delayed (or anticipated) respect to the FCFS sequence; and the Relative Position Shifting (RPS) that allows controllers to keep certain aircraft positions almost fixed when the aircraft are resequenced. The results showed that delay reductions and capacity increases are possible, specially looking at the runway scheduling problem from the TMA perspective.

GLOBAL AIRPORT TRAFFIC OPTIMIZATION In [12] is reported a global airport traffic optimization [11, Deau et Al.], in which have been considered the gate assignment or reassignment problem (that is part of SMAN system), the runway scheduling problem (for the AMAN and DMAN systems) and the conflict resolution problem (SMAN). The algorithm computes in different steps, for each traffic situation at each time, the following data:

- TLDT and TTOT with a Branch and bound algorithm;
- gate assignment with a Branch and bound algorithm;
- surface routing with a Branch and bound algorithm;
- TSAT deduced from TTOT and taxi time;
- conflict resolution under uncertainties on start up times and on taxi speeds, with a sequential method or Hybrid Genetic Algorithm;
- Holding positions and times.

The proposed global optimization scheme has been tested in fast time simulations on a sample of actual traffic at Roissy-CDG (France) and Roma Fiumicino (Italy) airports. The results showed a decrease in the mean delay in both the airports respect to FCFS procedures, with an increasing in the traffic predictability (in terms of deviations to the target take-off times).

Another study is that reported in [37, Lee and Balakrishnan], in which the authors compare an integrated approach to a three-step approach for the integrated problem DMAN-SMAN-AMAN, applied at Detroit airport (USA). The first is based on a single MILP model, in which the variables are the passage time of the i-th flight at each node, and the objective is to minimize the total taxi-out/in time and runway delays for departures. The main strength of this single MILP model is that it simultaneously implements runway scheduling and taxiway scheduling giving optimal results, but the computational time resulted higher than the second approach. This latter, in fact, is a sequential method that sequentially combines runway scheduling and taxiway scheduling algorithms:

- Step 1: Estimate the earliest runway arrival times for departures, based on the distance from gate to runway along the taxi route;
- Step 2: Optimize departure schedules using a CPS algorithm and initial take-off times from Step 1;

- Step 3: Optimize taxiway schedules using a MILP model and take-off times from Steps 1 & 2.

Both approaches showed significant improvements on surface traffic operations without affecting runway delays and throughput but, during peak times, the integrated approach provided the better optimal schedule at the cost of computational performance.

A third study that has to be mentioned is [36, Kyenstad et Al.] (and their previous work [35]), in which the authors present a mathematical model for the integrated AMAN-SMAN-DMAN problem. An optimization algorithm based on a heuristic decomposition of the integrated problem is presented. In this work is presented the *legal line graph*, which is a sub-graph of the airport graph, associated to every flight, with the property that every path contained into itself corresponds to a legal (or feasible) route for that specific flight. The algorithm, then, acts as following:

- Step 1: solve the ground routing problem, calculating for each flight the *shortest legal route* in its legal line graph, from its parking stand to the runway, and vice-versa;
- Step 2: compute a solution for the runway scheduling ILP problem, minimizing the delay of the aircraft, that is the time difference from the expected take-off and landing times, and the cost associated to dropped flights, that are those flights that are not able to take-off within their time window;
- Step 3: solve the ground scheduling LP problem, computing a complete conflict-free schedule for all the departing and arriving flights.

In this way, the algorithm is capable to compute the TTOT, TSAT and TLDT, which are useful to controllers and the other airport stakeholders to manage the airport traffic. The algorithm has been applied in a real time simulations at Hamburg (Germany) and Stockholm Arlanda (Sweden) airports, showing reductions in the mean delay and taxi times.

5

ALGORITHM DESIGN

5.1 PROBLEM DEFINITION AND SOLUTION APPROACH

As said in the previous chapters, in the perspective of a global optimization of the airport system, an algorithm should look at the ATM improvement problem integrating all the objectives and constraints deriving from the airport stakeholders. In order to understand them, some dialogues have been done with Linate airport stakeholders, in particular with SEA and ENAV personnel. Giving their personal judgements on the problem, it has been possible to comprise the specific needs of the airport. Thanks to the dialogues had with the ENAV ATCO, it resulted how complex is the design of an optimization algorithm looking from the ATC perspective. For the optimal aircraft sequence they must be considered many constraints such as, for example, the runway in use, the wake vortex separations, the minimal distances from an aircraft to the other or the departing/arriving windows. From the speeches had with SEA personnel, it emerged how the reliability of information included in the A-CDM is fundamental for the optimization process. An algorithm, in fact, is useful only if information on which it bases its computational analysis are reliable and correct, otherwise the output could even compromise the smoothness of the process. For example, this could be the case of the de-icing procedures, in which the time of the single de-icing process varies from day to day, aircraft to aircraft and airline to airline [1]. However, some optimization logics are already implemented at the airport thanks to the Airport Collaborative Decision Making (A-CDM) platform. For example, the Target Start Up Approval Time (TSAT) is computed taking into consideration the Target Off-Block Time (TOBT), the traffic demand, the availability of infrastructures, the weather conditions and the taxi time. The latter is computed and tabulated for different parking zones, in order to consider the zones with similar taxi times or EXOT (see table 5.3). Known the TSAT, the Target Take-Off Time (TTOT) is computed by the platform as the sum of TSAT and EXOT [42, Leaflet 7-8]. Although this way to proceed works quite well for the airports managed by SEA (Linate and Malpensa), it does not consider the globality of the procedure, as for example the integration with arriving aircraft or the ground routing and scheduling.

The algorithm designed within this thesis, instead, looks at the DMAN-SMAN-AMAN problem in an integrated way, computing first the TTOT and Target LanDing Time (TLDT) at the runway and, then, calculating the times through the airport

---

[1] In order to improve the accuracy related to the de-icing process a SESAR Solution is the "De-icing management tool", not implemented at the airport neither in this thesis. See [44] for insights.

taxiways, giving the optimal TSAT and Target In-Block Time (TIBT) to the airport stakeholders. Note that this way to proceed is in line with the SESAR Solutions, but it is the opposite to what actually is done at the airport.

In practice, looking at the aircraft management process, the algorithm is positioned between the handler's and the ATCO's procedures.

From the literature review has emerged that the integrated problem DMAN-SMAN-AMAN should be decomposed heuristically in some steps, meaning that the final solution is sub-optimal respect to that obtained solving the integrated problem. This way to proceed, however, is necessary in order to have low computational time and permit to the algorithm to follow dynamically the traffic variations. In reference [11, Deau et Al.] the problem was decomposed and solved with Branch and Bound algorithms and sequential or Hybrid Genetic Algorithm, considering also gate assignment problem. In [37, Lee and Balakrishnan] the authors solved the problem with a MILP formulation and with a three step decomposition. In [36, Kyenstad et Al.] the integrated problem is decomposed in three steps, and modelled with MILP. All the formulations show that ATM improvement is possible, so the choose from one to another has been dictated by the availability of information of the mathematical problems.

In this thesis, therefore, has been followed the work shown by Kyenstad et Al. in [36], decomposing the DMAN-SMAN-AMAN problem in three steps (ground routing problem, runway scheduling problem and ground scheduling problem) and making some changes to the model, in order to improve it and fit it to the context of Linate airport.

5.2 A-CDM DATA DESCRIPTION

In order to adhere as closely as possible to the real context of the airport of Linate, it has been decided to feed the algorithm with the data extrapolated from the A-CDM platform relative to two available case study days.

The first day considered is a standard day of November 2016, that was a day without ice or snow conditions or particular congestion problem. In table 5.1 the values of departures and arrivals managed by Linate stakeholders on 8th November 2016 can be observed: the total flights were 314, almost equally divided in departures and arrivals. 34 flights among them were private, in particular business aviation. In figure 5.1 the airlines operating at Linate on the same day have been showed: it can be noted that the major airline is Alitalia with 56% of total flights, followed by the principal European airlines that, however, do not exceed 5% of the total flights if taken individually. 10% of the total is composed by airlines that, individually, do not exceed 2%; the remaining 11% is composed of private flights (business and general aviation). In figure 5.2 the partition of the models of the aircraft operating at Linate is represented: it can be seen that the Airbus aeroplanes are the most present at the airport, followed by Embraer family aircraft. This happens because A319, A320 and A321 are Alitalia's medium haul aircraft, while E190 and E175 are its regional aeroplanes [4], and in general Airbus aircraft are the most common among European airlines.

The second day considered is the 15th February 2017. This was a day quite standard: the air traffic was in the usual amount, but in the morning 9 departures (equal to 5.4% of total departures) did a de-icing procedure. As said above, the data relative to de-icing procedure are not reliable for an optimization algorithm, so these flights have not been analysed. However, the total flights were 328, almost equally divided in departures and arrivals. 37 flights among them were private, in particular business aviation (see table 5.2). The comparison between the days of November and February is showed in figure 5.3: it can be noted that the airlines operating at Linate on the two days are almost equal in percentage, meaning that the flights slots are almost the same in different days (with the exclusion of particular periods like summer). The comparison among the aircraft manufacturers is reported in figure 5.4: for the same reasons explained for the day of November, also in February the Airbus company is the most present at Linate. In figure 5.5 is reported the comparison between the aircraft models: as said before, those owned by Alitalia and the other European companies are the most present at Linate, but it is interesting to note which aircraft are predominant, that are A319, A320 and E170. These data and the airlines companies data will be useful in order to compute the savings in terms of money and CO_2 obtained by the algorithm (see chapter 6).

Among all data that are present in the A-CDM platform, only some of them are useful for the algorithm implementation. For departing flights the parking position, the times EOBT, TOBT, EXOT, and CTOT are important for the computation of the optimal values TTOT and TSAT. In addition to them, also SOBT and actual values deriving from the FCFS concept have been extrapolated, because are useful for the final comparison and for the computation of "actual" values for the optimal ones, and to the algorithm to have an indication of the departed flights. Moreover, an indication if an aircraft has done the de-icing procedure is also useful, in order to exclude (for this version of the algorithm) that flight.

For the computation of TLDT and TIBT of arriving flights are useful the parking position, the times ELDT and EXIT, SIBT and the actual times AIBT and ALDT, in order to understand if a flight is landed or not. Note that the values TIBT and TLDT are not computed by the A-CDM platform so they are impossible to extrapolate and compare directly with the corresponding optimal values.

The explanation about how these values have been used within the algorithm is given in the following sections, while the comparison with what actually was done is described in chapter 6.

Flight type	Number of flights	Type/ Total flights (%)	Commercial flights	Private flights	Private/ Flight type (%)
Departures	156	0.496 (49.6%)	141	15	0.096 (9.6%)
Arrivals	158	0.504 (50.4%)	139	19	0.12 (12%)
All flights	314	1 (100%)	280	34	0.11 (11%)

Table 5.1: Linate airport: flights statistics relative to 8th November 2016.

Flight type	Number of flights	Type/ Total flights (%)	Commercial flights	Private flights	Private/ Flight type (%)
Departures	165	0.503 (50.3%)	146	19	0.115 (11.5%)
Arrivals	163	0.497 (49.7%)	145	18	0.110 (11.0%)
All flights	328	1 (100%)	291	37	0.113 (11.3%)

Table 5.2: Linate airport: flights statistics relative to 15th February 2017.

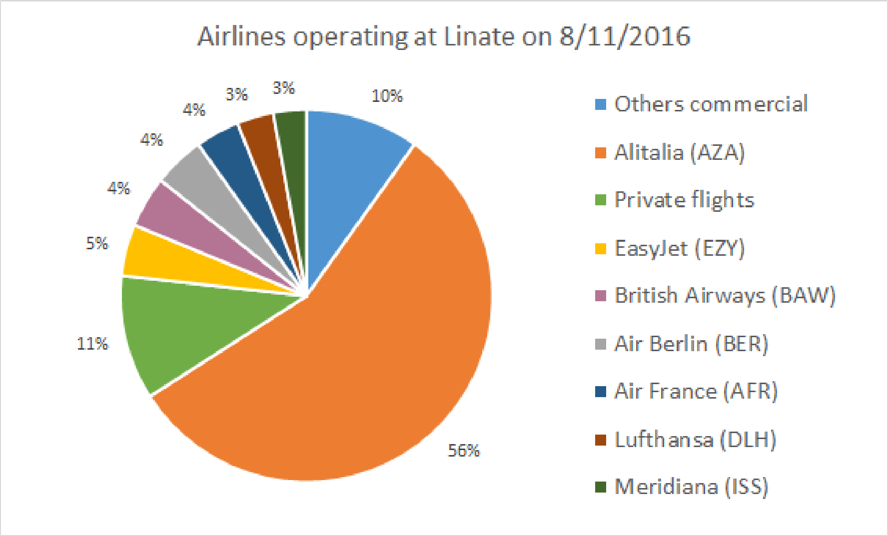


Figure 5.1: Airlines operating at Linate on 8/11/2016.

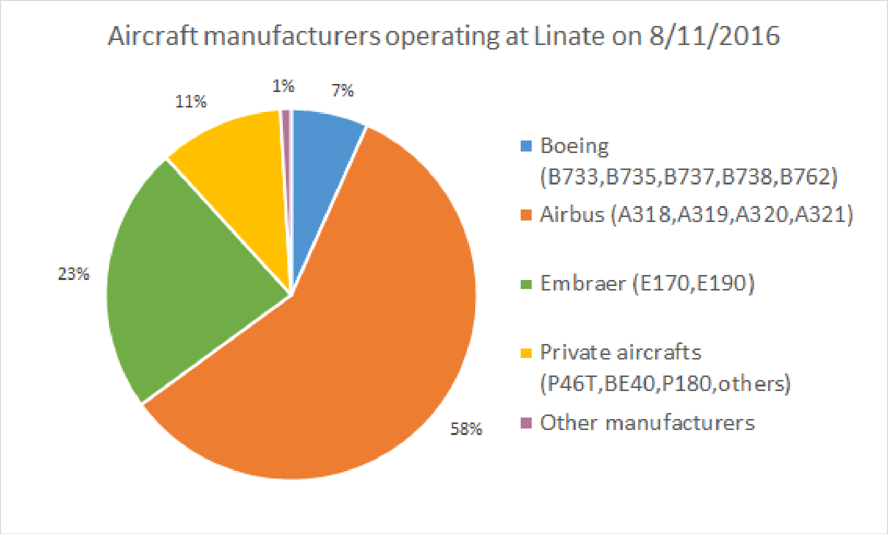


Figure 5.2: Models of aircraft operating at Linate on 8/11/2016.

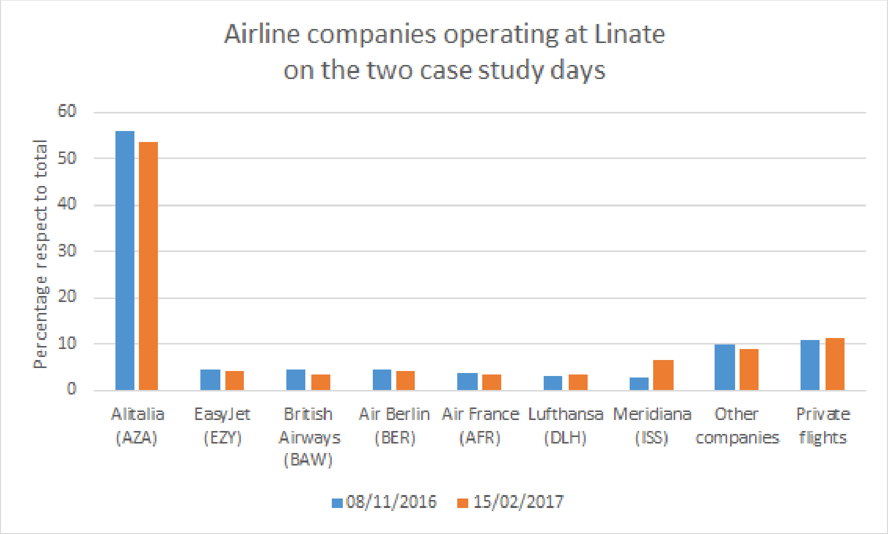


Figure 5.3: Comparison of the airlines operating at Linate on the two case study days.

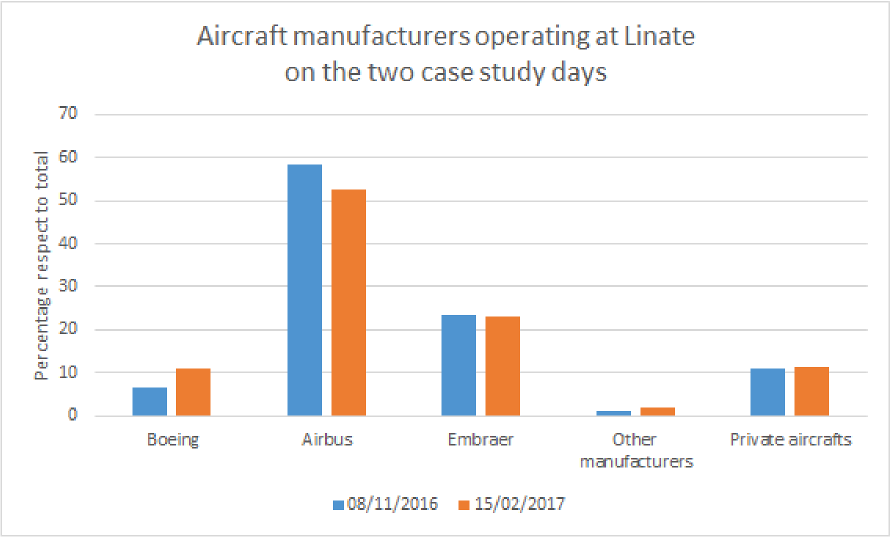


Figure 5.4: Comparison of the aircraft manufacturers operating at Linate on the two case study days.

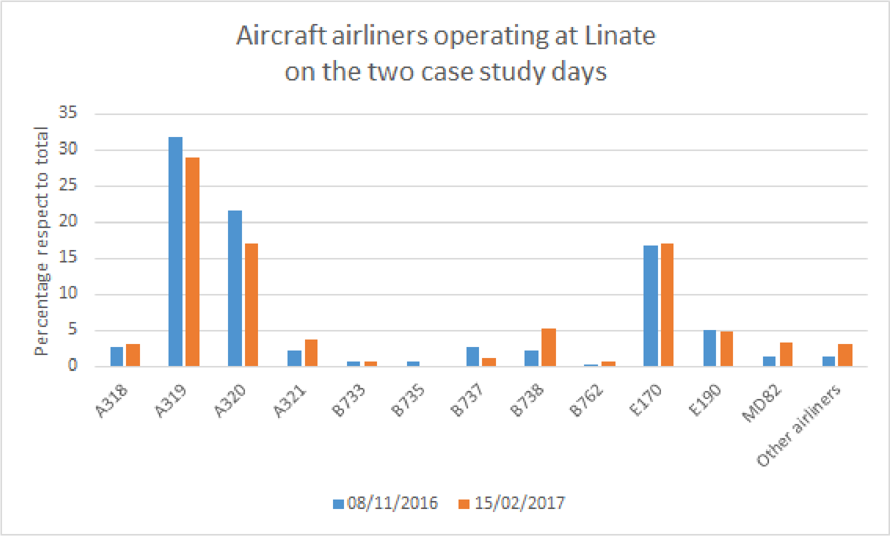


Figure 5.5: Comparison of the aircraft models operating at Linate on the two case study days.

5.3 GROUND ROUTING PROBLEM

The *ground routing problem* is the first step considered by the algorithm (SMAN). The aim of this step is to compute a feasible route for each aeroplane: not all paths in the airport, in fact, are feasible for every flight. In particular, some segments may be available only for a subset of flights, turning restrictions may exist and local procedures can impose some constraints to an aircraft instead of another. The objective in Step 1, then, is to find the shortest path that an aircraft can run from its parking position to the runway, and vice-versa. The computing of the shortest path has been done with a maximum flow model applied at each flight and imposing feasibility contraints, meaning that it has not been implemented the procedure of Kjenstad et Al.'s for the calculation of a "legal line graph". The maximum flow model concern to send as much flow as possible through a network but, if the network has just one unit (or some units) of supply and one unit (or some units) of demand, the optimal solution assumes a quite different nature. The variable associated with each arc of the graph is either 0 or 1, and the arcs whose variables have value equal to 1 comprise a minimum-cost path from the supply node to the demand node. Often the "costs" are in fact times or distances, so that the optimum gives a shortest path for each unit to send, in this case each flight [31, Ch. 15].

Simulating the passage of time through the day there will be more or less aircraft that have to be routed by the algorithm. Thinking at the real problem, if too much aircraft are routed on the same path it may happen a traffic congestion on the taxiway, while another alternative path would be unused. In fact, although in step 3 the algorithm schedules the flights in order to have the smoothest flow, a traffic congestion could happen in the real world if the preceding aircraft run the taxiway slower than the succeeding flight. So, in addition to Kjenstad et Al.'s model, a cost to the arcs of the graph has been added, variable with the usage of the arc itself, in order to permit the algorithm to utilize every resource of the airport. This new objective can also be useful in the case that the cost to reach two resources would be almost the same. Let's think about Malpensa airport in which there are two parallel runways (see appendix A), or the parking stands of de-icing procedures that, in general, are located in the same zone of the airport: one of them could have a very little cost time lesser than the other, so the algorithm would assign always it in the shortest path of the aircraft, halving, in fact, the airport capacity. The downside of this approach is that the model become non linear (NLP) in the variable describing the usage of the arcs of the graph, so the problem is NP-Hard in which the computational complexity is not polynomial and rapidly grows with the number of the instances of the problem (complexity of the graph and/or number of the aircraft to route). However, it has been verified that the computational time remains almost the same with or without the consideration of the cost variable with the arc usage, so it has been implemented.

Let $F = L \cup D$ be the set of flights to be controlled in the time horizon H, with L the set of arrival (landing) flights and D the set of departure flights, hereafter denoted as *arrivals* and *departures*. For each flight $f \in F$ and each arc $a \in A$ is defined a binary variable u_f^a which is 1 if the arc belongs to the shortest path of flight f, otherwise is 0.

With l_f^a is intended the running time for f through a. In order to assign a taxi time for each arc of the graph, they have been taken the EXOT and EXIT to each parking zone from the A-CDM, that are the times an aircraft spend, in average, to go from the parking situated in a particular parking zone of the airport to the runway and vice-versa. Then the EXOT and EXIT have been distributed on the arcs[2], in order to respect the running time for each departure/arrival zone and get l_f^a. Note that EXOT and EXIT values comprise the delay times at the holding points and at the parking positions: EXIT = AIBT - ALDT and EXOT = ATOT - AOBT. With the mean values the delays are uniform along the year (and so the day), but for a better formulation of the problem should be taken the actual taxi times of each taxiway segment, that are the running times without delays (EXOP and EXIP) updated with the effective delay, not present at the moment of writing in the A-CDM platform.

The objective function can be written as follows:

$$\min \sum_{f \in F} \sum_{a \in A} u_f^a \cdot \left(l_f^a + \frac{0.1}{\mathrm{card}(F)} \sum_{f \in F} u_f^a \right) \tag{5.1}$$

It can be noted that the second term within the parenthesis increases the time cost l_f^a of arc a proportionally to the usage of that arc by all considered flights, pre-multiplied by the term $\frac{0.1}{\mathrm{card}(F)}$ in order to give a lower weight to the resources utilization respect to the choose of the shortest path.

The constraints that have been considered regard the entry point (parking position for departures and runway for arrivals) and exit point (runway for departures and parking position for arrivals), the balance from an arc to another, the fact that cycles are prohibited, and the impossibility to run a specific road if the road is infeasible for an aircraft (for example a commercial aircraft can't pass through the private aircraft apron). Arrival and departure gates are assumed assigned (by the airport stakeholder in the A-CDM) and cannot be changed.

DATA USED FOR LINATE AIRPORT For the Linate ground problem it has been considered only the usage of RWY 36. The taxi times used in the A-CDM have been reported in table 5.3. They are variable with the parking zones, which have been defined considering the position and typology of parking stands (push-back or self manoeuvring), and runway used (figures 5.6 and 5.7). Namely these are Variable Taxi Times

---

[2] Note that the computation of the running times associated to each arc has been done, in the case of Linate, manually because of its quite simple topology and because have been used tabulated data. For more complex airports or the consideration of actual taxi times it should be implemented a computational routine.

(VTTs) and, in the experience of SEA personnel, they do not vary so much during the year. With these values it can be computed approximately the taxi speed that the pilots set to run the taxiways: for each parking zone it has been taken the distance to the runway, and the EXOT (from this latter has to be subtracted the push-back time, if needed, hypothesized to be of 1 minute). Then it has been computed the ratio between space and time in order to have the speed relative to each parking zone. Finally a mean value of these out-bound times is computed, equal to 18 $\mathrm{km\,h^{-1}}$. The same can be done for in-bound aircraft, which speed is about 20 $\mathrm{km\,h^{-1}}$. Clearly these values are not precise, first of all because the times consider also the waiting times at holding points (where the speed is null), then because the speed varies with the airlines and the type of aircraft, and finally because the accelerations/decelerations experienced by the aircraft are not considered. For these reasons, in the algorithm have been considered the mean times EXOT and EXIT instead of speed, logically imposing (and hypothesizing) that the pilots must set a constant run speed equal to the mean values described before. In this way, in Step 3 the algorithm is capable to compute a schedule for which the aircraft are equally spaced, trying to make the traffic flow as much as possible smooth, i.e. without stopping the aeroplanes at the holding points. In any case, in future versions of the algorithm the EXOT and EXIT times should be substituted with actual taxi times, and the speed should be varied accordingly with airlines procedures or imposing a more realistic value of it.

The airport topology is represented in figure 5.8 with a directed line graph. The green colour is assigned to parking positions, while the double arrow arcs symbolize the parking stands with push-back. The runway is depicted with blue colour, while the red nodes represent the holding points: as in the real airport they are useful to the algorithm to let the aircraft to wait and avoid conflicts, so are useful in Step 3 to obtain an optimal (feasible) solution of the ground schedule. The nodes indicated as Q_i represent the release points in which the aircraft that perform push-back procedures can start up in order to avoid unsafe jet blasts.

Parking zones	EXIT [min]	EXOT [min]	Parking positions
N1	4	13	1,2,3,4,5
N2	4	8	From 6 to 22, 120,121
N3	2	8	61,63,66,69
N4	2	10	62,64,65,67,68,70,71,72,73
W1	7	15	51,52,53,54,55,56
W2	4	15	GA1, GA2, H
W3	4	12	GA3, H

Table 5.3: Linate: definition of parking zones, parking positions and taxi times (RWY 36).

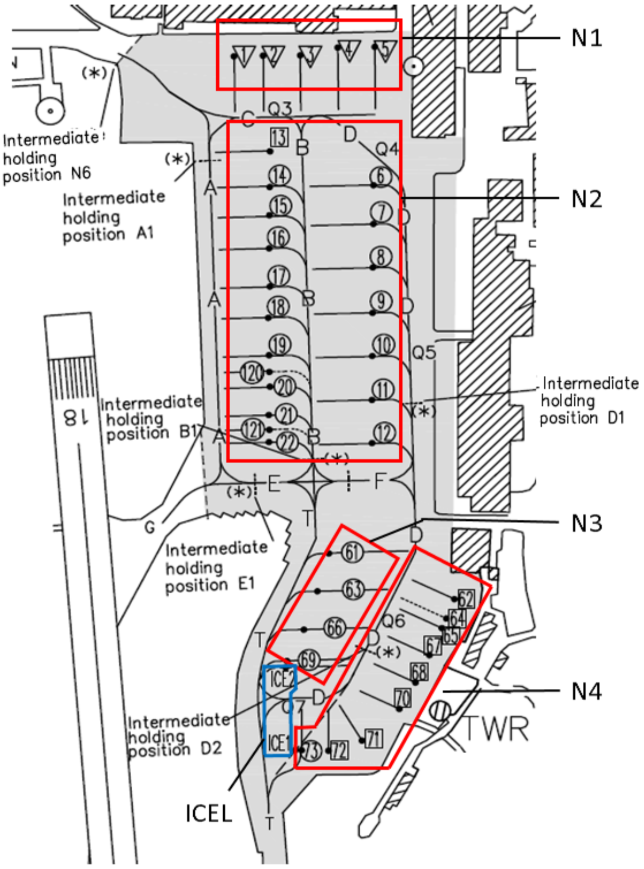


Figure 5.6: Linate: parking positions and parking zones of north apron. [13, ADPML2-1]

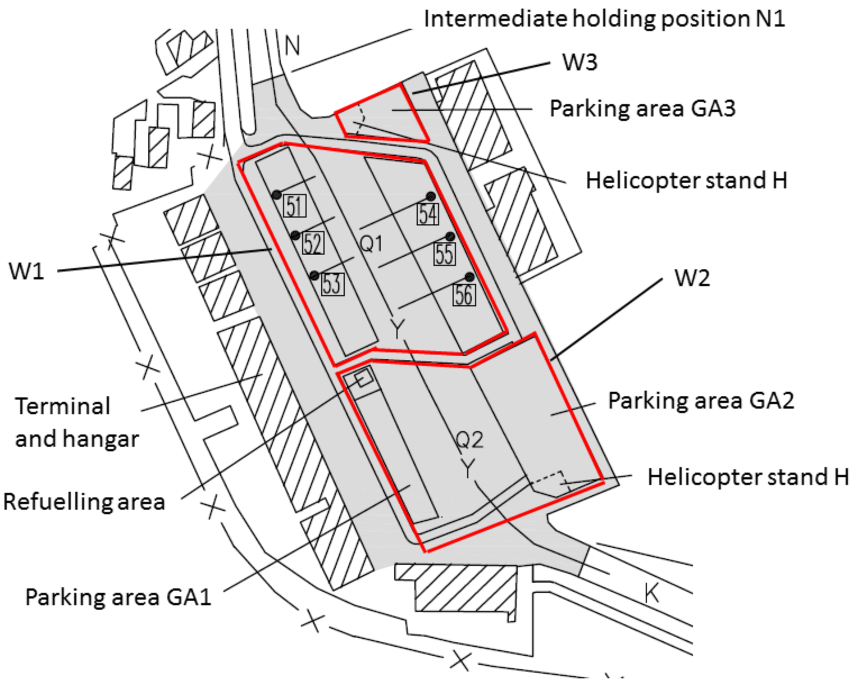


Figure 5.7: Linate: parking positions and parking zones of west apron. [13, ADPML2-1]

5.4 RUNWAY SCHEDULING PROBLEM

The *runway scheduling problem* is the Step 2 of the integrated problem decomposition, whose goal is to find an optimal scheduling for arrivals and departures at the runway (DMAN+AMAN). For departures and arrivals are defined the expected times at which the flights will become airborne or landed: ETOT = EOBT + EXOT for departures and ELDT for arrivals. The EOBT, in general, is given by airlines while ELDT is provided by ATC. In addition to the ETOT, for European ATM purposes, a CTOT could be assigned to a departing flight in order to obtain an optimal flow in the European skies or at the destination airport, and has to be respected as much as possible. Hereafter will be indicated with δ_d the time at which a departure d is expected to take-off, that is or ETOT or CTOT, and with λ_l the ELDT associated to arrival l. For each estimated or calculated time is associated a tolerance window in which the aircraft should take-off or land:

- Departure Tolerance Window (DTW), by default 15 minutes before and 15 minutes after ETOT;
- Slot Tolerance Window (STW), by default 5 minutes before and 10 minutes after CTOT;

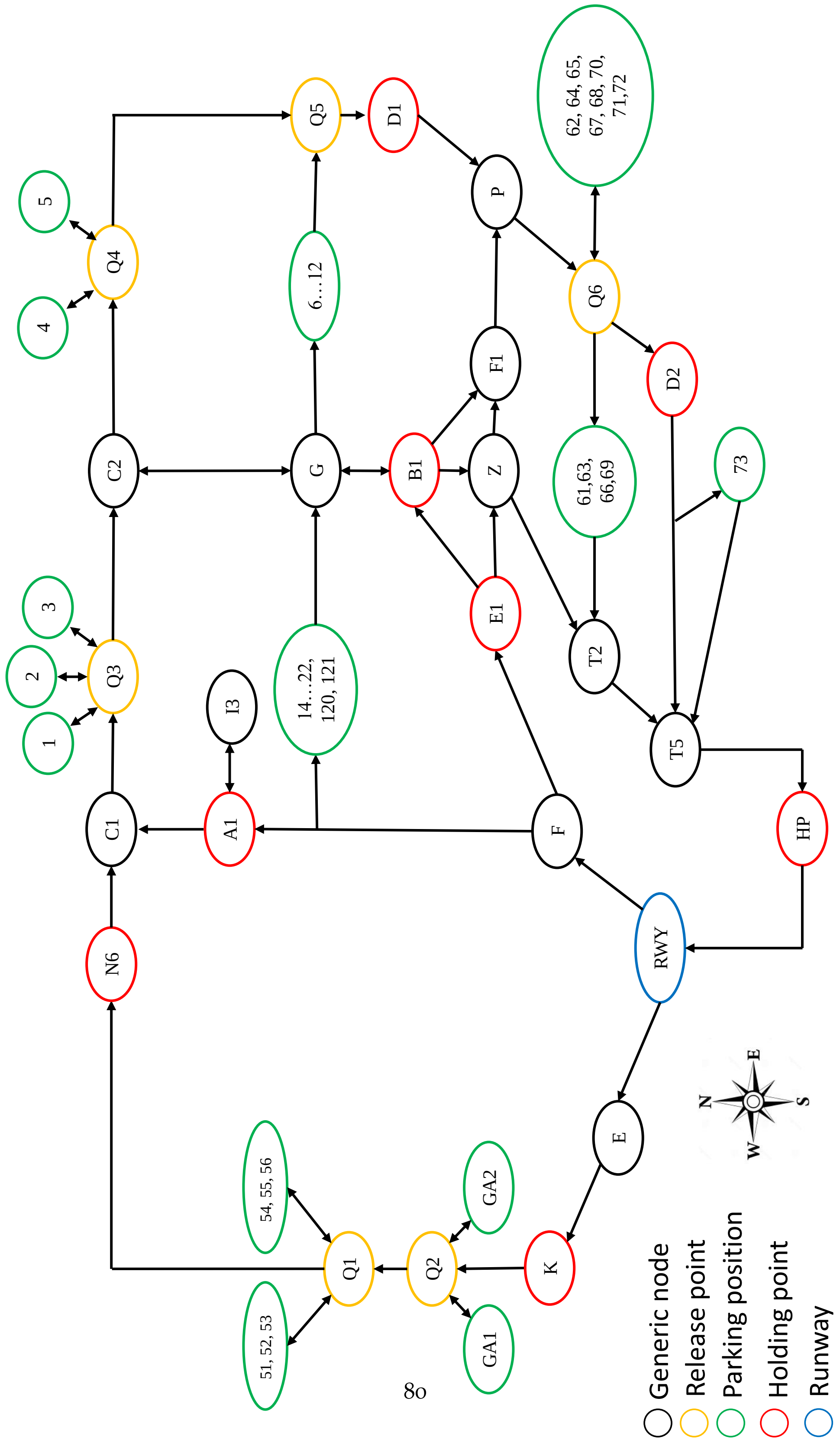


Figure 5.8: Graph of Linate airport.

- Arrival Tolerance Window (ATW), fixed at 15 minutes before and 5 minutes after ELDT.

Let α_d and α_l be the lowest times associated with the tolerance window of a departing flight (H_d, which can be the DTW or the STW) or of an arriving flight (H_l, equal to ATW), and β_d and β_l the highest values. So $H_d = \{\alpha_d \dots \beta_d\}$ and $\delta_d \in H_d$, $H_l = \{\alpha_l \dots \beta_l\}$ and $\lambda_l \in H_l$. Finally, the time horizon H is the time window between the lowest α and the highest β among all the flights that the algorithm has to schedule, for which $H_d \subseteq H$ and $H_l \subseteq H$. H is discretized with a step of 1 minute for computational time needs (see figure 5.9). τ_{fg} denotes the separation time between flight f and flight g at landing or take-off, depending whether f is arrival or departure and g is arrival or departure, when f precedes g. For any flight $f \in F$, let TX_f be the minimum time necessary to f to run the assigned route $r_f \in R$ computed at step 1.

For each departure (arrival) $f \in F$ and each time period $t \in H_f$ a binary variable x_{ft} is introduced which is 1 if and only if f takes off (lands) at time t. Taking-off or landing at time t has a cost c_{ft}. For departure d (arrival l) such cost increases with $|t - \delta_d|$ ($|t - \lambda_l|$). Looking at the real problem, because of the traffic separations imposed at the runway, a departure could not take-off within its tolerance window meaning that its departure time has to be postponed: the flight is said to be *dropped*. If a CTOT is assigned to a departing flight, this time should be respected as much as possible so, in the model, the flight is forced to depart within its STW with a specific constraint and cannot be dropped (unlike the approach taken by Kyenstad et Al.). Finally, for each departure d without a CTOT, a binary variable y_d is introduced which is equal to 1 if and only if d is dropped. Dropping a departure $d \in D$ has large cost w_d.

In practice the algorithm attempts to assign, within each specific tolerance window H_f, a departure time and an arrival time ($x_{ft} = 1$): the former is the optimal TTOT and the latter is the optimal TLDT for the integrated problem DMAN+AMAN. If a time departure cannot be assigned to a flight ($y_d = 1$), that flight will be postponed iteratively (in [36] the authors did not consider the re-allocation) until a time fits the global schedule, as will be explained in section 5.6.

The objective function can be formulated as the minimization of the cost of dropped flights plus overall deviation from the wanted arrival and departure times:

$$\min \sum_{d \in D} w_d \cdot y_d + \sum_{f \in F, t \in H_f} c_{ft} \cdot x_{ft} \tag{5.2}$$

The constraints can be written as follows:

- A landing time must be assigned to each arrival:

$$\sum_{t \in H_l} x_{lt} = 1 \quad \forall l \in L. \tag{5.3}$$

- A departure time must be assigned to each departure with a CTOT:

$$\sum_{t\in H_d} x_{dt} = 1 \quad \forall d \in D. \tag{5.4}$$

- A departure time must be assigned to each departure without CTOT or is dropped:

$$\sum_{t\in H_d} x_{dt} + y_d = 1 \quad \forall d \in D. \tag{5.5}$$

- A departure d cannot leave the stand before its off-block time, so it cannot take-off before $TX_d + TOBT_d$:

$$x_{dt} = 0 \quad \forall d \in D, t \in H_d \colon t < TX_d + TOBT_d. \tag{5.6}$$

- Time separations on runway between flights:

$$x_{ft} + \sum_{k\in\{t,\dots,t+\tau_{fg}\}} x_{gk} \leqslant 1 \quad \forall t \in H_f, (f,g) \in F \times F, f \neq g. \tag{5.7}$$

Note that, since the model has a linear objective function and constraints, but integer variables, it belongs to ILP problems.

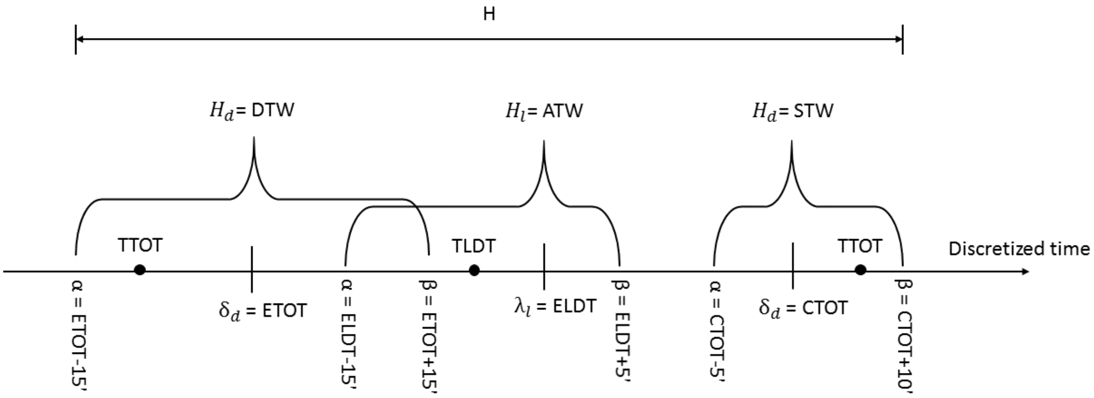


Figure 5.9: Times and tolerance windows for the runway scheduling problem.

DATA USED FOR LINATE AIRPORT On contrary to DTW and STW, the ATW is not defined by Eurocontrol. Moreover, the approach phase is particularly delicate for an aircraft, in which the configuration and the landing speed do not permit strong variations in time. So it has been though that an aircraft arrival time could be anticipated or postponed by 5 minutes with little speed variations (in general not more that 20 kn or 37 $\mathrm{km\,h^{-1}}$). If the ELDT should be postponed of more than 5 minutes, then the aircraft will be cleared to follow an *holding procedure* or delayed along the airway, so the delay time can be more than 5 minutes. For Linate airport it takes about 6 minutes for an aircraft to go from an holding to the runway (20 NM at almost 190 kn), so 15 minutes would be sufficient to route the aircraft to the holding, wait some minutes and continue the approach phase[3]. Moreover, in reference [22] is reported that for ATC the time-frame for swapping requests is between 10 to 13 minutes before landing, so the choose of 15 minutes is appropriated.

In the mathematical model the parameter τ_{fg} has been introduced to denote the separation time between flight f and flight g at landing or take-off when f precedes g. There can be different types of separations:

- Time separation between a departure and an arrival:
  - Runway usage: an arriving (departing) aeroplane cannot land (take-off) before that the preceding landing aircraft has vacated the runway: the time separation τ_{fg} is, then, the time necessary to the first aircraft to reach the node next to the runway (order of seconds).
  - Runway usage bis: a take-off is permitted up to 3 minutes before the estimated arrival of the landing aircraft [33, par. 5.7.1.2].
  - RADAR: not applied.
  - NON-RADAR: applied when operating on a runway with a displaced landing threshold, parallel runways in opposite directions or with touch and go procedures [13, ENR1-1,par. 9].
- Time separation between departures:
  - SID: departures are separated according to SID procedures, which are assigned according to the route the aircraft has to fly. It is preferred, then, to sequence the aircraft alternating the aircraft with different SIDs. Since SIDs have not been modelled due to lack of data it has been established that a departure cannot take-off before that the preceding departing aircraft has reached its assigned SID. From the dialogues had with the ATCO, then, τ_{fg} has been fixed at a mean value among all the SIDs, equal to 1.5 minutes.
  - RADAR: not applied.
  - NON-RADAR: time value (in minutes) which depends on the categories of the aircraft and the take-off position (single or parallel or crossing runways, intermediate take-off)[13, ENR1-1,par. 9].

---

[3] Conversion from aeronautical to SI units: 1 NM = 1.85 $\mathrm{km\,h^{-1}}$, 1 kn = 1.85 km/h, 1 feet = 0.3048 meter

- Time separation between arrivals:
  - STAR: not applied.
  - RADAR: radar separations are given in terms of distances in all cases (5 NM in general, 3 NM when radar capabilities at a given location permit it or 2.5 NM in other specific cases)[33, par.8.7.3.1]: for Milano TMA is applied 3 NM (5.56 km) [13, ENR2-1-1-1,par.2.2.2]. If greater, wake turbulence radar separation minima shall be applied and they are given as distance separations depending on the categories of the aircraft [13, ENR1-1,par. 9.4]. In order to convert the distances in times, from [13, ENR2-1-1-1,par. 2.2.2] the speed that pilots must comply at 5 NM from the RWY threshold is obtained, equal to 160 kn (296.3 $\mathrm{km\,h^{-1}}$) IAS for Linate airport. In the hypothesis of perfect instrument, no compressibility effects, standard atmosphere and no wind conditions (IAS=GS), and using this speed until the touch down, the times (in hours) are obtained dividing the prescribed distances (in NM) by 160 kn.
  - NON-RADAR: not given by the controllers as instructions if the aircraft (in particular the following) operates in Visual Flight Rules (VFR). For the ones operating following Instrument Flight Rules (IFR) there are time separations depending on the categories of the aircraft [13, ENR1-1,par. 9].

For wake turbulence separation purposes, aircraft are grouped by ICAO in four categories, three of which according to the maximum certificated take-off mass and one, "Super" category, based on the particular aircraft type:

- SUPER (J): Airbus A380-800 aircraft type;
- HEAVY (H): all aircraft types of $136,000$ kg or more;
- MEDIUM (M): aircraft types less than $136,000$ kg but more than $7,000$ kg;
- LIGHT (L): aircraft types of $7,000$ kg or less.

In recent years, however, knowledge about wake vortex behaviour in the operational environment has increased thanks to measured data and improved understanding of physical processes. For this reason the European Organisation for the Safety of Air Navigation (EUROCONTROL), in consultation with its stakeholders, has developed a re-categorisation of ICAO wake turbulence longitudinal separation minima on approach and departure, called *RECAT-EU* [25, RECAT-EU].

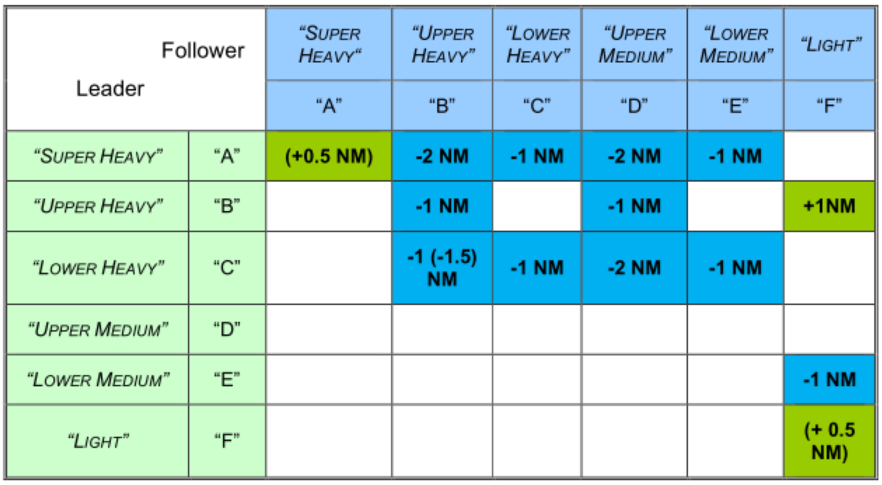
The RECAT-EU scheme is based on a set of principles, comparing the wake generation and wake resistance between aircraft types, and splitting ICAO HEAVY and MEDIUM categories into 'Upper' ('Larger') and 'Lower' ('Smaller'). This split has been based on aircraft type characteristics. This allows reduction of separation minima for some traffic pairs of aircraft, enabling runway throughput increase, whilst maintaining acceptable levels of safety.

Safety benefits are also delivered for some smaller aircraft types, by increasing their separation minima and/or change of category grouping, hence reducing the risk of wake turbulence-induced accidents for the most vulnerable types.

Taking into consideration both maximum certificated take-off mass and wing span, then, the aircraft are grouped in six categories, showed in figure 5.10 with some aircraft examples.

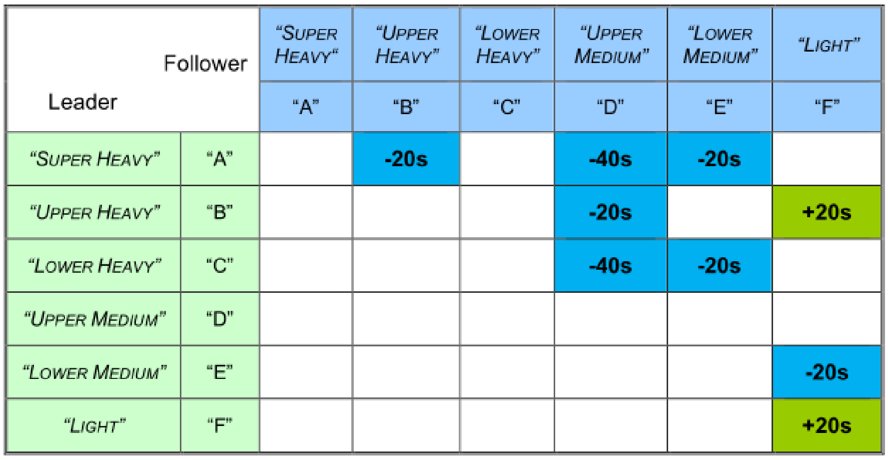
Figure 5.10: RECAT-EU Wake Turbulence Categories. [25]

Looking at the aircraft more common at Linate airport (figure 5.2) it can be noted that Airbus A318-A319-A320-A321 and Boeing B737-B738 belong to CAT-D; Boeing B733, Embraer E170 and E190 belong to CAT-E, some business aircraft belong to CAT-E while others switch to CAT-F category. Looking at figs. 5.11 and 5.12 in which the comparison between ICAO and RECAT separations has been showed, it can be noted that the re-categorization has effects principally on Heavy aircraft leading all other aircraft (categories), but these do not operate at Linate. In particular, in the interest of Linate, the re-categorization affects only lower medium (CAT-E) and light (CAT-F) aircraft, about 34% of the airport traffic, that are not concentrated in the same hour of the day but are spread and separated by upper medium (CAT-D) aircraft. For this reason, the re-categorization has small effects on the aircraft optimal schedule (delay is reduced of about 0.1%) and, maybe for the same reason, is not applied by air traffic controllers. However, the re-categorization has been considered in order to take into consideration future developments of the air traffic and to design an algorithm capable to schedule optimally the traffic also in other contexts (for example at Malpensa airport).



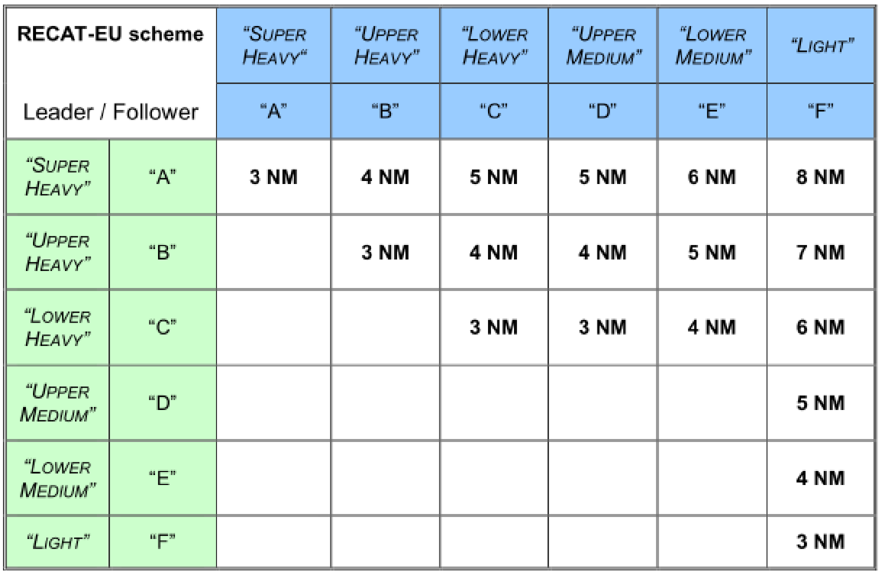
Follower Leader		“Super Heavy“	“Upper Heavy”	“Lower Heavy”	“Upper Medium”	“Lower Medium”	“Light”
		“A”	“B”	“C”	“D”	“E”	“F”
“Super Heavy”	“A”	(+0.5 NM)	-2 NM	-1 NM	-2 NM	-1 NM	
“Upper Heavy”	“B”		-1 NM		-1 NM		+1NM
“Lower Heavy”	“C”		-1 (-1.5) NM	-1 NM	-2 NM	-1 NM	
“Upper Medium”	“D”						
“Lower Medium”	“E”						-1 NM
“Light”	“F”						(+ 0.5 NM)

Figure 5.11: Difference in Wake Turbulence distance-based (RADAR) separation minima on arrivals between reference ICAO and RECAT-EU schemes. [25]



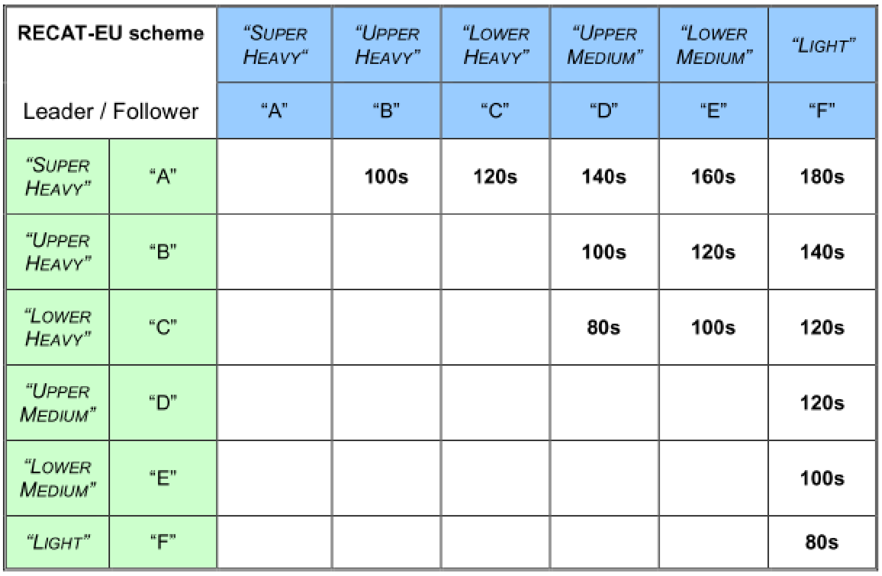
Follower Leader		“Super Heavy“	“Upper Heavy”	“Lower Heavy”	“Upper Medium”	“Lower Medium”	“Light”
		“A”	“B”	“C”	“D”	“E”	“F”
“Super Heavy”	“A”		-20s		-40s	-20s	
“Upper Heavy”	“B”				-20s		+20s
“Lower Heavy”	“C”				-40s	-20s	
“Upper Medium”	“D”						
“Lower Medium”	“E”						-20s
“Light”	“F”						+20s

Figure 5.12: Difference in Wake Turbulence time-based (NON-RADAR) separation minima on departure between reference ICAO and RECAT-EU schemes. [25]



RECAT-EU scheme		“Super Heavy“	“Upper Heavy”	“Lower Heavy”	“Upper Medium”	“Lower Medium”	“Light”
Leader / Follower		“A”	“B”	“C”	“D”	“E”	“F”
“Super Heavy”	“A”	3 NM	4 NM	5 NM	5 NM	6 NM	8 NM
“Upper Heavy”	“B”		3 NM	4 NM	4 NM	5 NM	7 NM
“Lower Heavy”	“C”			3 NM	3 NM	4 NM	6 NM
“Upper Medium”	“D”						5 NM
“Lower Medium”	“E”						4 NM
“Light”	“F”						3 NM

Figure 5.13: RECAT-EU Wake Turbulence distance-based (RADAR) separation minima on approach. Note: if no value is showed, minimum radar separations (MRS) are however applied. [25]



RECAT-EU scheme		“Super Heavy“	“Upper Heavy”	“Lower Heavy”	“Upper Medium”	“Lower Medium”	“Light”
Leader / Follower		“A”	“B”	“C”	“D”	“E”	“F”
“Super Heavy”	“A”		100s	120s	140s	160s	180s
“Upper Heavy”	“B”				100s	120s	140s
“Lower Heavy”	“C”				80s	100s	120s
“Upper Medium”	“D”						120s
“Lower Medium”	“E”						100s
“Light”	“F”						80s

Figure 5.14: RECAT-EU Wake Turbulence time-based (NON-RADAR) separation minima on departure. Note: If no value is showed, SIDs separations are however applied. [25]

5.5 GROUND SCHEDULING PROBLEM

The *ground scheduling problem* is the Step 3 of the integrated problem decomposition, whose goal is to establish the time t in which a flight $f \in F$ should enter every node and arc of its route $r_f = (v_0, a_1, v_1, a_2, \ldots, a_k, v_k)$, in order to obtain a complete conflict-free schedule, i.e it is needed to associate a schedule vector $t_f = (t_f^{v_0}, t_f^{a_1}, t_f^{v_1}, t_f^{a_2}, \ldots, t_f^{a_k}, t_f^{v_k})$ with the route of each flight (SMAN). The overall schedule t must:

- assign a schedule time (input time) to arcs and nodes of shortest paths computed at Step 1;
- satisfy the order of arrivals and departures on the runway established at Step 2;
- satisfy all precedence and separation constraints;
- minimize the overall taxi time, that is the time that the aircraft spend between the parking position and the runway with engines on, and vice-versa.

In order to minimize taxi times, departing aircraft are delayed as much as possible at the parking positions (looking for the greatest AOBT), while arrivals are scheduled to arrive as soon as at the assigned gate (looking for the smallest AIBT). Since the variable t represents the time at which the aeroplane enters in a node or arc, with $t_l^{g_{in}(l)}$ is denoted the time an arrival aircraft is scheduled to arrive to its gate, while $t_d^{g_{out}(d)}$ denotes the entry time in the arc following the node representing the gate, that is the time a departing aircraft leaves its gate. These times, from the algorithm perspective, correspond the former to Target In-Block Time (TIBT) and the latter to Target Start Up Approval Time (TSAT). During real operations TSAT is the time that an aircraft can expect to receive start up or push-back approval. From that time, it has a small window to start up and move out from the parking position: for self manoeuvring procedures the start up precedes the first movement, for push-back procedure the aircraft should be started-up only in particular zones called release points but in general the ignition is done also during the push-back. Since TSAT has a dual valence, in the modelling of the problem an approximation has to be done: TSAT is approximately equal to the "actual" time at which the pilots receive the start up and push-back approval (ASAT), but also the time at which the aircraft starts to move from the gate (AOBT).

If the entry and exit points at the runway, computed in Step 2, are indicated with t_l^{RWY} and t_d^{RWY}, then the objective function can be formulated as following:

$$\min \sum_{l \in L} \left(t_l^{g_{in}(l)} - t_l^{RWY} \right) + \sum_{d \in D} \left(t_d^{RWY} - t_d^{g_{out}(d)} \right) \tag{5.8}$$

Note that, since the times relative to the runway are fixed, they can be omitted in the formulation but, for the sake of clarity, they are left.

The ground scheduling problem can be seen as a job-shop scheduling problem, in which the aircraft represent the works that have to be processed by the machines, in this case the airport resources like nodes and arcs of the airport graph. The schedule, then, must satisfy *simple* and *disjuntive* precedence constraints:

- Respect the optimal runway schedule found at Step 2:

$$t_l^{RWY} = TLDT_l \quad \forall l \in L; \tag{5.9}$$

$$t_d^{RWY} = TTOT_d \quad \forall d \in D. \tag{5.10}$$

If arc $a = (u, v)$ belongs to route r_f of flight f (u and v are the nodes connected by a), then:

- Respect route sequence found at Step 1:

$$t_f^u = t_f^a \quad \forall f \in F, u \notin PKB \wedge u \notin HP; \tag{5.11}$$

$$t_f^u \leqslant t_f^a \quad \forall f \in F, u \in PKB \vee u \in HP. \tag{5.12}$$

- An aircraft cannot stop on arc:

$$t_f^a + l_f^a = t_f^v \quad \forall f \in F. \tag{5.13}$$

- Set a lower bound for the optimal TSAT:

$$t_d^{g_{out}(d)} \geqslant TOBT_d \quad \forall d \in D. \tag{5.14}$$

Disjunctive pairs of constraints: two aircraft cannot occupy the same node at the same time, and have to be divided in time for safety reasons, with the exception of holding points at which they can hold in queues. The separation on runway is defined in the first constraint, the separation at parking position in the last one. So, if p^v is the distance in time at a node v (processing time), then a boolean variable k and a big positive constant M (*Big-M*) can be introduced in order to activate only one constraint and make the other redundant.

- Precedence at a generic node: for every couple $f \neq g$ of aircraft which have the node v in common within their paths r_f or r_g, it is

$$t_g^v \geqslant t_f^v + p^v - M(1 - k_{f,g}^v) \qquad \forall v \neq pkb_f \text{ and } RWY \wedge v \notin HP; \tag{5.15}$$

$$t_f^v \geqslant t_g^v + p^v - M(k_{f,g}^v) \qquad \forall v \neq pkb_f \text{ and } RWY \wedge v \notin HP. \tag{5.16}$$

Since the constraints are valid for all departures and arrivals, a relation between the boolean variable has to be written as:

$$k_{f,g}^v + k_{g,f}^v \leqslant 1 \quad \forall v \neq pkb_f \text{ and } RWY \wedge v \notin HP. \tag{5.17}$$

- Since a release point can be got through by all aircraft because it is on the apron taxiways, if a departure is starting-up at the relative node, a distance in time has to be prescribed for an aircraft that follows the departure in that node. The disjunctive constraint is written as:

$$t_f^\nu \geqslant t_d^\nu + p^\nu - M(1 - k_{f,d}^\nu) \qquad \forall f \in F, d \in D, \nu \in Q; \tag{5.18}$$

$$t_d^\nu \geqslant t_f^\nu - M(k_{f,d}^\nu) \qquad \forall f \in F, d \in D, \nu \in Q. \tag{5.19}$$

- Precedence at parking position: an arrival cannot enter the gate until a departing aircraft has left it:

$$t_l^{g_{in}(l)} \geqslant t_d^{g_{out}(d)} + p^\nu - M(1 - k_{l,d}^g) \qquad \forall l \in L, d \in D, g \in PKB; \tag{5.20}$$

$$t_d^{g_{out}(d)} \geqslant -M(k_{l,d}^g) \qquad \forall l \in L, d \in D, g \in PKB. \tag{5.21}$$

Note that, since the model has a linear objective function and constraints, but both integer and continuous variables, it belongs to MILP problems.

DATA USED FOR LINATE AIRPORT The data used within Step 3 regards principally the waiting time p^ν used to separate the aircraft in the ground scheduling, in accordance with the local procedures. For the precedence at a generic node, p^ν has been fixed at 30 seconds: in this way if there are two aircraft that want to cross the same node at the same time, the algorithm will shift one or the other in order to separate them, always looking for the minimization of global taxi time. For release point and parking position constraints it has been chosen a value of 1 minute. With these values, and the real topology modelled with the graph of figure 5.8, the algorithm is capable to schedule all the aircraft in order to minimize the number of taxiing aircraft obtaining, then, the minimum possible taxi time and the maximum safety.

5.6 INTEGRATED VISION OF THE ALGORITHM

In the previous sections it has been described the heuristic decomposition of the integrated problem DMAN-SMAN-AMAN. In order to make the algorithm capable to help the airport stakeholders potentially in real time, the three problems have to be linked among them and the A-CDM platform, meaning that it is needed an integrated vision of the algorithm. The algorithm flowchart has been depicted in figure 5.15: it can be noted how the integration among the three steps is quite complex, because the inputs needed by a step depend on the outputs of the previous steps and by information stored in the A-CDM platform, and because it have been implemented some logical procedures in order to give to the airport stakeholders reliable and practical information.

In the present work the algorithm did not run in real time taking information directly from the airport A-CDM, but run in background basing the computation on a file of data extrapolated from the platform. So, in order to simulate a real time computation, it has been used a time parameter t with which it has been reproduced the flow of time. For each time, then, the algorithm bases its computation only on *current* flights, that are those aircraft for which is scheduled a departure or arrival at the assigned parking positions but are not yet *taken-off* or *on-blocks*. One of the first output of the algorithm, in the interest of the stakeholders, is the TSAT: from reference [26] it can be read that TSAT is provided p-minutes before EOBT, where p is a parameter agreed locally. Also for arrivals, however, it can be useful to know the optimal values some minutes in advance the target landing time. For these reasons, in the algorithm formulation, there is a single common parameter both for departures and arrivals, which is used to define the current flights, that are those for which $\text{SOBT} - p \leqslant t \leqslant \text{ATOT}$ and $\text{SIBT} - p \leqslant t \leqslant \text{AIBT}$. The scheduled times SOBT and SIBT have been chosen instead of the expected times EOBT and EIBT because for arrivals the EIBT is not present in the A-CDM platform, and because they are the reference time for the airport service provider. Note that the algorithm computes the "target" values that are ideal times, not "actual" or "real" times. In order to give to the algorithm an indication of when a flight can be considered taken-off or on-blocks, and so remove it from the set of the current flights, it have been added 10 minutes to the TTOT and TIBT obtaining the ideal ATOT and AIBT.

Following the flowchart, p-minutes before the SOBT or SIBT each flight enters in the set of current flights. For all of them, then, the algorithm computes the shortest path with the relative taxi time (Step 1), the TTOT or TLDT (Step2) and the TSAT or TIBT (Step 3). These optimal values, however, are computed each 10 minutes (time interval chosen for computational reasons), and every time the current flights are updated with new flights: like in the real world, the time passes and the aircraft that have to be managed are different. This means that the optimization is done over the all current flights, so the single optimal values of a specific flight can vary when is related to the other flights. So, in order to give to the airport stakeholders the final optimal values, two sets are defined: the *scheduled* departures and the *on-final* arrivals. If a departure start up is scheduled to be within k-minutes from the current time ($\text{TSAT} - k \leqslant t$), then that flight is considered scheduled so its TSAT, TTOT and path cannot vary any more. The same logical condition is applied to an arrival that is scheduled to land within 10 minutes from the current time ($\text{TLDT} - k \leqslant t$), so it is considered on-final and its TLDT, TIBT and path cannot vary any more. Another logical condition regards the flights for which, in the runway scheduling problem (Step 2), the algorithm can not assign a take-off time: these flights have been called *dropped*, and are flights without a CTOT assigned. If a departure is dropped its ETOT is postponed iteratively of 10 minutes: in this way, the DTW of a dropped flight will intersect the time windows of the other flights, both old and new, so the algorithm can try to re-compute a feasible take-off time and assign to the departure an optimal TTOT[4].

This procedure continue until the end of the day. The optimal values computed by the algorithm and assigned to the taken-off departures (TTOT and TSAT) and to the on-blocks arrivals (TLDT and TIBT) are then compared with the values present in the data file extrapolated from the A-CDM platform, which are calculated following a FCFS principle. The results are described in chapter 6.

DATA USED FOR LINATE AIRPORT The values that have to be assigned due to their specific application at Linate (and Malpensa) airport are the time parameters p and k. The first is used by the algorithm to define the current flights: in reference [42, Leaflet 3] it is stated that at Linate (and Malpensa) the first issue of TSAT is given at $\text{TOBT} - 40 \ \mathrm{min}$ (it is considered, indeed, TOBT instead of EOBT). The TOBT is updated until the Aircraft Operator or Ground Handler are confident to provide their most accurate value, taking into account the operational situation. This last value is provided j-minutes before EOBT, and j is agreed locally. Since in the A-CDM data is provided the last TOBT (often equal to EOBT) but not the time of when it has been inserted in the platform, for the first computation of TSAT and, then, for the computation of the time at which a flight is considered current, it has been considered $\text{SOBT} - p = \text{SOBT} - 40 \ \mathrm{min}$. In addition to this, a value of 40 min is considered reliable for an arrival aircraft.

The time parameter k is fixed at 15 min because it has been estimated that 15 min before a start up or landing the air traffic controller must know the final values of TSAT and TLDT and the optimal departure or landing sequences in order to give the specific authorizations to the pilots. Moreover, since TSAT is computed considering the last accurate TOBT, in this way is implicitly said that 15 min before the aircraft start up, the off-block time can be considered sufficiently precise for the computation of TSAT, so the algorithm can fix the TSAT computed on the last known TOBT (extrapolated by the A-CDM data).

---

[4] Note that in reference [36] the authors did consider the re-assignment of dropped flights and the definition of scheduled and on-final flights.

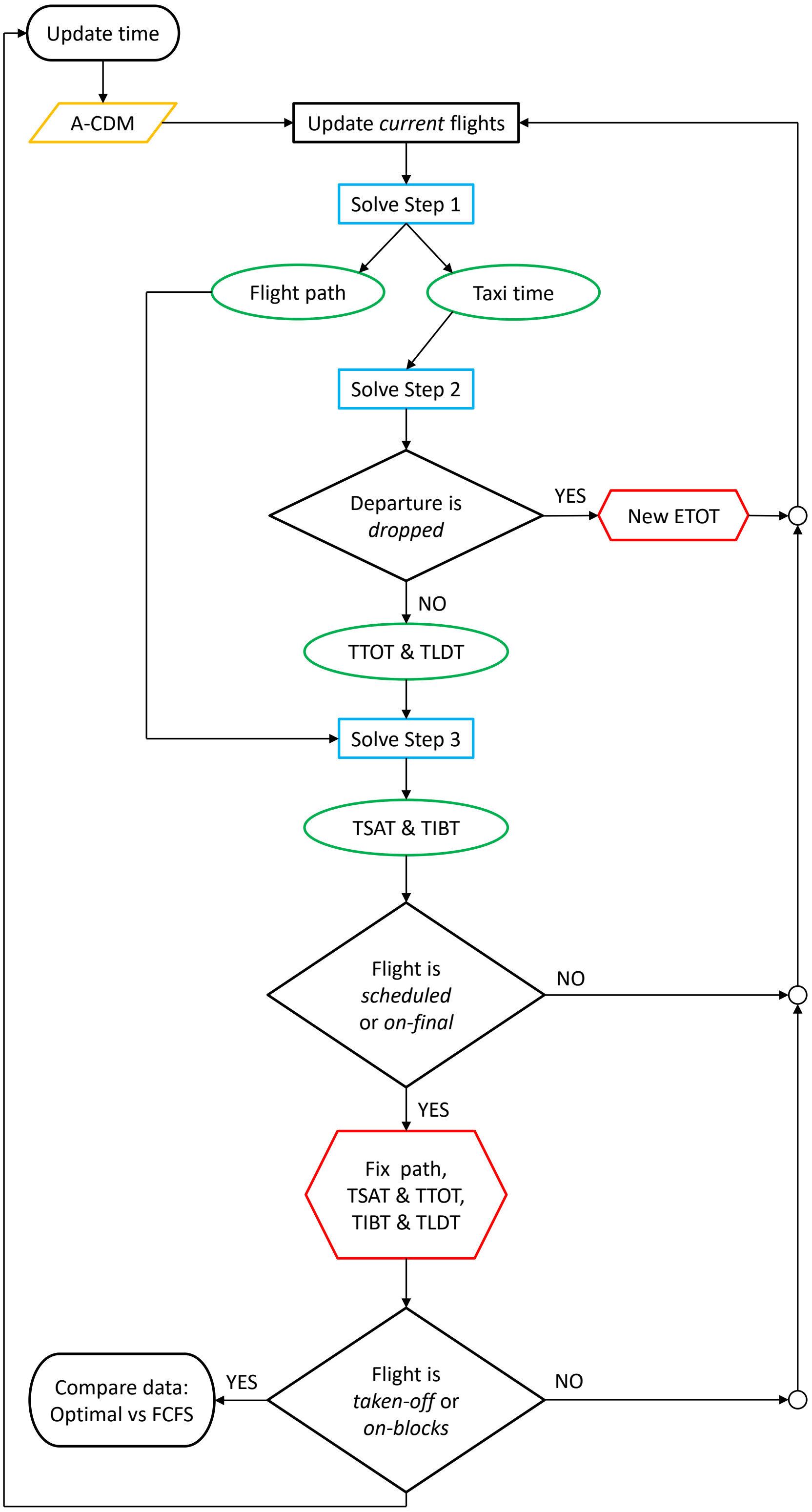


Figure 5.15: Algorithm flowchart.

6

RESULTS ANALYSIS

Once all flights have been optimally scheduled by the algorithm, it can be done a comparison between the optimal results and the ones stored in the A-CDM platform, obtained following a FCFS concept. The optimal values computed by algorithm are $\mathsf{TSAT}_{\mathsf{opt}}$, $\mathsf{TTOT}_{\mathsf{opt}}$, $\mathsf{TLDT}_{\mathsf{opt}}$ and $\mathsf{TIBT}_{\mathsf{opt}}$, which are ideal or "target" times, not "actual" or real times, since are the entry(exit) times computed by the algorithm into(from) arcs/nodes of the airport graph. Remember that the "target" times for arriving aircraft are not computed by the A-CDM platform[1], so it cannot be done a comparison between "target" times. So, in order to compare the optimal values with the FCFS ones, they can be considered two methods. The *first method* considers the optimal times computed by the algorithm as the "actual" times of the aircraft, in the case in which the algorithm is operating and there are no delays not provided by it (i.e. meteorological, operative, other). Then the "actual" FCFS values can be compared with the optimal "target-actual" ones: this is clearly a simplification of the real problem but, since the algorithm has not been applied in real-time to the departures and arrivals, the optimal "actual" values of the aeroplanes does not exists. Following this idealization, then, they can be summarized the optimal values computed by the algorithm and their approximations:

- $\mathsf{TSAT}_{\mathsf{opt}}$ is the time the pilots expect to receive the start up/push-back approval from the ATCO. Since, in the model, it is the time the aircraft leaves its parking position, it can be considered also the aircraft $\mathsf{AOBT}_{\mathsf{opt}}$. If the aeroplane needs a push-back, then it will be started-up at the release point (the algorithm considers this addition of time), otherwise it can be considered already started-up before it moves from the gate ($\mathsf{ASAT}_{\mathsf{opt}}$). So, not considering operative procedures due to handling procedure and real start up/push-back/off-block times, TSAT can be approximated as follows:

$$\mathsf{TSAT}_{\mathsf{opt}} \approx \mathsf{AOBT}_{\mathsf{opt}} \approx \mathsf{ASAT}_{\mathsf{opt}}. \tag{6.1}$$

- $\mathsf{TTOT}_{\mathsf{opt}}$ is the time at which a departure is expected to take-off: since the algorithm already considers "operative" delays such as traffic separations on the taxiways and at the runway, this time can be approximated to the $\mathsf{ATOT}_{\mathsf{opt}}$:

$$\mathsf{TTOT}_{\mathsf{opt}} \approx \mathsf{ATOT}_{\mathsf{opt}}. \tag{6.2}$$

---

[1] TLDT and TIBT are an AMAN output, but at Linate airport this tool is not already implemented. The aim of this thesis is to demonstrate, in fact, that it could be useful an implementation and integration between DMAN-SMAN-AMAN tools.

- $\mathrm{TLDT_{opt}}$ is the time at which an arrival aircraft is expected to land, considering the "operative" delays due to traffic separations. For this reason it can be considered equal to $\mathrm{ALDT_{opt}}$:

$$\mathrm{TLDT_{opt}} \approx \mathrm{ALDT_{opt}}. \tag{6.3}$$

- $\mathrm{TIBT_{opt}}$ is the time at which an arrival aircraft is expected to enter in its parking position and can be considered blocked-in. It is ideally approximated equal to the $\mathrm{AIBT_{opt}}$, even if they can be operative delays due to handling procedures:

$$\mathrm{TIBT_{opt}} \approx \mathrm{AIBT_{opt}}. \tag{6.4}$$

The *second method* of comparison applies operative delays to the optimal target values in order to obtain more realistic "target-actual" values. Looking, in fact, at the definitions of TSAT and TIBT, it is clear that considering these values as "actual" can be wrong or too much optimistic. Taking information from the A-CDM platform, then, some "errors" can be calculated for the target times and added to the optimal ones computed by the algorithm. Following this procedure, then, the operative time variations are considered along the day and from an aircraft to another, permitting a re-definition of the "actual" optimal values:

- $\mathrm{AOBT_{opt}}$: looking at the values of TSAT and AOBT for the departures managed following a FCFS procedure, it can be calculated, for each aircraft, a time-error from the difference AOBT-TSAT. In this way, then, it is considered the time that passes from the estimated reception of the start up clearance (TSAT) and the actual off-block time (AOBT). In the real operative context, in fact, the off-block procedure is not instantaneous, and a flight cannot leave the parking position until it is declared "ready" (Actual Ready Time (ARDT)), that is the time when all doors are closed, boarding bridge removed, push-back vehicle connected (if needed), ready to taxi immediately upon reception of TWR instructions. $\mathrm{AOBT_{opt}}$ is then

$$\mathrm{AOBT_{opt}} \approx \mathrm{TSAT_{opt}} + (\mathrm{AOBT_{FCFS}} - \mathrm{TSAT_{FCFS}})\,. \tag{6.5}$$

- $\mathrm{ASAT_{opt}}$: in the operative context some minutes can pass from the expected time of reception of the start up/push-back approval (TSAT) and the actual time (ASAT). In the pre-departure sequence, in fact, the ATCO tries to respect the TSAT as much as possible but the correct adherence to this time depends also by the other stakeholders (ramp agents, pilots, others). Moreover, if an aircraft needs a push-back its ASAT will be later than the AOBT, while if it can leave the stand by itself the ASAT will be earlier than AOBT. This means that ASAT is different from AOBT and TSAT, so it can be computed as:

$$\mathrm{ASAT_{opt}} \approx \mathrm{TSAT_{opt}} + (\mathrm{ASAT_{FCFS}} - \mathrm{TSAT_{FCFS}}). \tag{6.6}$$

- $\mathrm{ATOT}_{\mathrm{opt}}$: in the model formulation the delays due to traffic separation have already been taken into consideration but, if the aircraft leave the parking positions in advance or delay, the ground and runway scheduling could be compromised. Following the departure sequence, however, the ATCO has to respect as much as possible the $\mathrm{TTOT}_{\mathrm{opt}}$ computed by the algorithm. In order to do this, then, it is hypothesized that the ATCO can speed-up/slow-down the aircraft in order to respect the precedences and the separations along the taxiways and at the runway, and that meteorological conditions does not effect too much the runway scheduling. So it can be assumed that

  $$\mathrm{ATOT}_{\mathrm{opt}} \approx \mathrm{TTOT}_{\mathrm{opt}}. \tag{6.7}$$

- $\mathrm{ALDT}_{\mathrm{opt}}$: in the modelling of arrival sequencing the aircraft are obliged to land with a specific constraint so, hypothesizing that none of them makes a turn-around manoeuvre and that meteorological conditions does not affect too much the runway scheduling, and that the ATCOs (approach and tower controllers) can meet the algorithm scheduling, it can be assumed that

  $$\mathrm{ALDT}_{\mathrm{opt}} \approx \mathrm{TLDT}_{\mathrm{opt}}. \tag{6.8}$$

- $\mathrm{AIBT}_{\mathrm{opt}}$: in the daily operative operations a delay at the parking position can happen for arriving aircraft because of ground handling procedures. Since in the A-CDM platform there not exists a TIBT value, it can be estimated as

  $$\mathrm{TIBT}_{\mathrm{FCFS}} \approx \mathrm{EIBT}_{\mathrm{FCFS}} = \mathrm{ELDT} + \mathrm{EXIT}. \tag{6.9}$$

  Known the target in-block time, then, an approximation for $\mathrm{AIBT}_{\mathrm{opt}}$ can be done as:

  $$\mathrm{AIBT}_{\mathrm{opt}} \approx \mathrm{TIBT}_{\mathrm{opt}} + (\mathrm{AIBT}_{\mathrm{FCFS}} - \mathrm{TIBT}_{\mathrm{FCFS}}). \tag{6.10}$$

Defined the times with which can be done the comparison between the FCFS values and optimal ones, in the following points are explained the parameters for the evaluation and validation of the optimization algorithm:

- *delay at the runway*: it is defined as the average value of the time difference between the actual times and the target ones, taken with the absolute values in order to consider the time "distance", both positive (delay) and negative (advance). The delay performance can be evaluated, then, with both the methods above explained as:

$$\text{Arrivals methods 1 \& 2:} \begin{cases} \frac{1}{\mathtt{card}(L)} \sum_{l \in L} |TLDT^l_{opt} - ELDT^l| \approx \\ \frac{1}{\mathtt{card}(L)} \sum_{l \in L} |ALDT^l_{opt} - ELDT^l| \\ \frac{1}{\mathtt{card}(L)} \sum_{l \in L} |ALDT^l_{FCFS} - ELDT^l| \end{cases} \tag{6.11}$$

$$\text{Departures methods 1 \& 2:} \begin{cases} \frac{1}{\mathtt{card}(D)} \sum_{d \in D} |TTOT^d_{opt} - \delta^d| \approx \\ \frac{1}{\mathtt{card}(D)} \sum_{d \in D} |ATOT^d_{opt} - \delta^d| \\ \frac{1}{\mathtt{card}(D)} \sum_{d \in D} |ATOT^d_{FCFS} - TTOT^d_{FCFS}| \end{cases} \tag{6.12}$$

- *Taxi time*, defined as the average time that the aircraft is out of its parking gate:

$$\text{Arrivals method 1 :} \begin{cases} \frac{1}{\mathtt{card}(L)} \sum_{l \in L} \left(TIBT^l_{opt} - TLDT^l_{opt}\right) \\ \frac{1}{\mathtt{card}(L)} \sum_{l \in L} \left(AIBT^l_{FCFS} - ALDT^l_{FCFS}\right) \end{cases} \tag{6.13}$$

$$\text{Arrivals method 2 :} \begin{cases} \frac{1}{\mathtt{card}(L)} \sum_{l \in L} \left(AIBT^l_{opt} - ALDT^l_{opt}\right) \approx \\ \frac{1}{\mathtt{card}(L)} \sum_{l \in L} \left(AIBT^l_{opt} - TLDT^l_{opt}\right) \\ \frac{1}{\mathtt{card}(L)} \sum_{l \in L} \left(AIBT^l_{FCFS} - ALDT^l_{FCFS}\right) \end{cases} \tag{6.14}$$

$$\text{Departures method 1 :} \begin{cases} \frac{1}{\mathtt{card}(D)} \sum_{d \in D} \left(TTOT^d_{opt} - TSAT^d_{opt}\right) \\ \frac{1}{\mathtt{card}(D)} \sum_{d \in D} \left(ATOT^d_{FCFS} - AOBT^d_{FCFS}\right) \end{cases} \tag{6.15}$$

$$\text{Departures method 2 :} \begin{cases} \frac{1}{\mathtt{card}(D)} \sum_{d \in D} \left(ATOT^d_{opt} - AOBT^d_{opt}\right) \approx \\ \frac{1}{\mathtt{card}(D)} \sum_{d \in D} \left(TTOT^d_{opt} - AOBT^d_{opt}\right) \\ \frac{1}{\mathtt{card}(D)} \sum_{d \in D} \left(ATOT^d_{FCFS} - AOBT^d_{FCFS}\right) \end{cases} \tag{6.16}$$

- *Fuel consumption*, function of the time in which the aircraft has the engines on between its parking position and the runway, and vice-versa. For departures is considered the ASAT, while for arrivals is assumed that as soon as the aircraft reaches its parking position the pilots shut-down the engines. It has been calculated following reference [34], as explained below.

$$\text{Arrivals method 1}: \begin{cases} \sum_{l \in L} \dot{m}^l \cdot \left(\mathrm{TIBT}^l_{opt} - \mathrm{TLDT}^l_{opt}\right) \cdot 3600 \cdot N^l_e \\ \sum_{l \in L} \dot{m}^l \cdot \left(\mathrm{AIBT}^l_{FCFS} - \mathrm{ALDT}^l_{FCFS}\right) \cdot 3600 \cdot N^l_e \end{cases} \tag{6.17}$$

$$\text{Arrivals method 2}: \begin{cases} \sum_{l \in L} \dot{m}^l \cdot \left(\mathrm{TIBT}^l_{opt} - \mathrm{ALDT}^l_{opt}\right) \cdot 3600 \cdot N^l_e \approx \\ \sum_{l \in L} \dot{m}^l \cdot \left(\mathrm{AIBT}^l_{opt} - \mathrm{TLDT}^l_{opt}\right) \cdot 3600 \cdot N^l_e \\ \sum_{l \in L} \dot{m}^l \cdot \left(\mathrm{AIBT}^l_{FCFS} - \mathrm{ALDT}^l_{FCFS}\right) \cdot 3600 \cdot N^l_e \end{cases} \tag{6.18}$$

$$\text{Departures method 1}: \begin{cases} \sum_{d \in D} \dot{m}^d \cdot \left(\mathrm{TTOT}^d_{opt} - \mathrm{TSAT}^d_{opt}\right) \cdot 3600 \cdot N^d_e \\ \sum_{d \in D} \dot{m}^d \cdot \left(\mathrm{ATOT}^d_{FCFS} - \mathrm{ASAT}^d_{FCFS}\right) \cdot 3600 \cdot N^d_e \end{cases} \tag{6.19}$$

$$\text{Departures method 2}: \begin{cases} \sum_{d \in D} \dot{m}^d \cdot \left(\mathrm{ATOT}^d_{opt} - \mathrm{ASAT}^d_{opt}\right) \cdot 3600 \cdot N^d_e \approx \\ \sum_{d \in D} \dot{m}^d \cdot \left(\mathrm{TTOT}^d_{opt} - \mathrm{ASAT}^d_{opt}\right) \cdot 3600 \cdot N^d_e \\ \sum_{d \in D} \dot{m}^d \cdot \left(\mathrm{ATOT}^d_{FCFS} - \mathrm{ASAT}^d_{FCFS}\right) \cdot 3600 \cdot N^d_e \end{cases} \tag{6.20}$$

As said before, for the computing of the fuel consumption have been followed the ICAO directives [34]. ICAO defines a standard LTO cycle (approach, taxi, take-off and climb) upon which the Emission Indexes (EI) of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and smoke, and fuel flow data are computed for each operating phase. In accordance with the engines manufacturers, then, the engines data are collected in the Engine Emissions Data Bank (EEDB). ICAO aircraft engine emissions standards apply only to subsonic and supersonic aircraft turbojet and turbofan engines of thrust rating greater than or equal to 26.7 kN. ICAO excluded, from its standards, small turbofan and turbojet engines (thrust rating less than 26.7 kN), turboprop, piston and turboshaft engines, APU and general aviation aircraft engines because of the very large number of models, the uneconomic cost of compliance and small fuel usage compared to commercial jet aircraft. Business and general aviation aircraft are about 11% of total flights operating at Linate in the two case study days (see figure 5.3 at page 73) so, even if their contribution is small to the total fuel consumption and emissions, in order to obtain and assign some data to them some researches have been done in national databases (for example [30]) and on internet. For the computing of the fuel flow, then, it has been considered a taxiing executed in idle at a power setting of 7% for the commercial aviation, taking the precise values of fuel flow for the most operating aircraft at Linate (figure 5.5 at page 74) that, in average, is equal to $0.10\ \mathrm{kg\,s^{-1}}$. A mean value of $\dot{m} = 0.07\ \mathrm{kg\,s^{-1}}$ has been considered for business aircraft and $\dot{m} = 0.0014\ \mathrm{kg\,s^{-1}}$ for piston engine aircraft. Note that the overall procedure, as stated by ICAO itself, is approximated: deeper studies showed, in fact, that power levels around 5-6% are more realistic for most engine types [3], and that accelerations/decelerations during the taxiing have effects on fuel consumptions, but are difficult to evaluate [41]. So, the values computed by the algorithm are approximated but can show the impact that aircraft have on environment. In particular, following the ICAO procedure, it can be computed the CO_2 emitted by the aircraft. The carbon dioxide is, in fact, the reference gas against which the global warming potential of other greenhouse gases is measured and has a strict correlation with the fuel burnt by the aeroplanes. Knowing the fuel burnt by the aircraft it can be obtained the amount of CO_2 saved by the algorithm, with a simple (and so approximated) conversion of $3.16\ \mathrm{kg_{CO_2}/kg_{fuel}}$.

The delay at runway (its absolute value), taxi time and fuel consumption relative to the 8^{th} November 2016 have been computed with the two methods described before, and represented from tables 6.1 to 6.3. In table 6.3 has been showed the data relative to all flight of the day, computed as the sum of the mean delays, mean taxi times and fuel consumptions between departures and arrivals. Looking at the tables it can be noted how, in general, the values computed by the algorithm are better respect to the ones obtained with a FCFS procedure. The delay at the runway of departures, however, is not improved very much: as said in other sections, the day of November did not have particular congestion problems, so the algorithm worked as well as the ATCOs did. Another consideration that can be done looking at the values of the delay is that between the first and second methods there are not differences: this is due, obviously, to the fact that the actual and target times for take-off and landing are considered equal in the two methods. An evidence of the difference between the two methods is shown in the results relative to taxi time: considering the delays at the parking positions due to handling procedures (method 2), it can be noted that arrivals are blocked-in after the expected time and that departures are released after, meaning that the arrivals spend more time on taxiways, while departures less. Looking at the fuel consumption, since it is hypothesized that the pilots shut down the engines as soon as they are blocked-in, it can be noted that in the second method they consume more fuel respect to the first method, in which are neglected handling procedures. Looking at departures is evident how the first method is too much optimistic: referring to the values of the second method it's clear that the flights leave after the parking gate but they are started-up before that time. This fact suggest that there are more aircraft that do a self-manoeuvring procedure instead of the ones that need a push-back.

The same considerations can be done looking at tables 6.4 to 6.6, with the exception that the arrivals have the opposite behaviour (they spend less time on taxiways) and that the delay at the runway is reduced respect to the FCFS concept.

The comparison of the two methods shows, then, that both are an approximated view of the real world, but the second method can be considered more realistic than the first one. For this reason, in the following paragraphs, only this one will be considered.

The results for the two case study days (following the second method) are reported in tables 6.7 to 6.9, which show that the algorithm is capable to improve the air traffic management at Linate airport. Looking specifically at the two days, in November the delay (its absolute value) at the runway is equal between the optimal and the FCFS values, meaning that the ATCOs are able to sequence the aircraft in the proper way when the traffic is not intense, or reciprocally that the algorithm works, in the worst case, as well as ATCOs do. In a global optimization vision, however, both the taxi time and fuel consumption are reduced by the algorithm. In the day of February also the delay at the runway is reduced, meaning that an integrated DMAN-SMAN-AMAN could be useful at the airport, both in low and high traffic days. For what concern dropped departures, only one flight in the first day was dropped, while in the second day only three. None arrival has been sent to holding pattern procedures.

Another comparison that can been done regards the delay at parking position. Following reference [26], this is defined as the difference between AOBT and SOBT for departures, and AIBT and SIBT for arrivals. Having calculated the $AOBT_{opt}$ and $AIBT_{opt}$, it is possible to compute the mean optimal and FCFS delay as done for the delay at the runway. The results showed that also this parameter is improved but, in general, this is not expected, especially for departures. The departing aircraft, in fact, wait at their parking positions for the appropriate off-block time but this could result in greater delays respect to the FCFS concept[2]. For these reasons, further analysis are needed.

Note that, although the differences among the optimal and FCFS values may seem little, it should be considered that the optimization algorithm worked on two days in which the traffic congestion was almost absent. Thinking at months in which the number of movements is greater, for example in summer, the algorithm could achieve better results. However, every single minute saved in the aircraft scheduling represent a great improvement for the airport stakeholders and the environment. In the future, in which is expected an increase of air traffic demand, each saved minute will be important for the overall airport system.

From the fuel consumption values they can be done some considerations about CO_2 and money savings. Looking at table 6.9 it can be computed for the first day a saving

---

[2] Future releases of the algorithm could consider a maximum allowed gate-holding as done in [37], or gate re-allocation as in [11]. Both of them, however, need specific dialogues with ground handlers/airlines and airport services provider, which were not possible for this work.

of fuel consumption of 1,988 kg, for the second day 5,637 kg. In the first day there were 314 operating flights, while in the second they were 328 in total, but nine of them performed a de-icing procedure so have not been considered in the optimization computation, so the managed flight were 319 (see tables 5.1 and 5.2). Knowing this, it can be computed an average fuel saving for each aircraft equal to 6.3 kg (or 7.5 L [3]) for the first day, and 17.7 kg (or 21 L) for the second day.

From the conversion ratio of 3.16 $\text{kg}_{\text{CO}_2}/\text{kg}_{\text{fuel}}$ it can be computed that, in the first day, it would not have emitted in total 6,282 kg of CO_2, while in the second day the saving would have been equal to 17,812 kg, respectively almost equal to 20 kg and 56 kg of CO_2 saved by each aircraft in the two days. In general, the CO_2 is converted in acres of U.S. forests needed to store it, or in other fanciful (but rigorous) ways. From reference [14], $1000\ \text{kg}_{\text{CO}_2} = 0.947$ acres $= 3832\ \text{m}^2$. Imaging that the forest is let to grow in a field wide as a football (or soccer) field, the conversion is $1000\ \text{kg}_{\text{CO}_2} = 0.54$ football fields. So, wanting to compute the necessary fields to save the same amount of CO_2 that the algorithm saved, for the first day would be needed planting the forest in almost 3 football fields, for the second day in almost 10.

From reference [32] it is taken a mean value of the price of jet fuel for November 2016 and February 2017. Considering that the price in the two months was quite the same, it has been used a value of 0.40 €/L (63 €/barrel) in order to compute an estimation of the money saving associated to fuel consumption. Known that in the first day it would have been saved 1,988 kg = 2,486 L of fuel, and that in the second day the amount of fuel not burnt would have been 5,637 kg = 7,046 L, it can be computed a money saving equal to 994 € in the first day, and 2,818 € for the second day. In figure 5.3 at page 73 it has been shown that the principal airline operating at Linate is Alitalia. In average its presence is equal to 55% in the two days: if it wanted to compute, approximately, the money saving for this airline it can be hypothesized that 55% of fuel saved during taxi belongs to it, so can be said that Alitalia would have saved in average about 1,900 € each day. If it is hypothesized that the fuel consumption reduction and the cost of fuel remain equal also in other days, the amount of money saved becomes considerable and of interest for the company, but also for the airport service provider which could exploit the presence of an integrated DMAN-SMAN-AMAN like the algorithm developed in this thesis for attract the airline companies and give them better services.

A consideration about the algorithm efficiency can be done in terms of safety: in figs. 6.1 and 6.2 are showed the taxiing aircraft along the two days under study. It can be seen that, as consequence of the reduction of taxi time, the optimal scheduling has also less aircraft moving on taxiways, meaning that also the safety is increased thanks to the algorithm.

---

[3] It is considered a value of $800\ \text{kg}\,\text{m}^{-1}$ for kerosene density.

The NLP (Step 1), ILP (Step 2) and MILP (Step 3) problems have been implemented in the AMPL modelling language [31] and solved by CPLEX solver version 12.6.3.0 on a PC with Intel i7 CPU, 4 cores (4x1.6 GHz) and 4 GB RAM. AMPL and CPLEX have been chosen because of their ability in the modelling of mathematical problems (although AMPL could appear too much "rigid" respect to other modelling programs for the construction of iterative algorithms) and the computation of the optimal values in very little times. As an example, for the computational analysis of all 319 flights of 15/2/2015 the total elapsed time was about 25 seconds (21 if it is not considered the non-linearity in the objective function of Step 1). In the worst case the algorithm managed 18 departures and 12 arrivals at the same time, with solving times equal to 0.906 s for Step 1, 0.078 s for Step 2 and 0.109 s for Step 3. These are remarkable results if it is considered that, for a single departing flight from the west apron of Linate, the solver has to manage almost 19 constraints and 20 variables in Step 1, 3 constraints and 12 variables in Step 2, and 24 constraints and 25 variables in Step 3. The same values can be associated to an arriving aircraft, and if many aircraft are considered at the same time the number of variables/constraints are greater due to interactions among them. The computational times and values, then, prove that an heuristic decomposition of the integrated DMAN-SMAN-AMAN problem is the best possible solution.

	Delay at runway		Taxi time		Fuel consumption	
Method	1^{st}	2^{nd}	1^{st}	2^{nd}	1^{st}	2^{nd}
Optimal	1.19 min	1.19 min	3.99 min	4.13 min	7,576 kg	7,821 kg
FCFS	1.61 min	1.61 min	4.30 min	4.30 min	8,147 kg	8,147 kg
Opt/FCFS	0.74	0.74	0.93	0.96	0.93	0.96
Opt vs. FCFS	−26%	−26%	−7%	−4%	−7%	−4%

Table 6.1: Arrivals results (8/11/2016).

	Delay at runway		Taxi time		Fuel consumption	
Method	1^{st}	2^{nd}	1^{st}	2^{nd}	1^{st}	2^{nd}
Optimal	2.38 min	2.38 min	10.40 min	10.18 min	18,751 kg	22,074 kg
FCFS	2.38 min	2.38 min	11.31 min	11.31 min	23,736 kg	23,736 kg
Opt/FCFS	1	1	0.92	0.90	0.79	0.93
Opt vs. FCFS	−0%	−0%	−8%	−10%	−21%	−7%

Table 6.2: Departures results (8/11/2016).

	Delay at runway		Taxi time		Fuel consumption	
Method	1^{st}	2^{nd}	1^{st}	2^{nd}	1^{st}	2^{nd}
Optimal	3.55 min	3.55 min	14.39 min	14.31 min	26,327 kg	29,895 kg
FCFS	3.99 min	3.99 min	15.61 min	15.61 min	31,883 kg	31,883 kg
Opt/FCFS	0.89	0.89	0.92	0.92	0.83	0.94
Opt vs. FCFS	−11%	−11%	−8%	−8%	−17%	−6%

Table 6.3: All flights results (8/11/2016).

	Delay at runway		Taxi time		Fuel consumption	
Method	1st	2nd	1st	2nd	1st	2nd
Optimal	1.08 min	1.08 min	3.97 min	3.65 min	7,398 kg	5,754 kg
FCFS	1.71 min	1.71 min	4.01 min	4.01 min	7,473 kg	7,473 kg
Opt/FCFS	0.63	0.63	0.99	0.91	0.99	0.77
Opt vs. FCFS	−37%	−37%	−1%	−9%	−1%	−23%

Table 6.4: Arrivals results (15/2/2017).

	Delay at runway		Taxi time		Fuel consumption	
Method	1st	2nd	1st	2nd	1st	2nd
Optimal	2.36 min	2.36 min	10.53 min	9.59 min	18,852 kg	20,566 kg
FCFS	2.72 min	2.72 min	11.70 min	11.70 min	24,484 kg	24,484 kg
Opt/FCFS	0.87	0.87	0.90	0.82	0.77	0.84
Opt vs. FCFS	−13%	−13%	−10%	−18%	−23%	−16%

Table 6.5: Departures results (15/2/2017).

	Delay at runway		Taxi time		Fuel consumption	
Method	1st	2nd	1st	2nd	1st	2nd
Optimal	3.44 min	3.44 min	14.50 min	13.24 min	26,250 kg	26,320 kg
FCFS	4.43 min	4.43 min	15.71 min	15.71 min	31,957 kg	31,957 kg
Opt/FCFS	0.77	0.77	0.92	0.84	0.82	0.82
Opt vs. FCFS	−23%	−23%	−8%	−16%	−18%	−18%

Table 6.6: All flights results (15/2/2017).

	Delay at runway		Taxi time		Fuel consumption	
Day	8/11/'16	15/2/'17	8/11/'16	15/2/'17	8/11/'16	15/2/'17
Optimal	1.19 min	1.08 min	4.13 min	3.65 min	7,821 kg	5,754 kg
FCFS	1.61 min	1.71 min	4.30 min	4.01 min	8,147 kg	7,473 kg
Opt/FCFS	0.74	0.63	0.96	0.91	0.96	0.77
Opt vs. FCFS	−26%	−37%	−4%	−9%	−4%	−23%

Table 6.7: Arrivals: results comparison between the two case study days.

	Delay at runway		Taxi time		Fuel consumption	
Day	8/11/'16	15/2/'17	8/11/'16	15/2/'17	8/11/'16	15/2/'17
Optimal	2.38 min	2.36 min	10.18 min	9.59 min	22,074 kg	20,566 kg
FCFS	2.38 min	2.72 min	11.31 min	11.70 min	23,736 kg	24,484 kg
Opt/FCFS	1	0.87	0.90	0.82	0.93	0.84
Opt vs. FCFS	−0%	−13%	−10%	−18%	−7%	−16%

Table 6.8: Departures: results comparison between the two case study days.

	Delay at runway		Taxi time		Fuel consumption	
Day	8/11/'16	15/2/'17	8/11/'16	15/2/'17	8/11/'16	15/2/'17
Optimal	3.55 min	3.44 min	14.31 min	13.24 min	29,895 kg	26,320 kg
FCFS	3.99 min	4.43 min	15.61 min	15.71 min	31,883 kg	31,957 kg
Opt/FCFS	0.89	0.77	0.92	0.84	0.94	0.82
Opt vs. FCFS	−11%	−23%	−8%	−16%	−6%	−18%

Table 6.9: All flights: results comparison between the two case study days.

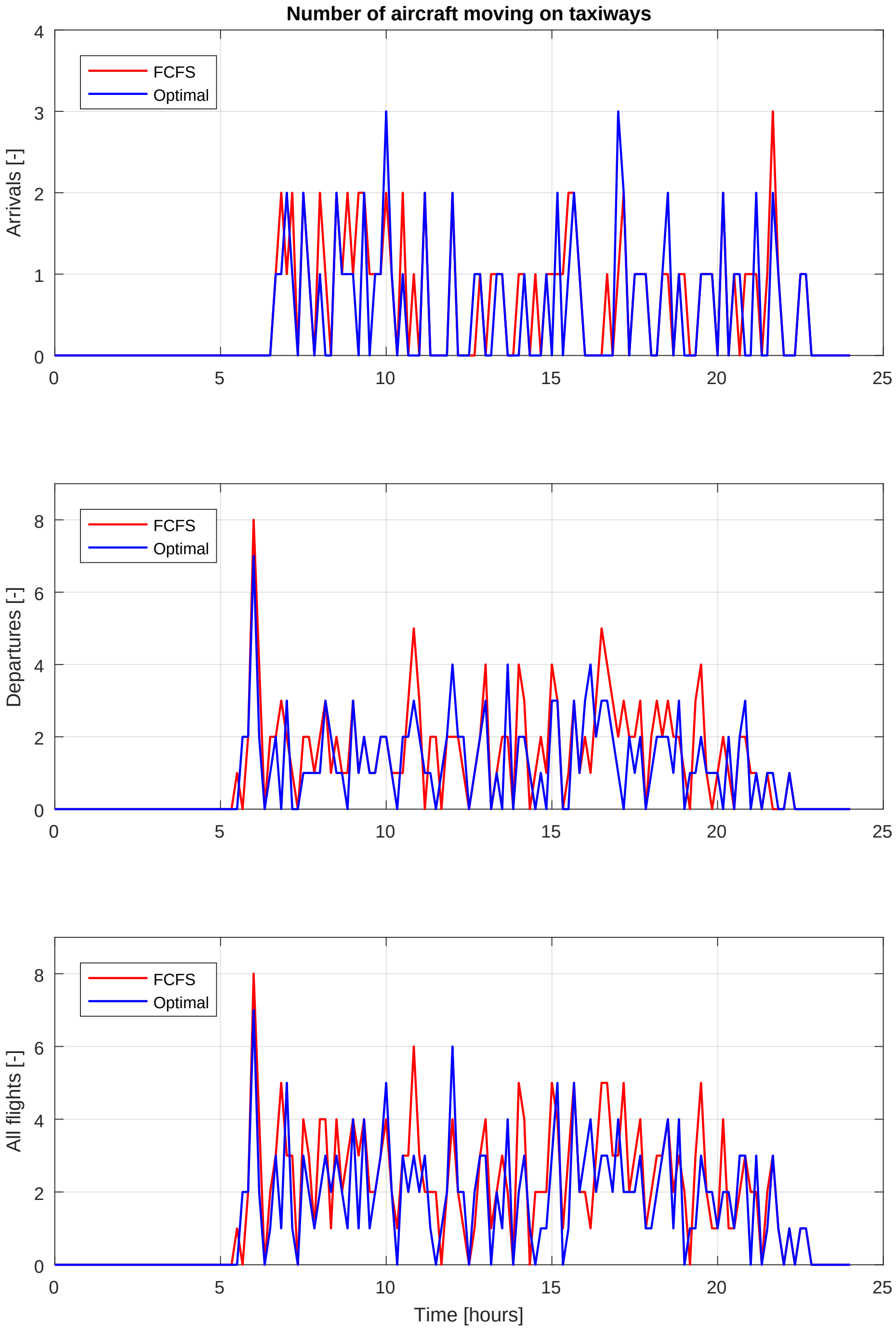


Figure 6.1: Number of taxiing aircraft on 8/11/2016.

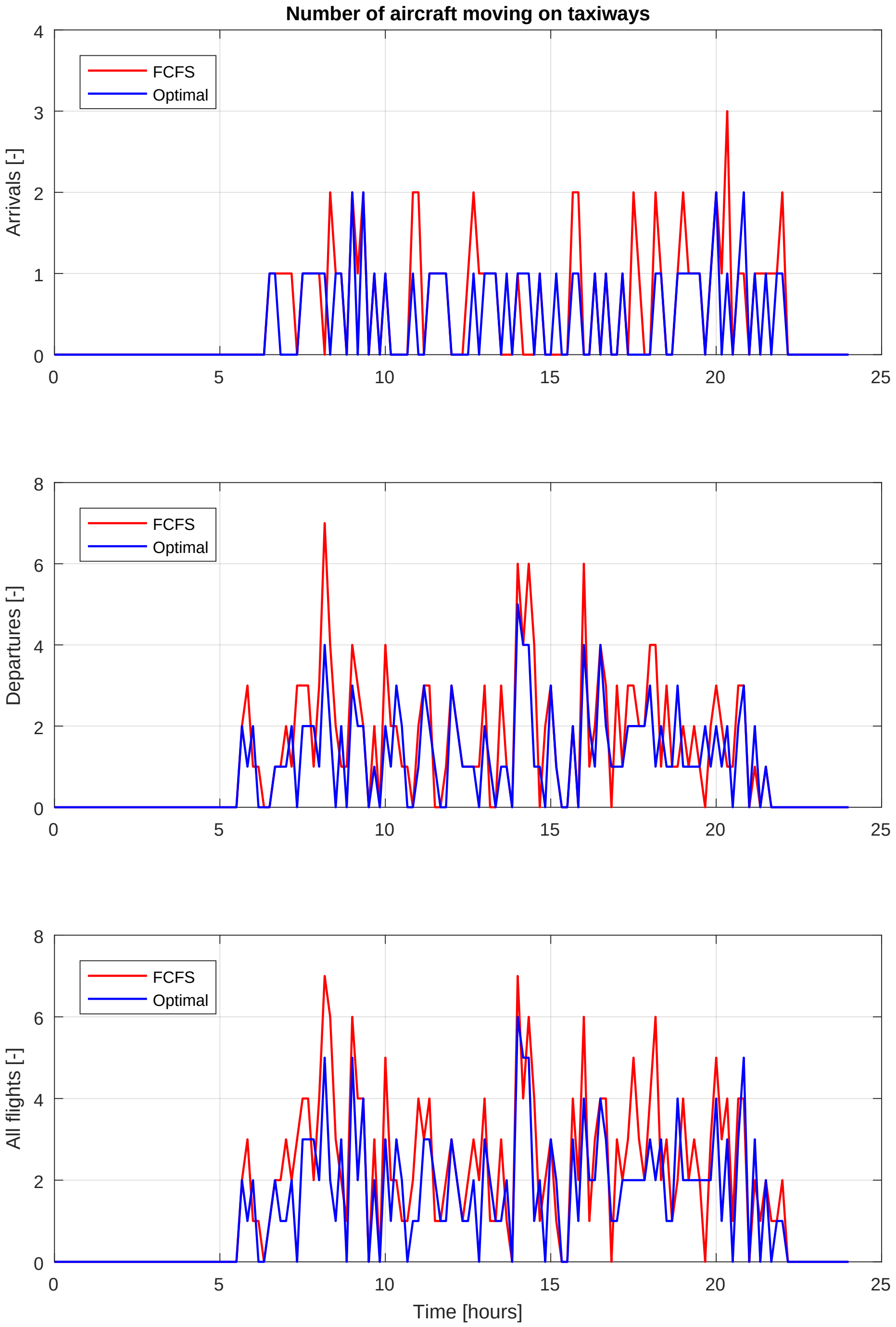


Figure 6.2: Number of taxiing aircraft on 15/2/2017.

7

CONCLUSIONS AND FUTURE DEVELOPMENTS

The ATM improvement is a fundamental objective for The European Union: every day the ATM system controls thousands of flights thanks to centralized and national organizations that cooperate in order to achieve the smoothest, the most efficient and safest air traffic flow. Moreover, in the future the air traffic is expected to grow of 14% in 2023 and 40% in 2035 respect the values of today (2016-2017). The SESAR programme aims to achieve the best solutions in order to increase the airspace capacity, safety, environmental sustainability and affordability, and through it have been reached important results.

The work presented in this thesis tried to understand if, following the European directives, the ATM could have been improved at Linate, one of the most important airport in Italy and the city airport of Milan (Italy). The objective was to design an algorithm capable to help the airport stakeholders, in particular the air traffic controllers, to make decisions on the start-up time, take-off time and landing time, optimizing the global efficiency of the airport system.

With specific tools of the Operational Research, then, the integrated problem DMAN-SMAN-AMAN has been heuristically decomposed in three linked sub-problems in order to have low computational time and adhere as much as possible to the real operative procedures and constraints, and to the objectives of the airport stakeholders.

The comparison of the computational results with what actually happened during a day of November 2016 and a day of February 2017 showed a potential reduction of the mean delay and taxi time, which corresponds to have less airport noise and an increased safety since there would be less aeroplanes running on taxiways, but also to save a considerable amount of fuel, CO_2 and money during the taxiing run. The designed algorithm, then, proved that looking at the global optimization of the airport system and considering all the expectations and constraints of the airport stakeholders through an A-CDM platform, they can be achieved better results respect to the classical First-Come-First-Served approach.

Further analysis should be conducted taking into consideration other days in different operative conditions, possibly running in real-time the algorithm in order to obtain the "actual" values and compare them to the "target" ones computed by the algorithm.

Future developments may comprise a dynamic calculation of the delay along the taxiways and gate re-assignment, in order to achieve a full implementation of the SMAN.

Then could be implemented the "De-icing management tool" defined by SESAR, which could help to obtain more reliable data of the de-icing procedures.

In addition to this, in the future will operate many aircraft in electrical mode when taxiing so their specific constraints/advantages should be analysed.

In order to respect the target landing time computed by the algorithm some optimal logics should be implemented in order to help the approach controller in his current job, maybe with the help of another algorithm.

Finally, an implementation in a bigger airport like Milano Malpensa could be interesting (see Appendix A), because it has two runways and a complex taxiway system where an algorithm like that presented in this thesis could help the controllers to manage the ground handling, trying to reach, as for Linate, a ”more sustainable and high-performing aviation”.

A

HINTS AT ATM OPTIMIZATION AT MALPENSA AIRPORT

As seen in chapter 3, Malpensa airport is the second airport in Italy for passenger traffic and aircraft movements, and the first one in terms of cargo traffic. Moreover, the airport belongs to the same catchment area of Linate airport, and is managed by the same company (SEA). For these reasons some hints and tips are reported in this appendix for the application of the algorithm developed for Linate also at Malpensa.

At Malpensa operate different types of aircraft, from business jet to very heavy liners as Airbus A380. The main topological difference between Linate and Malpensa is that the latter has two main runways instead of one. Looking at figure A.2, they can be noted the two parallel runways of length $3,920$ m, separated of 808 m and by a central taxiway. This taxiway can be run by the aircraft parked at terminal 1 that have to reach the thresholds of runway 35L or 35R. This taxiway, however, can be run only by aircraft that have a wingspan up to 68.5 m, so some of them can request to the air traffic controllers to cross the runway 35L and run the taxiway on the left of runway 35L. In any case, when the right runway is used by landing aircraft, those that must go to Terminal 1 have to cross the left runway in order to reach the assigned parking position. Note that the taxiway on the left is composed of two parallel taxiways, the outer used by aircraft with a wingspan up to 68.5 m, the inner by aircraft with a wingspan up to 80 m.

Since the airport has two runways, there exists specific procedures for the separation of departures and arrivals. The aircraft operating on parallel runways, in fact, have to be separated both longitudinally and laterally. In addition to this, the displacement of the thresholds and the distance between the runways involve other specific constraints. Finally, for noise abatement procedures, the usage of the runways is alternated between the first half of the day and the second one, in a continuous alternation among the days. In practice, the runways are used in a *segregated* mode, with cycling variations on the hours of the day and on the days of the months (see reference [13, ADPMC1-1] for insights).

Everything described before can be formulated as a Mathematical Problem, following the model designed for Linate airport and applying some modifications to the algorithm. For example, considering that the aircraft may cross the left runway, this one should be implemented as a sequence of nodes and arcs in which a landing aircraft cannot stop, and modelling the appropriate precedence constraints between crossing-landing aircraft. Also the limitations on entry/exit points and taxiways should be considered in order to respect the real configuration of the airport.

In addition to this, it could be interesting to relax the limitation on noise abatement letting the algorithm to use both the runways in *mixed* mode, and so compare the two operating mode. To model this thing, however, they cannot be assigned two exit points for departures or two entry points to arrivals (which represent the runways), because in the ground routing problem the algorithm computes the shortest path between only two assigned points. Having, however, added a time-cost variable with the arc usage in the objective function of Step 1, the problem can be solved adding two fictitious nodes to the extremes of the runways and computing the shortest path between the parking position and these nodes and vice-versa: the algorithm will distribute the departures and the arrivals on the two runways in order to limit the usage of only one of them (see figure A.1).

In conclusion, the algorithm developed within this thesis for Milano Linate airport could be applied also at the case of Malpensa airport and, then, to every other airport, studying with detail the specific constraints deriving from the airport topology and procedures, and considering the objectives and needs of the airport stakeholders.

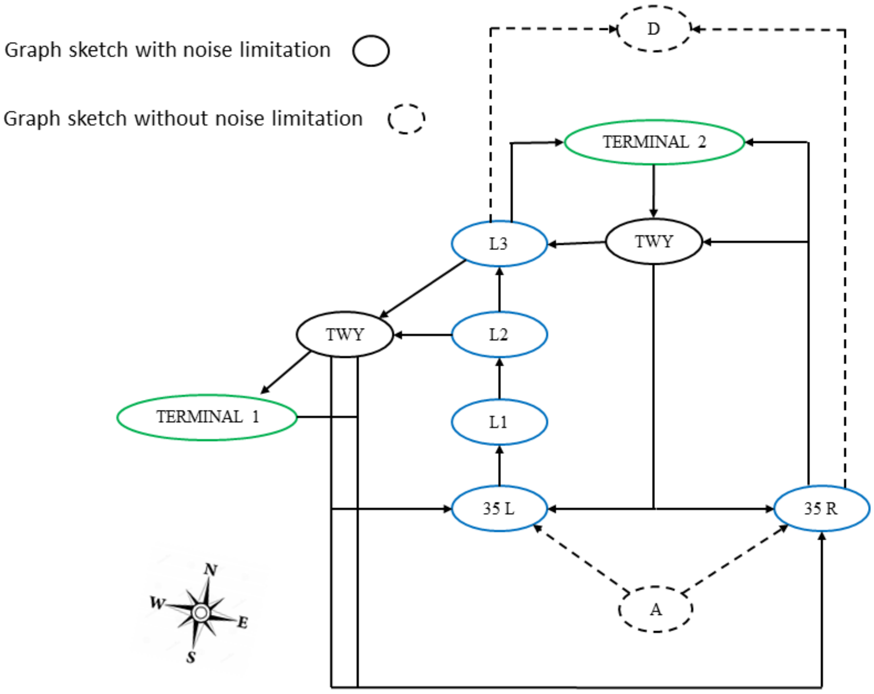


Figure A.1: Sketch of Malpensa airport graph.

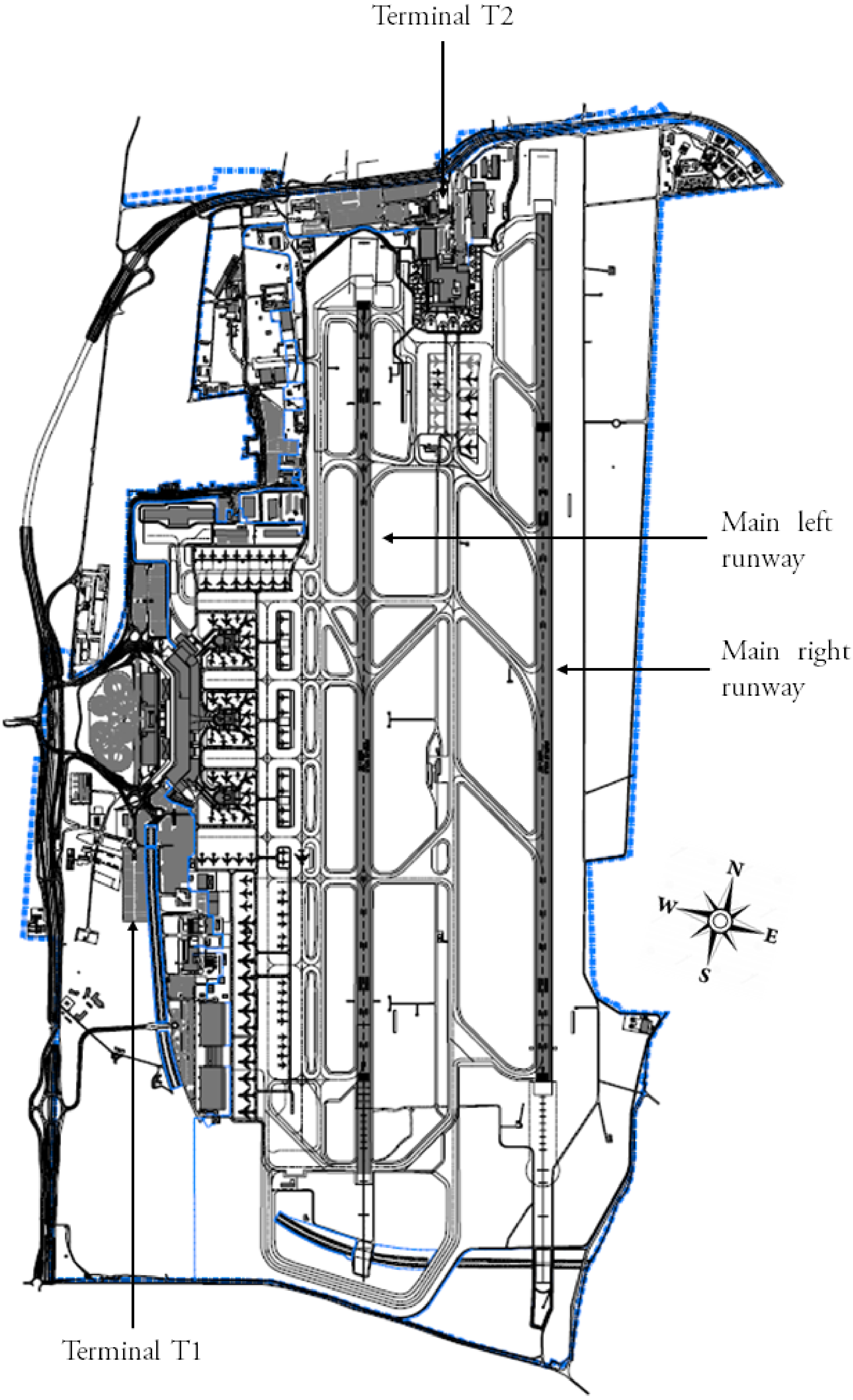


Figure A.2: Map of Malpensa airport. [https://goo.gl/k5fZTJ] (See ADPMC2-1 in ref. [13] for a detailed updated map.)

REFERENCES

[1] L. Adacher, M. Flamini, and M. Masi. "Heuristics for Limiting Pollution in Ground Control Optimization". In: *Recent Researches in Applied Economics and Management - Volume II*. Ed. by Proceedings of the 5th International Conference on Applied Economics Business Development (AEBD '13). 2013.

[2] Ludovica Adacher and Marta Flamini. "Aircraft Ground Routing and Scheduling Optimization". In: *AMSS 16th International Conference on Computer Modelling and Simulation*. Ed. by UKSim. 2014.

[3] British Airways. *Results from a number of surveys of power settings used during taxi operations*. 2006.

[4] Alitalia. *Fleet*. visited on 09.03.2017. URL: `http://corporate.alitalia.it/en/fleet/alitalia-fleet.html`.

[5] Assaeroporti. *Associazione Italiana Gestori Aeroporti*. visited on 03.03.2017. URL: `http://www.assaeroporti.com/`.

[6] Jason A. D. Atkin. "On-line decision support for take-off runway scheduling at London Heathrow airport". PHD Thesis. University of Nottingham, 2008.

[7] L. Bianco, P. Dell'Olmo, and S. Giordani. "Scheduling models for air traffic control in terminal areas". In: ed. by Springer Science+Business Media LLC. 2006.

[8] Maurizio Bruglieri and Alberto Colorni. *Ricerca Operativa*. 2012.

[9] G. Confessore, G. Liotta, and R. Grieco. "A simulation-based architecture for supporting strategic and tactical decisions in the apron of Rome-Fiumicino airport". In: *Proceedings of the 2005 Winter Simulation Conference*. 2005.

[10] SESAR Consortium. *Concept of Operations*. Definition Phase. 2007.

[11] R. Deau, J.-B. Gotteland, and N. Durand. "Airport surface management and runways scheduling". In: *Proceedings of the 8th USA/Europe Air Traffic Management Research and Development Seminar*. 2009.

[12] N. Durand, D. Gianazza, J.-B. Gotteland, and J.M. Alliot. *Metaheuristics for Air Traffic Management*. 2016.

[13] ENAV. *Aeronautical Information - AIP*. visited on 03.03.2017. URL: `https://www.enav.it/sites/public/en/Servizi/areonautical-information.html`.

[14] EPA. *Greenhouse Gas Equivalencies Calculator*. visited on 29.03.2017. URL: `https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator`.

[15] EU. *Single European Sky*. visited on 13.10.2016. URL: `http://ec.europa.eu/transport/modes/air/single-european-sky_en`.

[16] EU and Eurocontrol. *European ATM Master Plan Edition 2*. 2012.

[17] EU and Eurocontrol. *European ATM Master Plan - Executive View*. 2015.

[18] EU and Eurocontrol. *European ATM Master Plan - Implementation View*. 2015.

[19] EUR-Lex. *Traffic management: the creation of the single European sky*. visited on 05.10.2016. URL: `http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=URISERV:l24219`.

[20] Eurocontrol. *ATM Lexicon*. visited on 18.10.2016. URL: `https://ext.eurocontrol.int/lexicon/index.php/Main_Page`.

[21] Eurocontrol. *Eurocontrol seven-year forecast*. URL: `http://www.eurocontrol.int/articles/forecasts`.

[22] Eurocontrol. *Analysis of the information flows at airports with focus on the use of AMAN/ DMAN and CDM*. Version EEC Note No.16/02. 2002.

[23] Eurocontrol. *AMAN Status Review*. Version 0.1. 2010.

[24] Eurocontrol. *Arrival Manager, Implementation Guidelines and Lessons Learned*. Version 0.1. 2010.

[25] Eurocontrol. *RECAT-EU: European Wake Turbulence Categorisation and Separation Minima on Approach and Departure*. 2015.

[26] Eurocontrol, ACI, and IATA. *Airport CDM Implementation Manual*. Version 4. 2012.

[27] Eurocontrol and ENAV. *Local Single Sky ImPlementation (LSSIP) ITALY*. 2015.

[28] Eurocontrol and FAA. *Comparison of Air Traffic Management-Related Operational Performance: U.S./Europe*. 2016. URL: `http://www.eurocontrol.int/news/neck-and-neck-comparing-us-eu-atm-performance`.

[29] Eurostat. *Air transport statistics*. visited on 03.03.2017. URL: `http://ec.europa.eu/eurostat/statistics-explained/index.php/Air_transport_statistics`.

[30] FOCA. *Aircraft piston engine emissions*. 2007.

[31] Robert Fourer, David M. Gay, and Brian W. Kernighan. *AMPL: A Modeling Language for Mathematical Programming*. 2003.

[32] IATA. *Jet Fuel Price Monitor*. visited on 29.03.2017. URL: `http://www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx`.

[33] ICAO. *Air Traffic Management - Procedures for Air Navigation Services - Doc 4444 ATM/501*. 2007.

[34] ICAO. *Airport Air Quality Manual*. 2011.

[35] D. Kyenstad, C. Mannino, P. Schittekat, and M. Smedsrud. *Integrated Surface and Departure Management at Airports by Optimization*. SINTEF ICT, 2013.

[36] D. Kyenstad, C. Mannino, T.E. Nordlander, P. Schittekat, and M. Smedsrud. “Optimizing AMAN-SMAN-DMAN at Hamburg and Arlanda airport”. In: *Proceedings of the Third Innovation Days, 26th – 28th November 2013*. Ed. by SESAR. 2013.

[37] Hanbong Lee and Hamsa Balakrishnan. *A comparison of two optimization approaches for airport taxiway and runway scheduling*. Massachusetts Institute of Technology, 2012.

[38] Alessandro Mascis and Dario Pacciarelli. *Machine Scheduling via Alternative Graphs*. Università degli Studi Roma Tre, 2000.

[39] Dario Pacciarelli. *The alternative graph formulation for solving complex factory scheduling problems*. Università degli Studi Roma Tre, 2000.

[40] Chris N. Potts, Mohammad Mesgarpour, and Julia A. Bennell. *A review of airport runway optimization*. 2009.

[41] Stefan Ravizza, Jun Chen, and Jason A.D. Atkin. *The trade-off between taxi time and fuel consumption in airport ground movement*. 2013.

[42] SEA. *A-CDM*. visited on 09.03.2017. URL: `http://www.milanomalpensa-airport.com/en/airport/a-cdm-procedure`.

[43] SEA. *SEA*. visited on 03.03.2017. URL: `http://www.seamilano.eu/en`.

[44] SESAR-JU. *High performing aviation for Europe*. visited on 13.10.2016. URL: `http://www.sesarju.eu/`.

[45] SESAR-JU. *SESAR Step 1 - Start*. visited on 25.02.2017. URL: `http://www.sesarju.eu/news-press/news/sesar-conops-step-1-approved-1102`.

[46] SESAR-JU. *eATM PORTAL - Master Plan*. visited on 14.10.2016. URL: `https://www.atmmasterplan.eu/atm/`.

[47] SESAR-JU. *Basic DMAN Operational Service and Environment Definition (OSED)*. Version 00.02.00. 2011.

[48] SESAR-JU. *Concept of Operations Step 1*. Version 01.00.00. 2012.

[49] SESAR-JU. *6.8.4-S01V3 Final OSED*. Version 00.01.01. 2015.

[50] SESAR-JU. *Annual Work Programme 2016*. Version 1.1. 2016.

[51] Wikipedia contributors. *List of busiest airports by aircraft movements*. visited on 03.03.2017. URL: `https://en.wikipedia.org/wiki/List_of_busiest_airports_by_aircraft_movements#2015_statistics`.

[52] Wikipedia contributors. *List of busiest airports by passenger traffic*. visited on 03.03.2017. URL: `https://en.wikipedia.org/wiki/List_of_busiest_airports_by_passenger_traffic`.

[53] Wikipedia contributors. *List of the busiest airports in Europe*. visited on 03.03.2017. URL: `https://en.wikipedia.org/wiki/List_of_the_busiest_airports_in_Europe`.