Point Merge: A Feasible Arrival Procedure at Brussels National Airport?

Master Thesis - Aerospace Engineering (2018/19)
August 2019
In Partnership with *skeyes*

Saranne Verhellen

Technische Universiteit Delft

Delft University of Technology

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by

Saranne Verhellen

To obtain the degree of Master of Science at the Delft University of Technology,
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Delft
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PREFACE

In September 2014, I started as a first year Bachelor student at the Faculty of Aerospace Engineering in Delft. Five years later, the page is slowly turning over an incredible, rewarding adventure, beautifully ending with a Master degree in Air Transport & Operations.

In the present report, I am proud to present the outcomes of my thesis work. Such outcomes could not have been achieved without the help, support and guidance of many people.

First of all, I would like to thank Alex Van Biervliet, senior manager at *skeyes*, who took me under his supervision. His confidence in my work encouraged me to always push further the boundaries of knowledge and curiosity. I therefore would like to thank him for welcoming me in his team and giving me the opportunity to confirm my passion for the air traffic operations.

From an academic point of view, the guidance and support provided by my thesis supervisor, Paul Roling, and the assistant professor, Miheala Mitici, allowed me to clearly organise my work and efficiently achieve my end goals.

Regarding the project successful execution, I would like to thank Stéphane Thill and Juraj Grivna, the two cartographers who helped me translating conceptual ideas into professional mappings, as well as Robert Falk (*EUROCONTROL*) and Thierry Champougny (*EUROCONTROL*), who didactically provided me support to develop the simulation model and run the fast time simulations. The controllers Marc Lamotte, Carlo Vandersmissen and Filip Bettens, have been reference persons all along the thesis project. I therefore would like to thank them for their expertise, criticality and honest opinions. Last but not least, a big thank you to my colleagues for their warm welcome, guidance and availability. It was a great pleasure to be integrated in such a team.

Mom, Dad, thank you from the bottom of my heart for your inexhaustible trust in my capabilities and your love. Matthieu, my other half, not mentioning you would be terribly ungrateful from me. Thank you for always being there, motivating me during harder times and never giving up on me.

Saranne Verhellen
Steenokkerzeel, August 2019 [1]

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[1] *Cover Image:* Brussels Airport Control Tower - Belgocontrol)
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LIST OF ABBREVIATIONS

ACC	Area Control Centre
AMAN	Arrival Manager
AMSL	Above Mean Sea Level
APP	Approach
ATC(C)	Air Traffic Control (Centre)
BADA	Base of Aircraft Data
CANAC	Computed Assisted National Air Traffic Control Centre
CAPAN	Capacity Analyser
CDO	Continuous Descent Operation
CDR	Conditional Route
CTA	Control Area
CTR	Control Zone
EBBR	Brussels National Airport (ICAO code)
EEC	*EUROCONTROL* Experimental Centre
ETA	Estimated Time of Arrival
FABEC	Functional Airspace Block Europe Central
FDPS	Flight Data Processing System
FIFO	First In First Out
FIR	Flight Information Region
FL	Flight Level
FUA	Flexible Use of Airspace
IAA	Irish Aviation Authority
IAF	Initial Approach Fix
IATA	International Air Transport Association
ICAO	International Civil Aviation Authority
IFR	Instrument Flight Rule
ILS	Instrument Landing System
KIAS	Knots Indicated Airspeed
LoA	Letter of Agreement
LT	Local Time
MILP	Mixed Integer Linear Programming
PM(S)	Point Merge (System)
RDPS	Radar Data Processing System
RTS	Real Time Simulation
RWY	Runway
SAAM	System for Traffic Assignment and Analysis at Macroscopic Level
SID	Standard Instrument Departure
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route
STATFOR	Statistics & Forecasts
TMA	Terminal Manoeuvring Area
TRA	Temporary Restricted Area
TSA	Temporary Segregated Area
UAC	Upper Area Control Centre
UNL	Unlimited
UTC	Coordinated Universal Time
WTC	Wake Turbulence Category
XMAN	Extended Arrival Manager

SUMMARY

In response to the need of increasing the terminal airspace capacity at Brussels National Airport (EBBR), the concept of point merge (PM) has been identified as a potential solution. PM is a new air traffic control technique aimed at facilitating the merging of arriving traffic. It enables continuous descent operations (CDO) and the extensive use of lateral navigation. The working principle of PM is based on aircraft flying circular arcs – sequencing legs - before being turned towards a common merge point. These circular arcs are introduced as area navigation (RNAV) routes and consist, together with the merge point(s), of the route network associated to the concept of PM, the point merge system (PMS).

Although this concept has proven to be efficient at several airports all around the world, a specific investigation was required for EBBR to evaluate what operational benefits could be achieved given the dense and complex environment of the airport. The present study objective was therefore to demonstrate the feasibility of PM in the terminal airspace of EBBR, looking at system capacity, sequencing time, vertical profiles, impact on controller work, environment and mileage.

To reach such an objective, the study has been broken done into five different phases. First, research has been carried out to fully understand the problem statement, identify the requirements in terms of safety, efficiency and punctuality at EBBR, as well as to become familiar with the concept of PM. Once done, the concept development phase has been launched during which one specific PMS has been designed for each possible runway configuration at the airport – 25L/R, 19, 01, 07L. Next, the developed systems have been tested through fast time simulations with the *EUROCONTROL* simulation tool SAAM. In order to satisfy all operational requirements and match reality as close as possible, a specific simulation model has been developed. The simulation model has been built as a mixed integer linear programming problem. The fourth phase of the study was the solution design phase during which the simulation results have been processed, analysed and critically interpreted. By comparing the operational performances of the current arrival procedure - radar vectoring - with those that could potentially be achieved with a PMS, conclusions on the feasibility of PM at EBBR could finally be established. In total, six different parameters have been investigated to make sure all operational elements required for a complete conclusion were covered. A preliminary safety check has also been written.

- System capacity

  The main justification for the implementation of a PMS at EBBR lies in the system capability to maximise the runway capacity throughput with current staffing levels. The capacity results showed that the system capacity of every PMS could be as high as the corresponding declared runway capacity. Using a PMS at EBBR therefore has the potential to maintain, if not maximise, the current runway capacity throughput during long periods of time and with high accuracy.

- Sequencing time

  The only way to maintain a continuous pressure on the runway capacity throughput is to have aircraft always ready to land. With PM, this is done by making aircraft fly along the sequencing legs prior to turning them towards the merge points. The simulation results showed that most of the time, only the first half of the legs is flown when aircraft have to extend their trajectory along the sequencing legs. In other words, the sequencing time is minimised, resulting in enhanced flight predictability.

- Vertical profiles

  In a complex terminal airspace such as the one around EBBR, it is difficult to offer to a vast number of arrivals the possibility to perform CDO. PM, contrarily to radar vectoring, ensures the flight of CDO in the altitude layers ranging from the sequencing legs to the merge points. Although optimised vertical profiles are only performed in specific altitude layers, a reduction in fuel consumption, noxious emissions and noise is to be expected at low levels.

- Controller workload and efficiency

Safety is the core driving force in aviation. With a PMS at EBBR, it can be assured that safety would be maintained based on several contributors. First, the clear system structure and procedure systematisation would lead to a reduction in controller workload. The number of instructions required to guide the arrivals from the sequencing legs to the merge points – two only - is considerably lowered compared to what is currently done with radar vectoring. This inevitably results in a decrease in frequency occupancy. Reduced confusion and risk of misunderstanding, as well as a better situational awareness for the controllers and the possibility to anticipate more efficiently the traffic evolution, are other positive consequences of fewer messages between the controllers and the flight crews. Finally, the more intuitive and straightforward procedure introduced with PM is expected to standardise the controller performances.

- Mileage

  As testified by this analysis, using a PMS during low traffic loads and/or complexity is not optimal. If the traffic situation allows it, shortcuts along the PMS routes should be made possible to increase the overall system efficiency. In other words, the PMS at EBBR would only have an added value during periods of medium to high traffic loads and complexity.

- Track dispersion and overflown areas

  From the structure of a PMS, all flight trajectories are contained in a path envelope, which minimises the lateral dispersion of flights coming in to land. Beyond the merge points, all aircraft are flying along the same route segments at similar speed and altitude to maintain the most efficient landing sequence, as well as to reduce the number of inefficient manoeuvres at low levels. The flight trajectories along the designed PMS and radar vectoring are approximately covering the same areas. A priori, introducing PM at EBBR would have non perceivable impact on the Belgian population.

- Preliminary safety check

  The introduction of a PMS in the terminal airspace of EBBR is likely to impact controllers, current procedures and systems. Controllers trainings and refresher courses, communication to stakeholders, as well as system updates, are some of the actions required for an optimal use and implementation of PM, while maintaining satisfactory level of safety.

Following the outputs of the different simulation analyses, the applicability of a PMS in the terminal airspace of EBBR has been demonstrated positive. To further complete this conclusion, it was necessary to have a look at the conditions for optimal system performances;

- PM should be used in combination with an arrival manager (AMAN/XMAN).
- Negotiations should be opened with military partners. This is necessary for an optimal use of the PMS for runways 25L/R and 19, since these systems run within the TRA North Alpha, Two and Three. Modifications of the current flying windows are needed.
- Involvement of neighbouring ATC units to satisfy the pre-requisite of pre-sequencing and altitude feasibility is required.
- The so far investigated PMS should be validated by airspace procedure design experts and through real time simulations.
- Adjustments of the current operational environment at EBBR (controlled airspace boundary and EBBR standard terminal arrival routes) are required.
- A route network assessment is required to verify SID and STAR interactions of all controlled Belgian airports after the implementation of PM at EBBR.
- Clear definitions of the standard working methods to efficiently operate the PMS must be established.
- Contingency procedures in case of non-nominal events for which the standard working methods cannot be applied must be carefully derived (e.g. emergency, sequencing leg run-offs, adverse meteorological events, technical failures, non RNAV equipped aircraft, missed approaches, runway closure). These mainly include speed control, radar vectoring and alternative routes.

To give prospective to the study, the steps required for a successful implementation are hereafter listed. Accomplishment of these tasks is only required if PM is launched as a project at EBBR;

- Implementation plan (high level planning established at approximately 2 years)
- Real time simulations
- System updates (EUROCAT, AMAN, aircraft flight management system, controller display screen)
- Safety assessment
- Controller training programme including working methods for the transfer of responsibility between ACC and APP, and non-nominal conditions. Appropriate trainings and refresher courses are indispensable.
- Communication to stakeholders

1

INTRODUCTION

Airline operators, airport authorities and air navigation service providers are operating in a tense environment where requirements in terms of capacity, efficiency and safety are always getting more stringent. It goes without saying that all these stakeholders have different priorities with respect to their operations, increasing the complexity of the system. The most important priorities for the airline operators are high levels of predictability in their operations, the decrease in operational costs and the minimum investment in new navigational equipment. On the other hand, the air traffic control units and ground operators are aiming at achieving maximum returns with respect to efficiency, capacity and workload, if possible with a minimum initial investment.

With the continuous growing of air traffic demands all over the world, the accomplishment of such objectives becomes challenging. In Europe, the urgency to develop new strategies to cope with future aviation challenges has been made clear. If the current procedures used to handle the air traffic at European airports is not revised, 120 million passengers will be unable to fly, 1.9 million flights will be unable to land and more than 20 airports in Europe will have reached their maximum capacity by 2035, according to the European Commission [1].

Brussels National Airport (EBBR) is no exception to it. To efficiently accommodate the future growth in air traffic demands and prevent saturation of the terminal airspace capacity, new arrival procedures have to be established. On possible solution identified by *skeyes* - the Belgian air navigation service provider - is the concept of point merge (PM).

Prior to getting to the heart of the matter, the problem is first clearly stated in Section 1.1. In Section 1.2, the thesis project scope and objective are formulated. Finally, the methodology followed to meet the thesis objective is presented in Section 1.3.

1.1. PROBLEM STATEMENT

At EBBR, the progressive merging of arrival flows into a landing sequence is currently performed through the use of open-loop vectoring. Open-loop vectoring is far from being the best control strategy in terms of capacity, controller workload and environmental impacts, especially during medium to high traffic loads and/or complexity. The dense and complex terminal environment of the airport further jeopardises efficient operations. Hereafter, the current situation is summarised in a few points;

- Radar vectoring requires the issue of a large number of heading, speed and altitude tactical instructions to achieve path stretching and shortening. This results in an intensive use of radio telecommunication, leading to high frequency occupancy.

- Although this method is highly flexible, it results in high workload for both the flight crews and the controllers.

- Flight crew and controller situation awareness is poor due to a lack in flight predictability. Some flight management system functions become unavailable.

- Inefficiency in the ground system rises. Ground-based tools involving trajectory prediction cannot be updated appropriately since the time when/location where aircraft will resume their normal navigation is not known.

- In dense and/or complex environments, controllers tend to follow a strategy giving themselves more time and margins to implement and fine tune the sequence. This often results in aircraft flying low and slow, leading to non-optimal vertical profiles. Noise levels and noxious emissions are not minimised.

1.2. STUDY SCOPE & OBJECTIVE

PM is a flow integration technique developed by *EUROCONTROL* enabling extensive application of area navigation (RNAV) for arrivals in terminal airspace. It is based upon aircraft flying a quasi-arc at a specific altitude and speed. PM has already proved to be efficient at several airports around the world and for this reason, *skeyes*, has judged interesting the evaluation of the feasibility of such a strategy at EBBR.

The objective of the project was therefore to evaluate the feasibility of PM at EBBR, looking at mileage, system capacity, sequencing time, environmental impacts, and controller workload.

Out of the study scope are the training of the controllers, the technical aspects for the implementation of a point merge system and the contingency procedures to deal with non-nominal events. Restructuring the airspace above the territory of Belgium also falls behind the scope of the study as the main objective is to see if point merge is a feasible strategy to sequence the arrivals taking into account the current airspace structure.

1.3. METHODOLOGY

To optimise the quality of the study findings, the study has been broken down into five different phases. Hereafter, these phases are elaborated.

1.3.1. LITERATURE STUDY

During the first phase of the project, the problem statement has been fully understood and all necessary knowledge to initiate the project acquired. While the problem statement is formulated in Section 1.1, the concept of PM is detailed in Chapter 3.

1.3.2. CONCEPT DEVELOPMENT

After having identified the requirements in terms of capacity, efficiency and safety for the air traffic operations at EBBR, different systems have been designed. In total, four systems have been designed, one for each possible runway configuration – 25L/R, 19, 01, 07L. To deliver robust systems to be later tested and validated, the controllers, ACC and APP managers have been regularly consulted. The investigated PMS are presented in Chapter 4.

1.3.3. SIMULATION MODEL DEVELOPMENT

The feasibility of the developed systems has been assessed through fast time simulations (FTS). The reason to choose FTS above real time simulations (RTS) was mainly to optimise resources. FTS allow to draw preliminary conclusions on the validity of airspace design projects at low cost and fast time.

For the present study, SAAM revealed to be the most appropriate simulation system. This system has been developed by *EUROCONTROL* to support the design and simulation of strategic airspace scenarios [2]. SAAM stands for system for traffic assignment and analysis at a macroscopic level. The functionality of the system which was of interest for the present study is the possibility to design terminal airspaces and simulate the impacts of new procedures on several parameters. The database of SAAM is complex allowing deep and realistic analyses. Updates are regularly performed, and local procedures and regulations are easily inserted in the tool database.

Approximately twenty-five sessions have been organised with *EUROCONTROL* to set up, develop, refine and validate the simulation model. The simulation objective and model assumptions are provided in Chapter 5.

1.3.4. RESULT ASSESSMENT

Once the simulation model has been verified, the next step was to generate results and subsequently analyse them. Mileage, system capacity, sequencing time, vertical profile, impact on controller work and environment, are the parameters assessed during the result analysis phase.

The simulation results have continuously been subjected to the critically and expertise of controllers and airspace design experts. Carefully interpreting the gathered results was of utmost important due to the nature of the simulations. Feedback has been received during three sessions.

In parallel to the analysis of the results, a preliminary safety check has been carried out. This safety check does not replace in any case the safety assessment required before implementation. Highlighted in the safety check are hazards resulting from the implementation and use of a PMS at EBBR, as well as possible mitigation measures.

All analysis findings, together with the preliminary safety check, are presented in Chapter 6.

1.3.5. CONCLUSIONS

Based on the simulation results and their operational interpretation, conclusions on the feasibility of a PMS at EBBR have been drawn. These conclusions are formulated in Chapter 7, together with the condition for optimal system performances and recommendations for future work.

2

BRUSSELS NATIONAL AIRPORT

Prior to designing new procedures to be implemented in the Belgian airspace to further enhance air traffic operations, a thorough understanding of the airspace structure (Section 2.1) and the current arrival procedure at EBBR (Section 2.2) is required.

2.1. BELGIAN AIRSPACE

In Section 2.1.1, a high-level description of the Belgian airspace is provided. This is followed in Section 2.1.2 by the description of the strategy used in Belgium for the sharing of airspace between civil and military air traffic service units.

2.1.1. AIRSPACE STRUCTURE

The area of responsibility of *skeyes* is defined by the boundaries of Brussels FIR above Belgium and the Grand-Duchy of Luxembourg. As indicated by its name, a flight information region is an airspace of defined dimensions within which flight information service and alerting service are provided. Within Brussels FIR, two types of airspace are distinguished, public and military airspace. The basic structure of these airspaces is the same. Around each airport - public or military, a control zone (CTR) is established to control the landings and take-offs. Around the CTRs, terminal manoeuvring areas (TMA) are built in which departing and arriving traffic of a specific airport is handled. Next to the CTRs and TMAs, other areas such as other civil and military control areas, low flying, prohibited, restricted and danger areas, are put in place. In each of these areas, different requirements in terms of type of flight allowed, separation, communication, service, speed, and clearance, are attributed [3].

A CTR is a controlled airspace extending upwards from the surface of the Earth to a specific upper limit - 1,500 ft for the CTR of EBBR. Each public and military, controlled airport possesses its own CTR, which is centered around it. In a CTR, the traffic coming to land at an airport or departing from it is controlled via a control tower.

Around the CTRs, TMAs are found. In these areas, arriving and departing aircraft are respectively handled from en-route to tower control and inversely. Each airport may have several TMAs to ensure an optimal control of the traffic taking into account the airspace available, the aircraft capability and the directions of the main in- and outgoing streams. The design of the TMAs varies in terms of altitude, shape and location.

Next to the CTRs and TMAs, control areas (CTA), temporary reserved areas (TRA) and segregated areas (TSA) are established. These areas are portions of the airspace in which the traffic is controlled either by *skeyes* - in the civil CTAs, or by military control instances - in the military TRAs and TSAs. Elsewhere between 4,500 ft and FL195, the traffic is in the Brussels Lower CTA (LCTA).

Additionally to the different controlled areas aforementioned, transponder mandatory zones and radio mandatory zones are put in place. In these areas, the carriage and operation of transponder and radio equipment, respectively, are mandatory during the night. These areas correspond to Brussels FIR from the surface of the Earth to FL195.

Furthermore, prohibited, restricted and danger areas have been identified all over Belgium. These areas are airspaces of defined dimensions, above the land areas or territorial waters of the State of Belgium, within which the flight of aircraft is restricted in accordance with certain specified conditions. All arrival and departure procedures have to be designed in a way as to circumvent these prohibited zones. The most constraining area for the air operations at EBBR is the area centered on Brussels City. This area cannot be overflown below FL60, except if instructed by ATC.

Finally, low flying areas are portions of the airspace reserved for general aviation, aerial sporting and recreational activities. Although the altitude of the low flying areas around the airport does not exceed FL75, its proximity to the airport is not to be neglected, especially when new STARs and SIDs need to be designed. The low flying areas are only activated when the military are not using their airspace.

2.1.2. AIRSPACE USE

To get a better understanding of how the responsibilities over the Belgian territory are shared between civil and military air traffic service instances, and how flexibility for the daily operations is achieved between these two units and Maastricht UAC, two Letters of Agreement (LoA) have been consulted. A LoA defines the coordination procedures to be applied between two or more air traffic control units with conflicting interests.

FLEXIBLE USE OF AIRSPACE

As indicated in the title, the *LoA on Flexible Use of Airspace (FUA)* describes how the concept of FUA has to be applied within the airspace placed under the responsibility of the State of Belgium. FUA is a concept developed by *EUROCONTROL* and described by ICAO. As from December 2005, common rules for the flexible use of airspace have been set and must be applied by all Member States within the Single European Sky. Amongst others, these rules have as objective to ensure a better cooperation between civil and military entities responsible for air traffic management that operate in the airspace under the responsibility of Member States. Different levels of airspace management procedures exist. These levels range from strategic to tactical. FUA Level 1 covers the strategic planning of the operations. The planning is done yearly by the State. FUA Level 2 corresponds to the level at which pre-tactical operational decisions are taken with respect to the planning. The planning strategically derived is adjusted before each day by the airspace users, *skeyes* and the Belgian Air Component in the present case. FUA Level 3 includes all tactical decisions that are taken on a daily basis to optimally adjust the planning to the traffic situation. In Belgium, a FUA Level 3+ has been established to further increase the planning flexibility to three hours before the operations.

As stated in the LoA, "*The Agreed Practices (...) aim to establish an optimum and balanced use of the airspace with regard to flight efficiency, military mission effectiveness and ATC-capacity/throughput, while ensuring the required levels of safety.*" In other words, priorities with regard to the booking and use of the airspace have to be established. More concretely, the agreed procedures are only applicable to the airspace above FL105.

On a strategic level, military flying windows and orange slots have been put in place to ease the planning of the operation in the long-term. A military flying window is a time period during which the military training activities can be planned, and therefore during which the military airspace is by definition not available for civil operations.

- The Winter Flying Window (01 November till 28/29 February):
  - MON: 09:00-21:30 (Night 1)
  - TUE: 09:00-21:30 (Night 2)
  - WED: 08:30-17:30
  - THU: 08:30-17:30
  - FRI: 08:30-17:30
- The Summer Flying Window (01 March till 31 October):
  - MON: 08:30-24:00 (Night 1)
  - TUE: 08:30-24:00 (Night 2)
  - WED: 08:30-17:30
  - THU: 08:30-17:30
  - FRI: 08:30-1:30

An orange slot is a timeslot during which Brussels ACC and Maastricht UAC are facing operational constraints that jeopardize their optimal operations. Priority within the military used airspace may be claimed by Brussels ACC and/or Maastricht UAC, only if supported by collaborative decision making (CDM). Any other cases will remain under the decision of Belgian Air Component to attribute priorities to civil operations during military flying windows or not. The portions of the airspace that can be temporarily reserved for civil use are:

- TRA West
- TRA North
- TRA South
- TRA/TSA N1 (Brussels Area)
- TRA/TSA S5 (Neufchateau Aera)
- TRA/TSA S6 (Durbuy Area)

The above timing are provide in local time (LT). If no night flight is planned, the flying window is reduced to 08:30-17:30. Furthermore, night flights are never planned between the 1^{st} of July and the 31^{st} of August.

In case of modifications with respect to the baseline practices, an Airspace Use Plan (AUP) has to be formulated to communicate the daily decision on the temporary allocation of the airspace for a specific period of time.

MILITARY AND CIVIL OPERATIONS

Another relevant LoA to considered is the *LoA between Belgocontrol and Belgian Air Component* [1]. All the procedures described are additional to those described in national and international official documents regulating responsibility share. Focus of this LoA is on the delegation of the responsibility for the provision of air traffic services (ATS) between the military air traffic control center (ATCC) and Brussels ACC/APP, between Kleine Brogel (EBBL) APP and Brussels APP, and between Beauvechain (EBBE) APP and Brussels APP. The goal is to identify under which circumstances, at what time of the day, and which part of the airspace is shared between *skeyes* and the *Belgian Air Component*.

Share of the airspace is not only to accommodate civil air operations. For instance, Brussels TMA 4 extending upward from FL095 to FL145 can be claimed by the ATCC during ATCC operating hours. On request, the ATCC supervisor can obtain the delegation of the responsibility of this area from 4,500 ft to FL095. Regarding the use of military airspace for civil operations, some common practices also exist. During the peak hours, i.e. from 08:00 to 09:30 LT and from 17:30 to 20:00 LT, as well as outside the hours of military activity, Brussels CTA East 6 is controlled by *skeyes*, expect if the amount of traffic is limited, and that this airspace is no longer necessary for the efficient handling of traffic by Brussels APP/ACC. Another relevant example to consider is the share of the Tessenderlo area. During EBBL operational hours, between 08:00 and 09:30 LT, as well as between 17:30 and 20:00 LT, and only if runway 23 is in use at EBBL, the responsibility for the provision of ATS within the Tessenderlo area shall be delegated to Brussels APP. All of this information can be consulted in the Belgium and Luxembourg AIP [3].

In addition to the guidelines in terms of airspace share in the *LoA between Belgocontrol and Belgian Air Component*, conditional routes (CDR) are another option to optimise and increase the flexibility of the civil and military operations. A CDR is a pre-defined route in the airspace only available at pre-defined periods of time under specific conditions to complete the permanent route network. Three categories of CDRs exist. CDRs 1 are permanently planable CDRs during the times published in the AIP. CDRs 2, non-permanently planable CDRs, are CDRs whose availability is established daily based on conditions published in the European Airspace Use Plan (EAUP). The last category consists of non-planable CDRs. CDRs 3 are ATS routes that can only be flown following a controller clearance. It is not possible to plan the use of such CDRs [3].

2.2. ARRIVAL PROCEDURES

In Section 2.2.5, the current arrival procedure in place at EBBR is explained. Prior to that, the runway system and the traffic presentation at the airport are respectively presented in Sections 2.2.1 and 2.2.2. Finally, relevant operational concepts related to the arrival strategy at the airport are defined in Section 2.2.3 to Section 2.2.12.

2.2.1. RUNWAY SYSTEMS

As can be seen from Figure 2.1, the airport possesses three runways out of which two are parallel and the third one diagonally crosses the other two. Runways 25L and 25R are considered as independent parallel runways - even though they are not perfectly parallel. As the distance between these two runways is larger than 4,300 ft, the runways can be simultaneously operated as stated by ICAO [4].

- Simultaneous dependent arrivals: In reality, the aircraft are expected to land on runway 25L until the maximum runway capacity throughput is reached. After that, they will be sent onto runway 25R, which is an offload for runway 25L. Therefore, simultaneous approaches can take place when the traffic load increases. In addition to that, military traffic, helicopters from the federal police, cargo and aircraft whose assigned stand is at the north of the airport infrastructure can be sent to runway 25R as well. This traffic can either come from the west or east. To ensure safe and efficient simultaneous dependent operations, aircraft landing on the same runway must be at least separated by 3 NM (see Section 2.2.7). Aircraft coming to land on two different runways must be separated at all time by 2 NM.

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[1] *Belgocontrol* is still referred to on some official documents.

- Simultaneous independent arrivals: This operational model is only activated during high arrival peak periods. When simultaneous independent approaches are allowed on runways 25L and R, the traffic landing on runway 25L is independently handled from the traffic landing on runway 25R, so that two distinct landing sequences are built. Aircraft landing on the same runway must be at least separated by 3 NM (see Section 2.2.7). No separation with the aircraft landing on different runways is required. In other words, touch down can occur on runway 25L and 25R simultaneously.

Runways 01, 19 and 07R allows single runway operations. Runway 07L is only used in case of emergency or other non-nominal conditions. Runways 07L and 07R are never used simultaneously for arrivals.

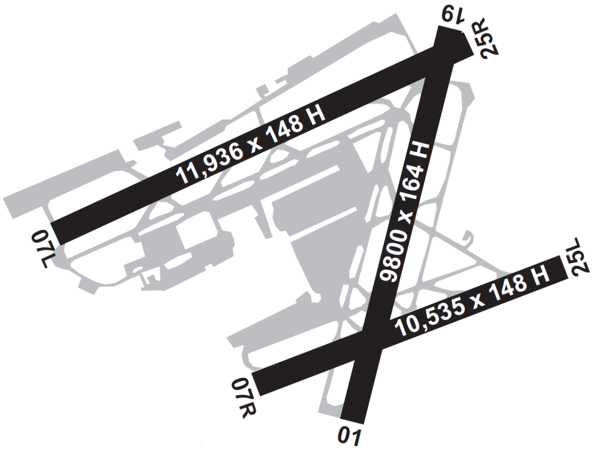

Figure 2.1: EBBR runway configuration. Distances are given in feet [5].

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Table 2.1: EBBR capacity (2018) [7] - Confidential data.

Runway configuration	**Runway for**		**Maximum capacity throughput**			**Declared capacity**		
	DEP	**ARR**	**DEP**	**ARR**	**Movements**	**DEP**	**ARR**	**MVT**
RWY01								
RWY19								
RWY07L								
RWY07R								
RWY25L								
RWY25R								
RWY01/07R								
RWY25L/R								
RWY25R/19								

……

2.2.2. TRAFFIC PRESENTATION

At EBBR, the traffic arrives via five main streams delivered in the Belgium FIR by five different ATC unit centres, as presented in Figure 2.2 and Table 2.2.

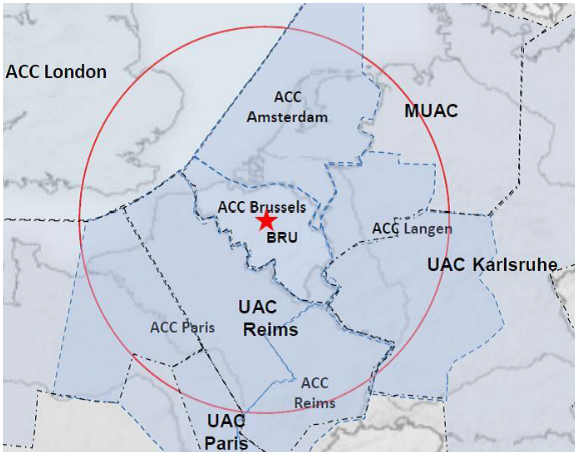

Figure 2.2: Neighbouring ACC/UAC [8].

Table 2.2: Traffic presentation per upstream ACC/UAC [8].

ACC/UAC		Arrivals
ACC Langen	**(North east & east)**	33%
UAC/ACC Paris + Reims	**(South)**	23%
Maastricht UAC	**(South east)**	20%
UAC/ACC London	**(West)**	12%
ACC Amsterdam	**(North)**	11%

When comparing the percentage of arrivals coming from the different directions (see Table 2.2), it is easy to identify that the most dense streams are the southern and eastern ones.

A last point interesting to discuss is the traffic distribution along the day at the airport. There are two arriving peak periods at EBBR. The morning peak takes place between 07:30 and 09:30 LT. The evening peaks starts at 18:00 and lasts until 20:00 LT.

2.2.3. STANDARD TERMINAL ARRIVAL ROUTES

As soon as an aircraft leaves the en-route control (MUAC) to land at EBBR, the control is taken over by Brussels ACC. The area of responsibility of Brussels ACC starts below the division flight level FL245 and extends to FL75. At FL75, the safety of the traffic is placed under the responsibility an APP controller. The main tasks of the ACC controllers is to meter the traffic, maintain separation minima in between the aircraft, as well as to build an efficient landing sequence. To facilitate these tasks, standard terminal arrival routes (STAR) have been introduced in the terminal airspace of the airport.

As indicated by its name, a STAR is a standard RNAV (area navigation) route along which aircraft fly the moment they leave the en-route phase to come landing at an airport. They are defined by navigational aids, such as very high frequency omnidirectional radio ranges, distance measuring equipment and non-directional beacons [9]. Navigating along standard routes is supported by the aircraft flight management system (FMS) which provides points along the routes to fly to. The last point constituting the STARs are initial approach fix (IAF). At EBBR, there three IAFs; KERKY, FLO and ANT. Along these routes, speed and level restrictions are imposed to the incoming flows in order to prevent conflicts between aircraft. Please note that the set of STARs changes as a function of the runway system in use. All the STARs of EBBR can be consulted in the Belgium and Luxembourg AIP [3].

The same concept of standard routes also exist for departing traffic. These routes are referred to as standard instrument departures (SID). The STARs and the SIDs must be designed in a way as to provide enough vertical separation by design at hot-spots where routes cross each other. When designing standard routes, several parameters have to be taken into account. The airspace structure, and in particular military, prohibited, restricted and danger areas have to be avoided. The interactions with the SIDs and STARs of the other controllers airports in Belgium also have to be carefully assessed. As a matter of fact, over the small territory of Belgium, there are five public airports where in- and outgoing traffic is controlled by *skeyes* (Antwerpen - EBAW, Oostende - EBOS, Charleroi - EBCI, Liège - EBLG and Brussels National Airport - EBBR), and one aerodrome at which only terminal services are provided (Kortrijk Airport - EBKT). Having these frequently used airports on such a small area is complex.

2.2.4. Holding Patterns

At the end of each STAR at EBBR - KERKY, FLO and ANT, a circular holding stack is present. These holding stacks can be visualised in Figure 2.3. By definition, an holding stack is used when the TMA capacity reaches its upper limit. They are designed in a way as to absorb delays by extending the aircraft trajectory prior to landing. If the incoming aircraft arriving at one of the IAFs does not receive the clearance from Brussels ACC to proceed for landing, the aircraft has to hold. The holding stacks at the airport consist of four elements, each corresponding of 1 minute of flight - two arcs and two straight legs. Due to this circular configuration, unecessary delay can be generated as the aircraft, at some point in holding, faces the opposite direction from the airport. The aircraft are flying longer and therefore consuming more fuel than necessary, resulting in higher quantity of emitted carbon dioxide. Furthermore, it is rather challenging to maintain the capacity throughput under pressure when aircraft are not always optimally positioned to integrate the landing sequence. To mitigate these drawbacks associated to the use of circular holding patterns, an expected approach time (EAT) is provided, which allows the aircraft to exit the holding stack in the most optimal way, as calculated by the flight management system. Additional information on flight management system is provided in Section 2.2.11.

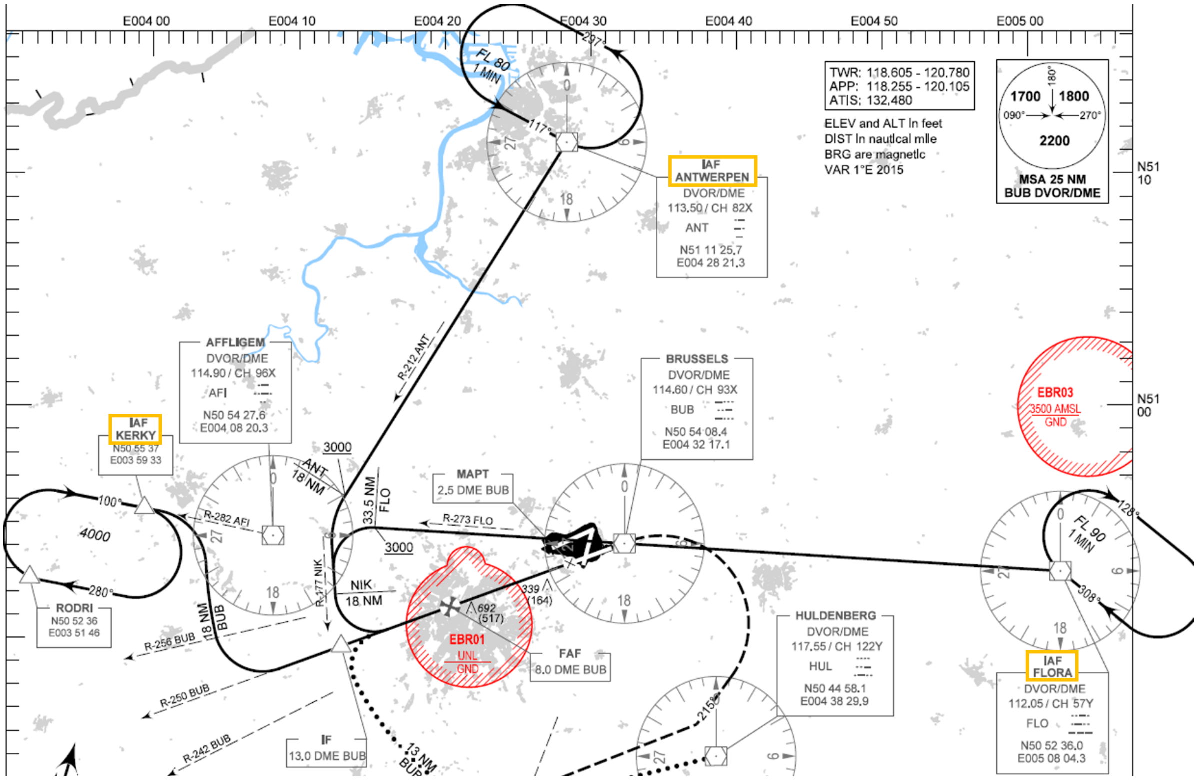
E004 00
E004 10
E004 20
E004 30
E004 40
E004 50
E005 00
FL 80
1 MIN
297°
117°
TWR: 118.605 - 120.780
APP: 118.255 - 120.105
ATIS: 132.480
ELEV and ALT In feet
DIST In nautical mile
BRG are magnetic
VAR 1°E 2015
1700
1800
090°
270°
180°
2200
MSA 25 NM
BUB DVOR/DME
N51 10
IAF
ANTWERPEN
DVOR/DME
113.50 / CH 82X
ANT
N51 11 25.7
E004 28 21.3
AFFLIGEM
DVOR/DME
114.90 / CH 96X
AFI
N50 54 27.6
E004 08 20.3
R-212 ANT
BRUSSELS
DVOR/DME
114.60 / CH 93X
BUB
N50 54 08.4
E004 32 17.1
EBR03
3500 AMSL
GND
N51 00
IAF
KERKY
N50 55 37
E003 59 33
3000
ANT
18 NM
33.5 NM
FLO
MAPT
2.5 DME BUB
R-273 FLO
R-282 AFI
100°
4000
280°
RODRI
N50 52 36
E003 51 46
3000
NIK
18 NM
R-177 NIK
692
(517)
339
(164)
EBR01
UNL
GND
FAF
8.0 DME BUB
HULDENBERG
DVOR/DME
117.55 / CH 122Y
HUL
N50 44 58.1
E004 38 29.9
FL 90
1 MIN
128°
308°
IAF
FLORA
DVOR/DME
112.05 / CH 57Y
FLO
N50 52 36.0
E005 08 04.3
18 NM
BUB
R-256 BUB
R-250 BUB
R-242 BUB
IF
13.0 DME BUB
13 NM
BUP
215°

Figure 2.3: Low level holding patterns (instrument approach chart for RWY 07R) [3].

As can be seen from Figure 2.3, the holding patterns start at a specific altitude. There is also a maximum level specified. These are summarised in Table 2.3. When several aircraft have to hold, they can be sent along the same holding stack. From a safety point of view, as soon as more than one aircraft are holding at the same holding stack, vertical separation of minimum 1,000 ft has to be ensured. Regarding the speed at which the aircraft have to hold, it all depends on the aircraft approach category (ICAO). For the aircraft of category A and B (small single and multi engine), a maximum indicated airspeed of 170 kts is imposed. For the aircraft of category C and D (airline jets, large jets and military jets), an indicated airspeed of 230 kts is the maximum [3]. A common practice at EBBR is to make the aircraft fly at an indicated airspeed of 185 kts when flying along an holding pattern.

Table 2.3: Maximum and minimum altitude of the three holding patterns at EBBR [3].

Holding pattern	Maximum FL	Minimum FL
KERKY	4,000 FT	FL90
ANT	FL140	FL80
FLORA	FL140	FL90 (FL60 when runway 25L/R is used for landings)

To re-integrate back the holding traffic into the arrival sequence at the proper altitude when some capacity has freed up, a continuous traffic monitoring is required. A good coordination between the ACC and the APP controllers is required to efficiently handle the traffic in holding. Given the dense and complex environment of the airport, controllers usually tend to follow a strategy giving themselves more time and margins to implement and fine tune the sequence rather than sending aircraft to hold. The main reason for that comes from the aforementioned facts. Therefore, holding stacks are not commonly used at the airport.

2.2.5. RADAR VECTORING

At the end of each standard route, the main strategy followed at EBBR to direct aircraft to one of the runway thresholds is radar vectoring, also referred to as open-loop vectoring in literature. As the territory under the responsibility of *skeyes* - delimited by the Belgium FIR - is rather small, the ACC and APP closely work together to ensure smooth, safe and efficient transition from the en-route segments to the tower control. For this reason, aircraft entering the Belgium FIR to land at one of the public Belgian airports, except at EBKT, must expect radar vectoring prior to the IAFs. Any aircraft in a radius of 30 NM around the airport is likely to be directed through radar vectoring. The principle of radar vectoring is based on the construction of landing sequences using heading, speed and altitude instructions. By instructing aircraft to fly on heading or to fly direct to some points, path shortening and/or stretching is ensured to efficiently and safely control the air traffic.

While radar vectoring enables a high level of flexibility to the controllers that have the only constraint of bringing the aircraft safely and efficiently onto the runway, while maintaining airborne spacing, a series of drawbacks and limitations rise. First, to make sure the streams coming from different directions efficiently merge into an optimal landing sequence, controllers have to continuously monitor the traffic situation, and provide tactical instructions to the flight crews. Unsurprisingly, the non-stop communication between the controllers and the pilots results in a very high frequency occupancy and peaks of workload for the controllers, accentuated during high traffic load conditions. Figure 2.4 illustrates this point. The number of instructions per aircraft from the end of the STARs to the interception with the instrument landing system (ILS) localiser or glide slope has been estimated to seven - four heading instructions and three altitude instructions - during the first feasibility study on PM at EBBR (2009-2011). This number varies depending on the runway system in use and the traffic loads. Therefore, during peak periods, such as the 28^{th} of June 2018 from 08:00 to 09:00 UTC, the frequency occupancy of Brussels Arrival (118.255), can be extremely high. During the aforementioned period of time, the frequency has been used 92.7% of the time. This does not give a lot of room for extra communication if needed, e.g. in case of emergency. At the bottom of Figure 2.4, the black intervals in the green bands represent the moment of silence on the frequency.

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Figure 2.4: Brussels arrival frequency occupancy (data: 28/06/2018 08:00-09:00 UTC). Brussels Arrival frequency changes from 118.250 to 118.255 the 6^{th} of December 2018 (VRPS screenshot).

Moreover, under high traffic load conditions, handling the arrivals by providing open-loop instructions is highly demanding [10]. Controllers have to take rapid and sound decisions that the flight crews have to execute as quickly as possible. The traffic mix experienced at the airport also adds complexity to the situation. All incoming aircraft vary in terms of type, size and speed to fly at during the approach.

Although common practices exist to guide the incoming traffic from the end of the STARs up to the runways threshold, the trajectories flown by the aircraft depend on the traffic load, the direction of the incoming traffic, and the runway in use, which results in great diversity in tracks flown in a dense area. This non-predictability in trajectory inevitably results in non-optimal fuel calculations by the aircrews and in large dispersion of the incoming traffic, as illustrated in Figure 2.5. The non-optimal situational awareness for the flight crews who cannot anticipate the next controller instruction is another drawback of radar vectoring. Furthermore, the uncertainty introduced with radar vectoring jeopardises the AMAN performance as this one is often not properly updated when the aircraft trajectory varies from the flight plan.

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Figure 2.5: Radar tracks (RWY07L, traffic sample: 06/04/2018 05:30-07:30 UTC).

Despite all the aforementioned disadvantages - which can be mitigated through systematic and rigorous training, radar vectoring proved to be, so far, an appropriate procedure to handle the arrivals at EBBR. However, space remains for improvement in efficiency and system performances.

2.2.6. Speed Limitations

To ensure an homogeneous and efficient landing sequence, speed limits are imposed to the traffic coming to land at the airport. These limitations are provided in Table 2.4.

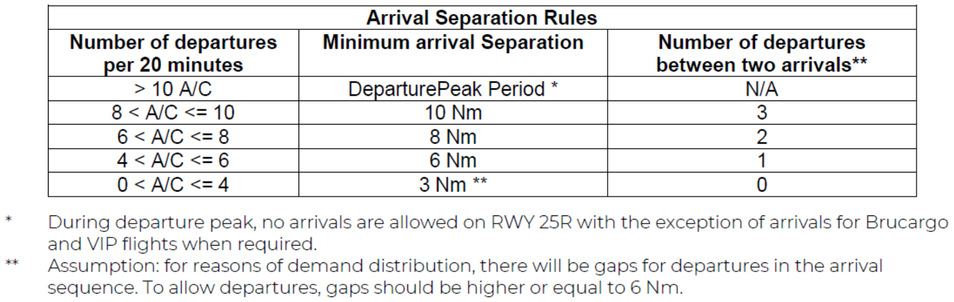
Table 2.4: Speed limitations for the IFR flights inbound at EBBR [3].

Speed limitations	**Where**
250 KIAS	Below FL100
220+ KIAS	From IAF to ILS LOC interception
180+ KIAS	~12 NM from touchdown to 6 NM from touchdown
160 KIAS	To outer marker (or 4 NM from threshold of runway19)

The speed limitations presented in Table 2.4 must be respected by all IFR flights performing an ILS approach, unless otherwise instructed by an air traffic controller. For the aircraft not able to fly at the specified speed, a tailored approach speed profile must be followed.

2.2.7. Separation Requirements

In the airspace under the responsibility of *skeyes*, aircraft must, in any cases, be separated at least in one direction - lateral and/or vertical. Vertically, aircraft must be separated by 1,000 ft. The lateral separation minima are 3 and 5 NM for the APP and ACC sectors, respectively. However, the lateral separation distance between two aircraft also depends on the traffic situation, the mix of arrivals and departures, runway exit times and the runway configuration in use. At EBBR, when arrivals are allowed on runway 25R, they are integrated in between departures. Therefore, the landing sequence has to be adjusted such that there is enough time in between two landings to clear an aircraft for take-off. The arrival separation rules for runway 25R are presented in Figure 2.6. More the number of departures per 20 minutes is high, larger the separation between the arrivals has to be.



Arrival Separation Rules		
Number of departures per 20 minutes	Minimum arrival Separation	Number of departures between two arrivals**
> 10 A/C	DeparturePeak Period *	N/A
8 < A/C <= 10	10 Nm	3
6 < A/C <= 8	8 Nm	2
4 < A/C <= 6	6 Nm	1
0 < A/C <= 4	3 Nm **	0

* During departure peak, no arrivals are allowed on RWY 25R with the exception of arrivals for Brucargo and VIP flights when required.

** Assumption: for reasons of demand distribution, there will be gaps for departures in the arrival sequence. To allow departures, gaps should be higher or equal to 6 Nm.

Figure 2.6: Arrival separation rules for runway 25R [11].

On runways 01, 19 and 07R, and when any other runway system than runways 25L/R are active, the arrival separation between two consecutive aircraft is based on a standard working method defined by ICAO. Depending on the aircraft maximum take-off mass - super heavy (S), heavy (H), medium (M), light (L), the separation requirement is determined to account for the formation of wake vortices by the leading aircraft. If this separation requirement is larger than the 3 NM established for approach at the airport, the separation minimum is increased to comply with the ICAO distance-based wake turbulence separation minimum. In Tables 2.5 and 2.6, the wake turbulence categories (WTC) defined by ICAO and the distance-based wake turbulence separation minima depending on the aircraft mix are provided.

Table 2.5: Wake turbulence categories defined by ICAO [12].

WTC	Maximum take-off mass
S	Only A380-800
H	MTOW ⩾ 136,000 kg
M	7,000 kg ⩽ MTOW <136,000 kg
L	MTOW <7,000 kg

Table 2.6: Distance-based wake turbulence separation minima [12].

[NM]		Training aircraft			
		S	H	M	L
Leading aircraft	S	(3)	6	7	8
	H	(3)	4	5	6
	M	(3)	(3)	(3)	5
	L	(3)	(3)	(3)	(3)

2.2.8. NOISE ABATEMENT PROCEDURES & POLLUTANT EMISSIONS MINIMISATION

With respect to the environment, different procedures have been agreed upon to minimise the noise and air pollution due to airport activities. The procedures are reflected in the design of the SIDs and STARs. Furthermore, the concept of continuous descent operations (CDO) is integrated to the approach procedure at the airport. In Section 2.2.9, the CDO strategy in place at EBBR is described.

Located just outside Brussels City, the operations at the airport are restricted in a way as to minimise the number of complaints about noise and emission pollution. A night curfew from 23 pm to 6 am is activated every day. A restricted area over Brussels unlimitedly extending from the surface of the Earth (EBR01) prevents aircraft to fly over the city and generate aircraft disturbance.

In addition to all the restrictions due to environmental consideration, political constraints also appear to limit the flexibility of the operations to and from EBBR. The approach and departing procedures have been designed as to circumvent sensitive areas for political reasons, such as the area around Chaumont-Gistoux at the south-east of EBBR.

2.2.9. CONTINUOUS DESCENT OPERATIONS

A Continuous Descent Operation (CDO) is an aircraft operating technique with the main objectives of lowering the aircraft noise during approach and final, reducing the fuel consumption and minimising the emissions of pollutant gases. CDO defines an continuous descent along which the aircraft have to fly in low drag configuration with minimum thrust. Levelling-off along the descent is avoided as much as practicable. Ideally, a CDO procedure starts at the TOD up until the intersection with the ILS localiser or the glide slope. By initiating CDO as high as possible, better results in terms of noise, fuel consumption and pollutant emission reduction are achieved [13].

In reality, the story is somehow more complex. First, flight levels in certain areas are restricted by the airspace structure and specific LoAs. Furthermore, the runway system in use is another parameter influencing CDO as some runways are better positioned than other to bring the incoming traffic along a continuous descent. Finally, the lack of flight predictability due to radar vectoring is also limiting the optimum use of CDO. With radar vectoring, the controllers provide instructions to one aircraft at a time. Therefore, optimising the vertical profile of each arrival is challenging, and rarely achieved. CDO is especially unfeasible during peak periods during which the vertical separation between a lot of aircraft coming from different directions must be maintained. Flight trajectory adjustments are unavoidable which results in segmented vertical profiles. Vertical separation must also be provided between the arriving and departing flows, which forces the aircraft to level off in some cases. It can happen that aircraft are descended to a low altitude far from the runway to avoid trajectory conflicts (separation minima infringements), resulting in low altitude overflying of areas surrounding the airport. In addition to disturb the population living in the vicinity of the airport due to the aircraft noise, the negative environmental impact of such a practice is not to be neglected.

The concept of CDO is not a standard practice for the arrivals at EBBR. The rare cases during which CDO is applied at the airport are during low traffic situations or on request of the pilots. During the 6th *EUROCONTROL* workshops on Vertical Flight Efficiency (VFE), the actual situation at the airport regarding CDO has been presented. The main observation is that CDO is not a popular practice. Most of the time, CDO is replaced by a levelling off of the aircraft at different altitudes prior intercepting the glide slope, as testified by Figure 2.7.

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Figure 2.7: Vertical flight profile for the arrivals at EBBR on runways 25L/R (dates: 30/04/2018-27/05/2018 & 03/09/2018-30/09/2018) [6].

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2.2.10. AREA NAVIGATION

Nowadays, the main trend at the European airports to guide the air traffic is RNAV, area navigation. While in the past, aircraft trajectories were restricted to route segments connecting ground-based navigation equipment, RNAV has made air navigation enter a new era. Aircraft are now able to fly along trajectories defined by waypoints. At all times, the aircraft knows its position with reference to these waypoints using satellite navigation. The main advantages of such a technology are the increase in path flexibility, time and fuel saving, and mileage reduction - although trade-offs are always required to get the best compromise out of it [14].

RNAV does not require the implementation of costly equipment since it uses virtual points. As the technology is based on a database of waypoints, the FMS navigation database of each aircraft has to be properly updated to take full advantage of the technology, and to be able to follow the most optimal routes. RNAV procedures are also used to support CDO and designed in a way to deliver the traffic at an appropriate altitude for the distance to touch-down.

Initially, a basic RNAV system has been developed in 1998, which was referred to as B-RNAV. This system offered an accuracy of ± 5 NM which was suitable for en-route operations [13]. To optimise the air traffic operation and offer increased airspace capacity, a more accurate monitoring of the aircraft movements was required. For this reason, the basic principle of RNAV has been upgraded to P-RNAV, precision area navigation. With the upgrade, the navigation accuracy has been increased to ± 1 NM. This navigation accuracy requirement of ± 1 NM allows to efficiently handle aircraft in dense and busy airspace, such as terminal airspace. Furthermore, RNAV routes can be brought closer together increasing the density of the route network. P-RNAV, sometimes referred to as RNAV1, provides reference trajectories and a pattern to merge the arrivals on the final approach segment.

Although RNAV-capable aircraft are free to follow any desired paths from point to point as long as the flight plan is accepted, and if not resulting in trajectory conflicts, standard routes have been pre-defined at locations where the traffic density and complexity rise. A typical airspace area where standard routes are defined is the TMA. These routes are referred to as STARs and SIDs, as elaborated in Section 2.2.3. These RNAV routes are defined according to strict guidelines to ensure realistic, safe and efficient route structures for all aircraft types [15].

While nowadays RNAV1 is used to support radar vectoring by pre-defining reference vectoring patterns to bring the aircraft toward the runway, the utopian goal is to replace open-loop vectoring in its entirety by the RNAV1 technology [16]. While this goal could be achieved in ACC sectors where the traffic density is usually low to medium, the human intervention in the dense and busy terminal area is likely to never go away. This statement can be supported by the current procedures used in TMA sectors at European airports. In case of low to medium traffic situation, most of the flights are following the pre-defined RNAV routes, and are only taken over by the controllers at a later stage during the approach. When the traffic load increases, it has been observed in several operational contexts that controllers revert to radar vectoring to maximise capacity and efficiency [17]. This directly results from the fact than RNAV is less flexible than radar vectoring since aircraft have to fly along pre-existing routes [10]. Radar vectoring is also used in case of high traffic density and complexity to handle non-RNAV equipped traffic. As a matter of fact, being RNAV1 capable is not mandatory. The minimum requirement of B-RNAV capable is sufficient to operate at Brussels National Airport. Two different options are available to handle traffic mix. Being B-RNAV capable means that the RNAV routes can be followed. However, the reduced accuracy of the FMS of such aircraft requires a close monitoring by the controller if the aircraft are not controlled with radar vectoring but are allowed to follow the standard routes. This close monitoring is especially required when parallel RNAV routes are at 5 NM from each other. Although controllers are trained to cope with this kind of situation, in September 2018, only 0.08% of the traffic handled was RNAV1 non-capable. This number comes from the *EUROCONTROL* FPL-database for the month of September 2018.

2.2.11. FLIGHT MANAGEMENT SYSTEM

The flight management system (FMS) is an electronic device installed on board of aircraft with the primary function of flight optimisation. By continuously providing pilots with the most optimal speed, altitude and engine setting to fly at, the operational costs can be minimised and the flight efficiency increased. Nowadays, all modern commercial airliners are equipped with a FMS to closely monitor and optimise their performances.

In FMS are embedded several functions that together constitute the core mission of the system. Flight planning, navigation and guidance, optimisation and performance prediction, all these are enhanced and supported by the system capability to take aircraft characteristics, the evolving operational context, phase of the flight and navigation sources, into account to derive the most optimal profile, route and flight parameters for each flight segment [18]. FMS is able to dynamically optimise the flight plan of the aircraft using the RNAV technology [13]. Furthermore, a better predictability on aircraft behaviour and performance can be achieved if the system is properly updated all along the flight [10].

2.2.12. ARRIVAL MANAGER

An arrival manager (AMAN) is the ultimate planning tool to optimally handle the arrivals at controlled airports. An AMAN extracts and combines all existing navigation capabilities of ATC and aircraft equipment to support the operations. Amongst others, it gives indication to pre-sequence the aircraft prior the IAFs, supports the controller decisions when handling the arriving traffic, builds an optimal landing sequence which is continuously updated based on the traffic situation, calculates target landing times, and finally maintains an overview of the incoming traffic organisation [13]. All these functions bring benefits in terms of workload, efficiency and predictability if combined appropriate RNAV and FMS technologies are used.

In Table 2.7, the inputs and output of the system are provided.

Table 2.7: AMAN inputs and outputs [13].

Inputs	Outputs
• Flight plans from FDPS	• Initial arrival sequence based on FIFO rule
• Updated estimates from the F/RDPS	• Flight sequence based on ETA
• Wind information	• Optimised arrival sequence
• Runway acceptance rates	• STA of arrival at IAFs and runways
• Slot availability	• Arrival sequence at IAFs and runways
	• Action for delay absorption

An AMAN reveals to be extremely useful in busy TMAs where its functionalities can be tailored for a specific need and adjusted depending on the operational context. It is important to notice that if AMAN is not properly designed or if its functionalities are not in line with AMANs of neighbouring ANSPs, all the aforementioned benefits can be shattered.

To increase the predictability performances of the system, an extended arrival manager (XMAN) can be used. Instead of organising the traffic only as soon as within the Belgium FIR, predictions can be made up to 200 NM [19].

The AMAN currently in place in the control centre of *skeyes*, CANAC2, is far from being the tool of reference to handle the arrivals. While a series of operational benefits can be achieved when no route deviations rise compared to the initially filed in flight plans, a modification of these routes that is not updated in the AMAN is likely to provide an optimal landing sequence based on the old, inaccurate information. This situation frequently occurs in the control center of Brussels due to the unfriendly procedure to update a route modification. As a matter of fact, every change has to be manually entered in the system. This inevitably affects the efficiency of the AMAN and ultimately decreases its success among the controllers.

3

POINT MERGE

Over the last few years, evolution regarding the strategy to handle the arrivals at EBBR has been observed. Starting from the time when radar vectoring was the only available strategy, the introduction of RNAV considerably simplified the air traffic control [17]. However, radar vectoring - even if supported by the RNAV technology - is far from being the optimal solution in terms of, notably, controller workload and flexibility, radio frequency occupancy, sector capacity and pilot situational awareness. Because the concept of PM is claimed to be a suitable solution to optimise the aforementioned parameters, it has seemed logical to further investigate this option for EBBR.

This chapter is structured as follows. First, the general concept of PM is described in Section 3.1. In Section 3.2, the route structure of the system is presented. This is followed, in Section 3.3, by a description of the operating method in nominal and non-nominal conditions. Finally, the operational considerations for an efficient system use and implementation are explained in Section 3.4.

3.1. CONCEPT DEFINITION

PM is a systematic flow integration technique developed by the *EUROCONTROL* Experimental Centre (EEC) in 2006 [20]. The development of PM is part of the *EUROCONTROL* Terminal Airspace Improvements Programme, and is in line with the objectives defined in the general context of SESAR [16]. As indicated by its name, the working principle of PM is to merge the arrivals into an efficient and orderly sequence, enabling CDO and keeping aircraft under lateral navigation guidance during the entire procedure.

To this day, the concept of PM has been implemented at eighteen different airports all over the world. The first application took place in Oslo in 2011. Nowadays, the airport of Dublin, Seoul, Paris Charles De Gaulle, London City, and others, are also using PM as main arrival strategy [20]. Out of these applications, a series of advantages and hazards have been identified. These can directly be associated to the clear system structure and the procedure systematisation.

Advantages:

- Terminal airspace capacity increase
- Maintained/increased current runway capacity throughput
- Enhanced flight predictability and efficiency
- Controller workload reduction
- Environmental benefits through the achievement of CDO
- No need for new or expensive navigational equipment

Hazards:

- Reduced flexibility compared to radar vectoring
- Risk of controller boredom
- Risk of confusion regarding the transfer of control
- Fuel management issue

The achievement of such advantages highly depends on the operational environment where PM is used, as well as on the way it has been designed and implemented. The challenge to evaluate the feasibility of PM at EBBR is therefore to see to which extent such advantages can be reached. Regarding the hazards, mitigation measures, such as adequate trainings and refresher courses, exist to minimise unwanted and negative operational impacts.

3.2. CONSTITUENTS

The route structure associated to the concept of PM is a triangle-shaped RNAV route structure, and is referred to as a point merge system (PMS). In Figure 3.1, the general architecture of a PMS is presented.

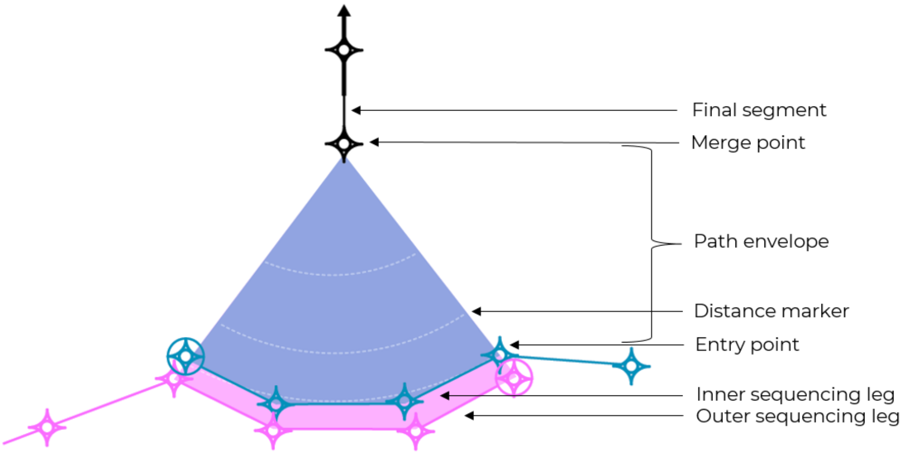

Figure 3.1: PMS architecture [20].

A PMS consists of two main elements, namely a merge point and one or several sequencing legs. Each of these elements has a specific purpose reflected by its design.

The sequencing legs are designed in a way as to allow path stretching or shortening depending on the traffic volume and complexity, and to ultimately build the most optimal landing sequence [16]. Two important properties associated to the sequencing legs are the isodistance and equidistance properties [17]. An isodistant sequencing leg is a leg that is, at all points, at the same distance from the merge point. Equidistant legs are different legs located at the same distance from the merge point. Satisfying at best these two properties is necessary to make the controlling procedure with PM as intuitive and accurate as possible, especially if multiple sequencing legs are used. In reality, these two properties can only be approximated due to technological and operational restrictions. As PMS are RNAV routes, the aircraft are flying from point to point along the sequencing legs. Segmented legs are therefore flown by the aircraft, which jeopardises the isodistance property. With regard to the equidistance property, as the legs have to be separated at least in one dimension - vertical, lateral or longitudinal, it might occur that one of the leg is closer to the merge point than the other(s), especially when the sequencing legs are parallel to each other. The best practice regarding the equidistant property is to minimise the lateral separation between the legs while separating them by 1,000 ft vertically.

The merge point, as indicated by its name, is the location where the traffic is integrated in an efficient and orderly sequence prior to landing. The merge point is placed a few NM away from the sequencing legs. The main difference with radar vectoring enhanced with RNAV capabilities is the way the arrivals are merged together. With the current arrival procedure at EBBR, the incoming traffic is merged on an axis. With PM, the traffic is merged at a specific point, beyond which the same trajectory is followed by all aircraft.

3.3. OPERATING METHOD

The intuitive and systematic strategy to handle the arrivals at an airport with PM is directly linked to the system architecture. The sequence of actions to guide the arrivals with such a system is described in Section 3.3.1. In Section 3.3.2, a high level description of the contingency procedures available to operate a PMS in non-nominal conditions is provided.

3.3.1. Nominal Condition

Prior to entering the system sequencing legs, the arriving traffic has to be pre-sequenced. This pre-sequencing procedure is important to prevent the need of separating the aircraft once on the legs, which would jeopardise the efficiency and the controller-friendliness of the procedure. Furthermore, pre-sequencing the incoming traffic prior to the entry points of the PMS is the best strategy to maintain high throughput levels, avoid too frequent occurrences of sequencing leg run-offs and the use of conventional holding stacks.

Once in the system, aircraft must comply to speed and altitude restrictions. Along the sequencing legs, the aircraft must fly at the same speed and altitude to ensure homogeneous traffic operations. As long as no controller instructions are provided, the aircraft are required to extend their trajectory to the next waypoint on the sequencing leg. The aircraft having flown the longest along the sequencing legs can be turned towards the merge point as soon as the separation requirement is ensured with the closest aircraft on its course to the merge point. To do so, a "Direct to" instruction is communicated by the controller to the flight crew. This situation is illustrated in Figure 3.2. In Figure 3.2, the orange aircraft is allowed to turn towards the merge point as the grey aircraft is sufficiently far away - past the first distance marker (see Figure 3.2).

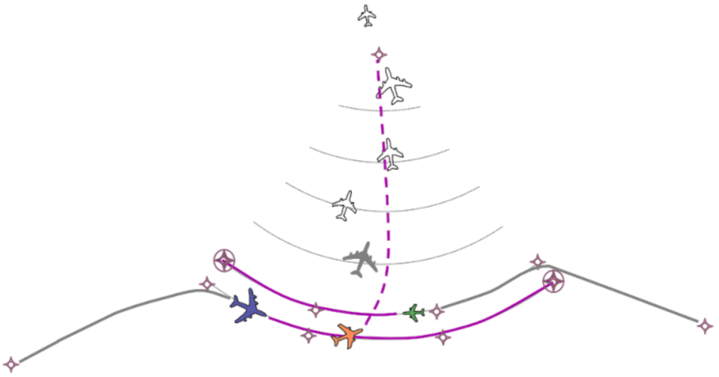

Figure 3.2: PMS operating method [16].

The "Direct to" instruction is time critical as the system capacity, pressure on the runway throughput and safety mainly depend on it. If the instruction is given too early, a risk of separation infringement may rise. On the other hand, if the controller waits too long prior to providing the instruction, the runway capacity throughput might decrease. To support this task, graphical markers are displayed on controller screens (see Figure 3.1 and Figure 3.2).

From the sequencing legs to the merge point, the aircraft are required to fly a CDO. However, an explicit instruction has to be communicated prior the descent can be initiated. The "Direct to" instruction does not imply a CDO. Therefore, the normal procedure to handle the traffic from the sequencing legs to the merge point of a PMS requires two interventions. The "Direct to" instruction - lateral intervention - and the descent clearance - vertical intervention - are the only two instructions the controller has to communicate to the flight crew.

Although the procedure is highly standardised, some level of flexibility must be retained to offer the best and most suited experience to all users. This means that at all times, the controller is allowed to revert to radar vectoring and use speed control to avoid/resolve a conflicting situation.

3.3.2. Non-Nominal Condition

For several reasons, it can happen that the standard procedure to operate a PMS, described in Section 3.3.1, cannot be followed as prescribed. In case of adverse meteorological conditions or change in wind direction, non-equipped aircraft, P-RNAV equipment failure, missed approaches, sequencing leg run-offs, runway closure, runway change or emergency, contingency procedures must be available to ensure undisturbed operations while maintaining a satisfying level of safety. For the alternative procedures to be as efficient as possible, the controllers have to be sufficiently trained to quickly and appropriately react to the problematic situation.

Mainly, the suggested contingency procedures are radar vectoring, speed control, the use of alternative routes and capture holding stacks. To best fit the operational environment at EBBR, the contingency procedures need to be designed accordingly to ensure safety in all cases, smooth transition from one operating strategy to another, as well as a minimum impact on the departures.

3.4. OPERATIONAL CONSIDERATIONS

When designing a PMS, a series of operational considerations need to be carefully considered. The implementation of a PMS, as any new airspace procedures, is likely to affect the current operational performances if not properly adjusted to the operational environment. In Section 3.4.1 to 3.4.5, the most important aspects to take into account when designing and operating a PMS are elaborated.

3.4.1. MANAGEMENT CHANGE

With PM, different viable models exist to share the traffic control responsibilities between ACC and APP. The most important is to end up with a clear, balanced and non-confusing task sharing model [16]. For EBBR, the best practice would be to handle the arriving traffic in three phases. First, the traffic would be sequenced by an ACC controller. Once done, the traffic would be transferred to an APP controller, who is responsible for the traffic up until the aircraft leave the sequencing legs. He/she provides sufficient separation in between the aircraft and direct the aircraft towards the merge point at the most appropriate time. The traffic transfer should take place a few NM in front of the system entry points. On their course to the merge point, the aircraft control is taken over by a final director. He/she makes sure the separation minima are maintained between the aircraft and the landing sequence is efficiently built.

3.4.2. FUEL MANAGEMENT

Fuel management is probably the biggest issue when using PM, and Oslo - where the first PMS implementation took place - has paid the price for it. Rapidly after the implementation, the airline operators observed an increase in fuel consumption when landing at Oslo Airport. Although it is better to carry more fuel on board than not enough, an optimal, accurate and conservative fuel planning is what every airline operator is aiming for.

To understand the cause of the increase in fuel burn, the way fuel is planned for a flight has to be looked at. The fuel to take on board prior to each flight is evaluated based on the route to fly. This route is filled in a flight plan based on standard routes and expected approach at the airport of destination. Therefore, if these standard routes are wrong representations of what the aircraft is really going to fly, fuel discrepancies may rise.

Initially at Oslo Airport, the full PMS was filled in the flight plans. Therefore, the flight crews had to take enough fuel to make sure the entire sequencing leg could be flown. In practice, it revealed that the complete length of the sequencing legs was almost never flown, resulting in more fuel taken on board than necessary.

To solve this issue, a direct RNAV route has been designed for the airline operators to predict the fuel needed for a specific flight. This direct RNAV route was simply the shortest planable route to fly from the entry point of the sequencing legs to the merge point. This practice has became a common and recommended practice by the International Air Transport Association (IATA) at all airport operating a PMS [21].

To illustrate the explanation above, Figure 3.3 presents both PMS routes published by the Irish Aviation Authority (IAA) for runway 28 at Dublin Airport.

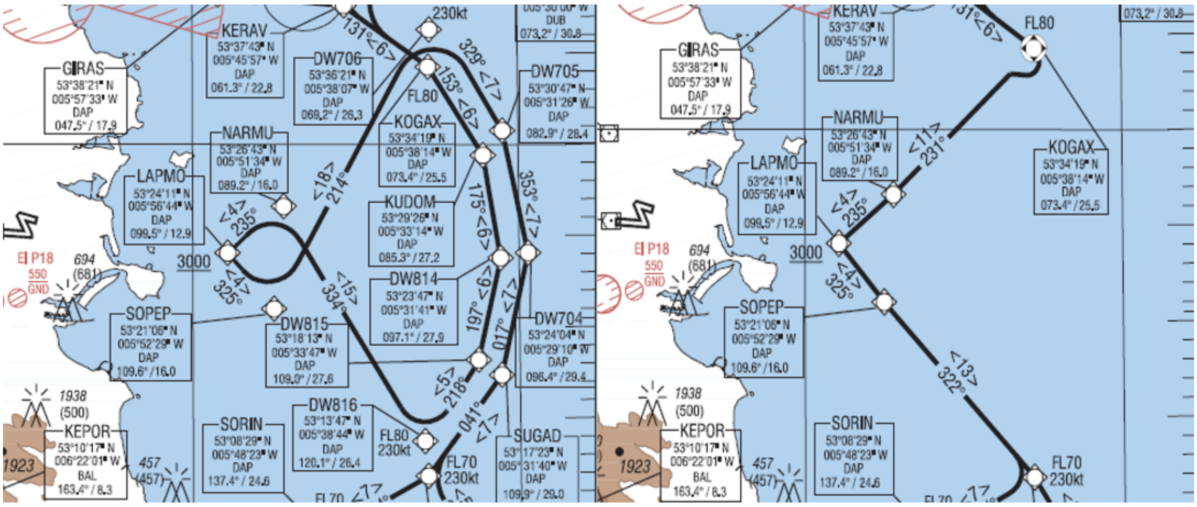

Figure 3.3: RNAV routes published by IAA for runway 28 at Dublin Airport (left: full RNAV PMS routes, right: direct RNAV routes) [22].

3.4.3. AIRCRAFT SPACING

The currently used separation minima at EBBR would be maintained with PM (see Section 2.2.7). The PMS design and operation must be such that the separation minima can easily be ensured, maintained and monitored at all times.

Along the sequencing legs, longitudinal separations larger than the standard minima are recommended [10]. Adding extra separation between two successive aircraft ensures that when the leading aircraft is turned towards the merge point, no separation infringement rises with the following aircraft on the leg.

3.4.4. AIRCRAFT SPEED

Based on the aircraft mix to handle, the approach speed to fly the PMS can either be fixed or adapted based on each aircraft type. The first strategy is definitely the most appealing as making the aircraft all fly at the same speed reduces the number of instructions to control the aircraft speed and maintain an homogeneous traffic evolution.

At EBBR, a fixed approach speed of 230 kts along the sequencing legs would be appropriate. Aircraft would need to be established at that speed a few NM prior to reaching the system entry points. 230 kts is a speed that has been identified in the OSED for PM in complex TMA to be acceptable for a wide variety of aircraft [10] and is used, amongst others, at Dublin and Leipzig Halle Airport.

3.4.5. ARRIVAL MANAGER

It has been claimed after the ENAV prototyping sessions for the implementation of PM in Rome terminal area [23] and in the IATA position on PM [21], as well as during the visit at Dublin ACC, that combining a PMS with an adequate AMAN, would lead to better system performance. To further enhance the system performances in terms of predictability and efficiency, an XMAN could be used. The working principle between AMAN and XMAN is the same, only the range differs (Belgium FIR boundary versus 200 NM).

4

CONCEPT DEVELOPMENT

In Sections 4.1, 4.2 and 4.3, the design strategy considered to develop feasible PMS for EBBR, the outputs of the concept development phase and the scenarios tested through FTS with the different investigated PMS are respectively presented.

4.1. DESIGN STRATEGY & ASSUMPTIONS

The design criteria, assumptions and guidelines considered to design feasible PMS for EBBR are hereafter listed;

- One PMS has been designed for each possible runway configuration.
- All PMS have been designed within the boundary of the Belgium FIR.
- The area at the south east of the airport - currently prohibited for political reasons - has been avoided.
- Due to the complex structure of the Belgian airspace, positioning the PMS as close as possible to the airport revealed to be the best solution (Brussels terminal areas).
- Military areas have been avoided when possible.
- A separation of 2.5 NM between the PMS routes and the boundary of TRA/TSA has been provided when possible.
- Restricted areas have been avoided as much as possible.
- The PMS have been positioned in a way as to optimise the traffic flow integration from en-route segments to landing.
- The inner leg is always higher than the outer one(s). This is required for safety reason. By doing so, there are no risks that an aircraft descending towards the merge point from an outer leg collides with an aircraft flying along an inner leg.
- A vertical separation of 1,000 ft in between each leg of the PMS has been introduced.
- A lateral separation of 1.5 or 2 NM has been designed between the sequencing legs.
- Sequencing legs oriented in the same direction or in opposite directions are possible.
- The length of the different sequencing legs is somehow proportional to the traffic density of the incoming streams (see Section 2.2.2).
- Depending on the distance separating the sequencing legs to the runway threshold, specific altitude levels have been identified along the sequencing legs. The basic principle "3,000 ft for 1 NM" has been used as guiding rule.

- The impact of the new routes on the departures of EBBR, as well as on the route network of the other controlled Belgian airports (SIDs & STARs), has been minimised as much as possible.
- The new routes are provided with realistic turns. If the maximum recommended turn angle of 90° is not always the maximum angle that has been designed along the different systems, angles larger than 120° never occur. 120° is defined as the upper limit for turn angles along approach segments [24].
- Only fly-by waypoints are used.
- The design guidelines for a successful PMS contained in the *EUROCONTROL* OSED "Point Merge Integration of Arrival Flows Enabling Extensive RNAV Application and Continuous Descent" [16], the OSED for PM in complex TMA [10] and the *EUROCONTROL* TMA Design Guidelines [15], have been referred to during the concept development phase. Amongst others, recommendations on the number of sequencing legs, the length of the legs and the altitudes in the systems, have been looked at.
- To optimise the chance of developing successful PMS, controllers and airspace design experts have been consulted on a number of occasions.

Please note that a detailed assessment and validation of the different systems by a team of airspace procedure design experts will be required before implementation - if PM at EBBR is launched as a project.

4.2. INVESTIGATED POINT MERGE SYSTEMS

In Sections 4.2.1 to 4.2.4, the designed PMS for runways 25L/R, 19, 07L and 01 are presented. Each time, information on the system structure, altitudes, design limitations and considerations is provided.

4.2.1. POINT MERGE SYSTEM - RUNWAYS 25L/R

Designing parallel PMS with distinct merge points is a possible strategy to efficiently integrate the streams coming from various directions. This design strategy has been considered for the PMS for runways 25L/R, as can be seen in Figure 4.1.

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Figure 4.1: The PMS for runways 25L/R.

By positioning the system in a way that facilitates the integration of the different arriving streams, military areas are penetrated. The impacted areas are the TRA North Alpha (4,000 ft AMSL - FL195), the TRA/TSA North Two - Balen Area (FL95 - UNL), and the TRA/TSA North Three - Meeuwen Area (FL95 -UNL). A conflict also rises with the restricted areas EBR05 A - Helchteren (GND - FL100) and E - Helchteren Medium Level (FL100 - FL240). These zones are reserved for firing and bombing aircraft and their entry is prohibited for all aircraft non-participating in the exercises. In addition to that, the 2.5 NM separation required along the boundary of military airspace is neither respected. This area is represented by the dashed area in Figure 4.1. Although, at first sight, all of this seems to jeopardise an efficient implementation and use of the system, solutions exist. Nowadays, agreements for an efficient and flexible use of the airspace between civil and military operations are already in place. Bringing modifications to them to best suit the new arrival procedure is not impossible. Negotiations, however, would need to be opened with the military.

In addition to the impact on military airspace, the east system is not entirely contained in controlled airspace. The legs are going out of the terminal airspace of Brussels. This operational obstacle could be circumvented by (temporary) airspace modifications or clear coordination.

Regarding the altitudes in the system, FL90 is the altitude the aircraft have to fly along the outer legs of the system and FL100 along the inner ones. Actually, along the inner legs, altitudes above FL100 are also acceptable if cleared by the controllers. This cannot be done on the outer legs since this could lead to losses of aircraft separation as introduced in Section 4.1. For the aircraft coming from the west and the most north east directions, FL90 must be maintained as from the waypoint MOTTO and TERRY respectively. For the two other directions, the altitude constraints are imposed at WOD01 and LEG01. An altitude of 4,000 ft or above has been set at the merge point EASTO and of 3,000 ft or above at the merge point WESTY.

The characteristics of the PMS for runways 25L/R are hereafter summarised;

East system:	West system:
• Distance between the sequencing legs: 2 NM	• Distance between the sequencing legs: 2 NM
• Distance between the merge point and the most inner leg: 17.0 NM	• Distance between the merge point and the most inner leg: 17.0 NM
• Route distance between the runway threshold and the most inner leg: 33.9 NM	• Route distance between the runway threshold and the most inner leg: 34.9 NM
• Length of TER (blue) leg 32.2 NM	• Length of MOT (orange) leg: 30.0 NM
• Length of LEG (purple) leg: 29.0 NM	• Length of WOD (green) leg: 20.5 NM
• Length of the final segment: 16.9 NM	• Length of the final segment: 17.9 NM
• Altitude along TER (blue) leg: FL90	• Altitude along MOT (orange) leg: FL90
• Altitude along LEG (purple) leg: FL100+	• Altitude along WOD (green) leg: FL100+
• Altitude at the merge point EASTO: 4,000 ft+	• Altitude at the merge point WESTY: 3,000 ft+

In Figure A.1 in Appendix A, the PMS for runways 25L/R is presented at larger scale, including the distance of each segment. In Table A.1 in Appendix A, the coordinates of the waypoints constituting the system are available.

4.2.2. Point Merge System - Runway 19

Unlike the PMS for runways 25L/R, the PMS for runway 19 only serves a single runway. The way the incoming streams feed the system, as well as the overall structure of the system, can be visualised in Figure 4.2.

An interesting physical feature of this system is the integration of the western flows in the system through the east. This design strategy has been considered to minimise the impact on the departures flying outbound EBBR towards the north west.

What can also be seen from Figure 4.2 is the penetration of the TRA North Alpha (4,500 ft AMSL to FL195) and the non-existence of the 2.5 NM lateral separation along the boundary of the military airspace (dashed area in Figure 4.2). Furthermore, with such a design, the main issue is the shooting range Brasschaat EBR20 located at the most westerly part of the TRA North Alpha. This area extends from the ground upwards up to FL140, which can be temporarily decreased to FL70. This area is a military gunnery and air exercises area which is prohibited for any flights not participating in such activities. Next to that, as for the PMS for runways 25L/R, a small portion of the system at the east is running outside controlled airspace.

Regarding the altitudes in the system, the traffic coming from MAK and CIV is required to have reached an altitude of FL80 at AFI and maintain it while crossing the runway axis. As from BUB, the aircraft must initiate a descent to reach FL70 at BLU09 - which is the altitude specified all along the corresponding leg (BLU). For the traffic coming from the east, an altitude of FL80 is required at the navigation point FLO, and subsequently of FL60 at ORA00. For the traffic coming from the north and entering the PMS via the waypoint GIN01, the altitude constraint is imposed as from GIN03. From GIN01 to GIN03, aircraft are allowed to fly above FL80. As from GIN03, all aircraft must fly at FL80 - the altitude required along the leg (GIN). The reason why the flight level constraint has been shifted to GIN03 instead of being imposed at GIN02 - the entry point of the sequencing leg - is to make sure the aircraft coming from WOODY would be able to descend to FL80 along a suitable vertical profile, knowing that the aircraft overfly WOODY at FL150 or above (LoA with Amsterdam ACC). In reality, if an aircraft is able to reach FL80 at GIN02, it could be directly turned towards the merge point without the need to fly to GIN03.

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Figure 4.2: The PMS for runway 19.

The characteristics of the PMS for runway 19 are hereafter summarised;

- Distance between the sequencing legs: 1.5 NM
- Distance between the merge point and the most inner leg: 14.7 NM
- Route distance between the runway threshold and the most inner leg: 24.0 NM
- Length of GIN (green) leg: 24.8 NM
- Length of BLU (blue) leg: 39.2 NM
- Length of ORA (orange) leg: 42.8 NM
- Length of the final segment: 9.3 NM

- Altitude along GIN (green) leg: FL80+
- Altitude along BLU (blue) leg: FL70
- Altitude along ORA (orange) leg: FL60
- Altitude at the merge point NORTY: 3,000 ft+

In Figure A.2 in Appendix A, the PMS for runway 19 is presented at larger scale, including the distance of each segment. In Table A.2 in Appendix A, the coordinates of the waypoints constituting the system are available.

4.2.3. POINT MERGE SYSTEM - RUNWAY 07L

As from the beginning of the concept development phase, it has been clear that the airspace at the west of the airport was more favourable to the design and implementation of a PMS. In Figure 4.3, the PMS designed for runway 07L is presented.

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Figure 4.3: The PMS for runway 07L.

Unlike for the PMS for runways 25L/R and 19, the complete structure of the PMS for runway 07L stands outside military airspace, and the 2.5 NM separation with the military airspace boundary is respected. However, the final segment connecting in a straight line the merge point to the runway threshold goes straight through the restricted area above Brussels City, EBR01. This area is prohibited below FL60, unless instructed by air traffic control.

The system consists of three parallel sequencing legs separated by 1.5 NM. This separation is sufficient since the different sequencing legs are vertically separated by 1,000 ft. The traffic coming from the north shall be established at FL90 as from the radio navigation point ANT. Higher altitudes are not allowed not to impact the SIDs going outbound the airport towards the north west. The traffic coming from the east should overfly FLO at FL90 and reach the waypoint CAR00 at FL80. From that point onwards, FL80 must be maintained. Looking at Figure 4.3, it can be seen that the arrivals coming from the west and the south west are merged together prior being loading on a common sequencing leg. To avoid any conflicts, each of these flows must fly at a specific altitude prior merging. FL60 must be flown by the aircraft coming from the west, FL70 for those coming from the south west. Therefore, all along the outer sequencing leg (MIA), aircraft can fly at FL60 or FL70, depending on their origin. Respecting these altitude constraints is primordial in order to prevent the loss of separation between aircraft and reduce the controller workload. Furthermore, these altitudes are coherent given the distance of each leg to the runway threshold.

The characteristics of the PMS for runway 07L are hereafter summarised;

- Distance between the sequencing legs: 1.5 NM
- Distance between the merge point and the most inner leg: 14.9 NM
- Route distance between the runway threshold and the most inner leg: 24.0 NM
- Length of ALO (orange) leg: 28.0 NM
- Length of CAR (green) leg: 30.8 NM
- Length of MIA (blue) leg: 25.23 NM
- Length of the final segment: 9.1 NM
- Altitude along ALO (orange) leg: FL90+
- Altitude along CAR (green)leg: FL80
- Altitude along MIA (blue) leg: FL60/70
- Altitude at the merge point MARKY: 3,000 ft+

In Figure A.3 in Appendix A, the PMS for runway 07L is presented at larger scale, including the distance of each segment. In Table A.3 in Appendix A, the coordinates of the waypoints constituting the system are available.

4.2.4. POINT MERGE SYSTEM - RUNWAY 01

The designed PMS for runway 01 is displayed in Figure 4.4. From this figure, it can be seen that the PMS does not go within military airspace. Furthermore, the 2.5 NM separation with the boundary of the TRA South Alpha is respected and the overflight of Brussels City, as well as the area at the south east of the airport, is prevented.

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Figure 4.4: The PMS for runway 01.

If the PMS for runway 01 was to be designed neglecting the aforementioned airspace constraints, the operational performances could be optimised. A parallel combination of two PMS to bring the traffic onto the runway could facilitate the integration of the traffic coming from the different directions. In Figure A.5 in Appendix A, a draft version of a design alternative for the PMS for runway 01 is presented. This design is not further investigated in the present report.

For now, the system presented in Figure 4.4 is considered. As for the PMS for runway 07L, two different traffic streams are sent to a common sequencing leg. Along this particular sequencing leg (MAT), two different altitudes are therefore allowed, FL90 and FL100. FL90 has to be flown by the aircraft coming from the west as from MAK01, FL100 by the aircraft coming from the north as from the waypoint ANT01. As when runway 07L is in use, aircraft coming from the east should overfly FLO at FL90 and be levelled at BIB02 at FL80. BIB02 is the entry point of the system - and not BIB01 positioned upstream - in order to provide a feasible turn angle. Finally, the flow coming from ARVOL must fly an altitude of FL110 or above along the corresponding sequencing leg as from CIV.

The characteristics of the PMS for runway 01 are hereafter summarised;

- Distance between the sequencing legs: 1.5 NM
- Distance between the merge point and the most inner leg: 17.0 NM
- Route distance between the runway threshold and the most inner leg: 35.0 NM
- Length of KIK (blue) leg: 28.0 NM
- Length of MAT (green) leg: 27.2 NM
- Length of BIB (orange) leg: 33.0 NM
- Length of the final segment: 17.9 NM
- Altitude along KIK (blue) leg: FL110+
- Altitude along MAT (green) leg: FL100/90
- Altitude along BIB (orange) leg: FL80
- Altitude at the merge point BETTO: 6,000 ft+

In Figure A.4 in Appendix A, the PMS for runway 01 is presented at larger scale, including the distance of each segment. In Table A.4 in Appendix A, the coordinates of the waypoints constituting the system are available.

4.3. SCENARIOS

With the designed PMS presented in Sections 4.2.1 to 4.2.4, different operational scenarios have been tested. The PMS for runway 01, 19 and 07L have been used to test single landing operations.

Regarding the use of the PMS for runways 25L/R, the situation is more complex. As the runway system 25L/R can be operated under different models, the designed PMS has been tested under different conditions. First, single landing operations on runway 25L have been simulated. Next, simultaneous dependent and independent arrivals have been tested. Please note that traffic crossing has not been simulated. Traffic crossing is the possibility for the aircraft coming from the east to land on runway 25L and for the aircraft coming from the west to land on runway 25R. The last scenario tested with the PMS for runways 25L/R was similar to single landing operations on runway 25L, with a different traffic sample. Currently, the traffic distribution between the navigational points BATTY and LNO is uneven (approximately BATTY: 87.5%, LNO: 12.5%). Although in reality this distribution is not problematic, this traffic unbalance has been identified as a potential limitation to the maximum system capacity. To evaluate the impact of the traffic distribution between these two navigational points, a balanced traffic distribution (BATTY: 60% and LNO: 40%) has been simulated.

Hereafter is the list of all scenarios tested, together with their name later used in the report;

- PMS RWY01: single landing operations
- PMS RWY19: single landing operations
- PMS RWY07L: single landing operations
- PMS RWY25L: single landing operations
- PMS RWY25L BATLNO: balanced traffic distribution between BATTY and LNO
- PMS RWY25L/R SimDep: simultaneous dependent approaches - no traffic crossing
- PMS RWY25L/R SimIndep: simultaneous independent approaches - no traffic crossing

5

SIMULATION MODEL DEVELOPMENT

In order to meet the thesis objective stated in Chapter 1, a specific simulation model has been developed to test the different PMS presented in Chapter 4. Prior to presenting the simulation model, the simulation objective is first clearly stated in Section 5.1. Next, Section 5.2 contains all that needs to be known about the simulation model. Finally in Section 5.3, the model assumptions are listed.

5.1. SIMULATION OBJECTIVE

The simulation objective was to compare the operational performances of the current arrival procedure - radar vectoring - with those that could potentially be achieved with PM at EBBR.

5.1.1. RADAR TRACKS & CALCULATED TRAJECTORIES

To meet such a simulation objective, radar tracks - accurate representations of the real trajectories flown by the aircraft when guided with radar vectoring – have been compared to calculated trajectories - aircraft trajectories along the different PMS designed for EBBR. In Figures 5.1 and 5.2, these two types of data are respectively presented.

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Figure 5.1: Radar tracks (RWY07L, traffic sample: 06/04/2018 05:30-07:30 UTC).

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Figure 5.2: Calculated trajectories (RWY07L, traffic sample: 06/04/2018 05:30-07:30 UTC).

The radar tracks have been retrieved from the airport movement system (AMS) of *skeyes*. The radar tracks provided by the AMS are contained within a pre-defined area. This area is a cylinder centered around the airport with a radius of 85 NM extending from the ground surface upwards to 25,000 ft.

The calculated trajectories have been generated by the simulation tool SAAM. Such trajectories are ideal to observe traffic behavior and evolution along specific route networks. In this case, the route networks are the investigated PMS for EBBR. The way these trajectories are obtained is rather straightforward although several steps are needed. First, a traffic demand needs to be extracted from a traffic sample. This is done in a way as to calculate trajectories for a specific set of flights. From this extract, all routing information is removed so that the traffic demand only contains basic flight information (airport of departure and of arrival, the aircraft type, the flight identification, the time of departure, the requested flight level and the call sign). From the extracted traffic demand, 2D trajectories can be created through the assignment process. The assignment process is an automatic algorithm that finds the shortest path from the airport of origin to the destination on a given network - the PMS designed for each runway system. Once done, 3D trajectories can be obtained through profile processing. For that, flight level constraints and aircraft performance are taken into account. The performance model used is BADA, which stands for Base of Aircraft Data. The version of the database used for the simulation (3.14) can be used for close to 100% of the aircraft types in the European Civil Aviation Conference (ECAC) area [25]. Amongst others, BADA specifies at which speed a particular aircraft type has to fly in cruise and what is its optimal rate of descent as a function of its distance to the runway threshold and its weight. Additional information about BADA can be found in Section C.1 in Appendix C.

5.1.2. TRAFFIC SAMPLES

To test the different PMS designed, one traffic sample per runway system has been identified. Morning and evening peak periods have been selected during which arrivals only occurred on the considered runway(s). In Table 5.1, the time period used for each scenario presented in Section 4.3 is provided, together with the number of flights arriving at the airport during this time interval and the military activity status.

Table 5.1: Traffic samples - Confidential data.

Time period	**Runway**	**Number of arrivals**	**Military activity**

The traffic samples have been chosen such that the operational conditions experienced in reality allows an optimal use of the different PMS. A particular attention has been required for the selection of the traffic sample for runways 25L, 25L/R and 19. As a matter of fact, the PMS for these runway systems have portions of their sequencing legs running inside the military airspace. Therefore, the traffic samples selected for these three runway systems had to cover periods of time during which no military activities took place. Finally, all traffic samples occurred during off periods for the military.

Furthermore, it has been verified that in each of the samples provided in Table 5.1, aircraft are coming from all directions according to the traffic presentation per upstream ACC/UAC calculated by *FABEC* and presented in Section 2.2.2. This is important in order to get a complete and realistic picture of the traffic interactions when entering the system from different directions.

5.2. MODEL DEVELOPMENT

To end up with a model that could support sound decision-making regarding the use of PM at EBBR, the model development has been organised around five main packages. These packages are hereafter listed;

- Pre-sequencing optimisation (Section 5.2.1)
- Trajectory generation (Section 5.2.2)
- Conflict detection (Section 5.2.3)
- First in first out principle (Section 5.2.4)
- Solution optimisation (Section 5.2.5)

Please note that numerous iterations have taken place during the model development phase. In the following sections, only the final version of the model is described.

5.2.1. PRE-SEQUENCING OPTIMISATION

The main function of a PMS is to organise the traffic coming from various directions into an efficient landing sequence, while maximising runway capacity throughput, reducing controller workload and optimising vertical descent profiles. Handling and separating bunches of traffic is therefore not what a PMS is made for. For this reason, loading the aircraft on the sequencing legs with a specific separation in between them is primordial, and considered as a pre-requisite to maximise the system performances, as well as to prevent a premature system saturation.

Nowadays, the sequencing of the incoming traffic at EBBR is performed by Brussels ACC. The ACC controllers are required to deliver the traffic sequenced at the different IAFs before the APP controllers take over. The exact procedures are described in the LoAs between Brussels ACC and Brussels APP for the different runway systems. If PM was to be implemented at the airport, these procedures would need to be adjusted. As a matter of fact, the time so far dedicated to pre-sequencing would be shortened since some of the entry points of the designed PMS are located a few NM prior to the current IAFs. One possible solution to ensure efficient sequencing despite this airspace design modification is the involvement of neighbouring ATC units. Coordination with neighbouring ATC units is already done nowadays, and therefore adjustments of the existing methods would be, a priori, possible to optimise the new system performances.

To test the PMS under realistic operational conditions, the concept of pre-sequencing has been implemented in the simulation model. The way this has been introduced is as follows. First, for each flight, several time options are generated. The time options are such that a flight can be shifted positively or negatively by 0 to 20 minutes in time. This results in forty time options per flight. This step is necessary in order to give some flexibility to the model to build efficient pre-sequenced arrival flows. Out of all these possible time options, the model is then required to select a single time option for each flight. The selected flight time option must satisfy, at all times, the pre-sequencing separation distance of 5 NM with other flights. This separation requirement is measured in specific areas. These areas have been defined in front of the PMS entry points, and are extending upwards from the ground surface to FL245. To make sure the 5 NM separation is ensured in all cases - even when a 90° turn is flown, the pre-sequencing areas extend to the end of the first segment of each sequencing leg after the system entry point. The pre-sequencing area of the PMS for runway 01 is illustrated in Figure 5.3. The pre-sequencing areas of the other systems can be found in Figures B.2 to B.4 in Appendix B. When selecting the flight time options, the amount of minutes the flights have been shifted in time is minimised to maintain a coherent arrival sequence. Once the pre-sequencing problem solved, the combination of flight time options that has been identified corresponds to the sample used as input in the second part of the model - explained in Section 5.2.5.

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Figure 5.3: Pre-sequencing areas (RWY 01).

The above procedure has been implemented into the simulation model as an optimisation problem. The problem is a mixed integer linear programming problem (MILP) and has been written in *Python*. The solver *Gurobi* (V8.1 64 bits) has been used to optimise the solution, and the processor characteristics are the followings: i7-8700K, 6 cores, 12 threads, 3.7 Ghz and 32 Gb of memory. Hereafter, the sets and decisions variables, the objective function, as well as the constraints used to resolve the complete pre-sequencing problem are provided and discussed;

Sets, Decision Variables & Parameters

- Sets:
  - F: Set of flights i contained in the traffic sample
  - $T(i)$: Set of possible time options j for the flight i
  - $P(i,j;m,n)$: Set of pairs of conflicting flight time options (i,j) and (m,n), with $i \neq m$

  The $P(i,j;m,n)$ set is derived prior launching the optimisation problem. The identification of the pairs of conflicting flight time options is completely separated from the optimisation problem. It is integrated in a conflict calculation module of the simulation tool SAAM. The result of this calculation is a list of pairs of flight time options conflicting with each other. From this list, the conflict constraints are derived.

  The conflict calculation module of SAAM uses the orthodromic distance (law of cosines) to evaluate the distance between two flights at a given point in time. The formula to evaluate the distance between the pairs of flight time options (i,j) and (m,n), with $i \neq m$, at a given point in time t_a, is hereafter provided;

$$dist^{ta}_{i,j;m,n} = R_e \cdot cos^{-1}\left[sin\phi_{i,j} sin\phi_{m,n} + cos\phi_{i,j} cos\phi_{m,n} cos(\lambda_{m,n} - \lambda_{i,j})\right] \tag{5.1}$$

  Where $(\phi_{i,j}, \lambda_{i,j})$ and $(\phi_{m,n}, \lambda_{m,n})$ are the geodetic coordinates of the flight horizontal positions $(i \neq m \in F, j \in T(i), n \in T(m))$

  This calculation is performed for each flight time options in a pre-defined area (pre-sequencing area) at discrete times t_a;

$$t_a = t_0 + a \cdot \Delta t \tag{5.2}$$

  Where t_0 is the simulation start time and Δt equals 1 second.

  The distance between each pair of identified flight time option within the pre-sequencing areas is compared to the minimum separation requirement distance, which is as follows;

$$dist_{pre-seq} = 5NM \tag{5.3}$$

  If $dist^{ta}_{i,j;m,n} < dist_{pre-seq}$, a conflict is detected and the corresponding pair of flight time options is stored in the set $P(i,j;m,n)$.

- Decision variable:
  - $x_{i,j} \in \{0,1\}$: Binary value. $x_{i,j} = 1$ if the time option j is selected for the flight i, else $x_{i,j} = 0$.

- Parameter:
  - $cost_j$: Cost of the time option j. A flight can be positively or negatively shifted in time by a multiple of one minute up until 20 minutes. The cost associated to each time option is linked to the number of minutes it is shifted in time, and can be expressed as in Equation 5.4;

$$cost_j = (\left|j\right| \cdot 100) + 100 \tag{5.4}$$

Objective Function

$$\text{Minimise: } \sum_{i \in F} \sum_{j \in T(i)} cost_j \cdot x_{i,j} \tag{5.5}$$

CONSTRAINTS

The first constraint, expressed by Equation 5.6, stipulates that only one time option j for each flight i of the traffic sample can be selected.

Subject to:

$$\sum_{j \in T(i)} x_{i,j} = 1 \quad \forall i \in F \tag{5.6}$$

Next, selecting flight time options conflicting with each other is out of the question. The constraint expressed in Equation 5.7 is a hard constraint. No conflicting pairs of flight time options are permitted.

And subject to:

$$x_{i,j} + x_{m,n} \leq 1 \quad \forall \text{ conflicting pairs (i,j) and (m,n)} \in P(i,j;m,n), \text{if } P(i,j;m,n) \neq \emptyset \tag{5.7}$$

The output of the pre-sequencing problem is a set of conflict-free flight time options, having a minimum impact on the pre-established arrival sequence. In Table C.1 in Appendix C, the outcomes of the pre-sequencing problem for each tested scenario are presented.

5.2.2. TRAJECTORY GENERATION

The following package consists of an algorithm able to generate all possible trajectory options for each flight. Possible trajectory options are all the routes connecting the sequencing legs to the merge points of the different systems. Only the flight time options identified after the pre-sequencing problem are taken into account.

In the simulation, a route is defined by a segment connecting two points. Therefore, an aircraft can only fly from a sequencing leg to the merge point along pre-established routes. Initially, routes only existed between the waypoints describing each segment of the sequencing legs to the merge points (Figure 5.4). With so few connecting routes, the number of possible trajectories to fly from the sequencing legs to the merge points was considerably limited compared to what could be done in reality. As a matter of fact, a controller handling the traffic using a PMS is able to instruct an aircraft to turn towards the merge points irrespective of its location along the sequencing leg - either on a waypoint or not. For a better approximation of the reality, intermediate points have been added (Figure 5.5). By doing so, the number of trajectory options has been increased, increasing the model flexibility when investigating the best solution. In Table B.1 in Appendix B, the total number of possible trajectories from the sequencing legs to the merge point of each system is provided.

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Figure 5.4: Possible flight trajectories - waypoints only (RWY01).

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Figure 5.5: Possible flight trajectories - intermediate points (RWY01).

The outcome of this phase are sets of possible trajectory options for each flight.

5.2.3. CONFLICT DETECTION

Out of all possible flight trajectories, only the flight trajectory options not conflicting with each other in a pre-defined zone can be valid candidates for an optimal simulation solution. This phase of the model highly resembles to what has been done with the pre-sequencing problem, introduced in Section 5.2.1. The principle is the same but the conflict areas and the separation requirement are different. In this case, the conflict zone identified for each PMS is around the final segment - approximately the last 10 NM in front of the runway threshold. In Figure 5.6, the conflict area of the PMS for runway 01 is presented (see Figures B.5 to B.10 in

Appendix B for the conflict zones of the other systems). The separation requirement selected is 4 NM. 4 NM has been selected to absorb some of the model assumptions detailed in Section 5.3. In reality, the separation between aircraft can go down up to 3 NM on final (see Section 2.2.7). Only loss in longitudinal separation are investigated. Vertical separation is not considered.

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Figure 5.6: Conflict zone (RWY01).

The outcome of this phase is a set of pairs of conflicting flight trajectory options. A pair of conflicting trajectory options is added to the set each time there is a loss of aircraft separation occurring in the established conflict areas.

5.2.4. FIRST IN FIRST OUT

To approximate reality as close as possible, it was necessary to add an extra operational condition to the model. This condition is the principle of first in first out (FIFO). The principle of FIFO is the funding principle of air traffic control. According to this principle, the aircraft entered first in the system should always exit the system before a trailing aircraft.

To integrate such a concept in the model, the pairs of aircraft violating the FIFO rule had to be identified. This is done by recording the entry time and exit time of each aircraft at the system entry point and merge point respectively, and subsequently identifying which aircraft has an exit time inferior to an aircraft with a smaller entry time.

The outcome of this phase is a set of pairs of trajectory options not respecting the FIFO principle.

5.2.5. SOLUTION OPTIMISATION

In order to select the best combination of calculated trajectories without any conflicts rising and satisfying the FIFO principle, an optimisation problem has been derived. As for the pre-sequencing problem, the problem is a mixed integer linear programming problem (MILP). The same server and processor have been used. Hereafter, the optimisation problem is introduced;

SETS, DECISION VARIABLES & PARAMETERS

- Sets:
    - F: Set of flights i contained in the traffic sample
    - S(i): Set of possible trajectory options j for the flight i
    - C(i,j;m,n): Set of pairs of conflicting flight trajectory options (i,j) and (m,n), with $i \neq m$

    The $C(i,j;m,n)$ set is derived prior launching the optimisation problem. The identification of the pairs of conflicting flight trajectory options is completely separated from the optimisation problem. It is integrated in a conflict calculation module of the simulation tool SAAM. The result of this calculation is a list of flight pairs conflicting with each other. From this list, the conflict constraints are derived.

The conflict calculation module of SAAM uses the orthodromic distance (law of cosines) to evaluate the distance between two flights at a given point in time. The formula to evaluate the distance between the pair of flight trajectory options (i,j) and (m,n), with $i \neq m$, at a given point in time t_a, is hereafter provided;

$$dist_{i,j;m,n}^{t_a} = R_e \cdot cos^{-1}\left[sin\phi_{i,j} sin\phi_{m,n} + cos\phi_{i,j} cos\phi_{m,n} cos(\lambda_{m,n} - \lambda_{i,j})\right] \tag{5.8}$$

Where $(\phi_{i,j}, \lambda_{i,j})$ and $(\phi_{m,n}, \lambda_{m,n})$ are the geodetic coordinates of the flight horizontal positions $(i \neq m \in F, j \in S(i), n \in S(m))$

This calculation is performed for each flight time option in a pre-defined area (conflict zone) at discrete times t_a;

$$t_a = t_0 + a \cdot \Delta t \tag{5.9}$$

Where t_0 is the simulation start time and Δt equals 1 second.

The distance between each pair of identified flight trajectory options within the conflict area is compared to the minimum separation requirement distance, which is as follows;

$$dist_{separation} = 4\text{NM} \tag{5.10}$$

If $dist_{i,j;m,n}^{t_a} < dist_{separation}$, a conflict is detected and the corresponding pair of flight trajectory options is stored in the set $C(i,j;m,n)$.

- $R(i,j;m,n)$: Set of pairs of flight trajectory options (i,j) and (m,n), with $i \neq m$, violating the FIFO principle

  As for the construction of the $C(i,j;m,n)$ set, the $R(i,j;m,n)$ set is built prior running the optimisation problem. For each flight trajectory option, the time of entry in (entry points) and exit of (merge point) the system are recorded and stored in a file. After that, a process takes place to identify which pairs of flight trajectory options violate the FIFO principle.

  If $t_{i,j}^{entry} < t_{m,n}^{entry}$ and $t_{i,j}^{exit} > t_{m,n}^{exit} (\forall i \neq m \in F, j \in S(i), n \in S(m))$, then the pair (i,j) and (m,n) is identified as a pair of flight trajectory options violating the FIFO principle and is stored in the $R(i,j;m,n)$ set.
  Where;

  - $t_{i,j}^{entry}$: Entry time in the system of the flight trajectory option (i,j)
  - $t_{m,n}^{entry}$: Entry time in the system of the flight trajectory option (m,n)
  - $t_{i,j}^{exit}$: Exit time of the system of the flight trajectory option (i,j)
  - $t_{m,n}^{exit}$: Exit time of the system of the flight trajectory option (m,n)

  The result of this process is a list of flight trajectory options not respecting the FIFO principle. From this list, the FIFO constraints are derived.

- Decision variable:
  - $x_{i,j} \in \{0,1\}$: Binary value. $x_{i,j} = 1$ if the trajectory option j is selected for the flight i, else $x_{i,j} = 0$.
  - $d_i \in \{0,1\}$: Binary value. $d_i = 1$ if the flight i has to be deleted, else $d_i = 0$.
  - $c_{i,j;m,n} \in \{0,1\}$: Binary value. $c_{i,j;m,n} = 1$ if the flight trajectory options (i,j) and (m,n) are conflicting, else $c_{i,j;m,n} = 0$.
  - $r_{i,j;m,n} \in \{0,1\}$: Binary value. $r_{i,j;m,n} = 1$ if the flight trajectory options (i,j) and (m,n) do not respect the FIFO principle, else $r_{i,j;m,n} = 0$.

- Parameters:
  - $cost_j$: Cost of the trajectory option j
  - $cost_C$: Cost of allowing a conflict to rise on final between two different flight trajectory options
  - $cost_R$: Cost of violating the FIFO principle
  - $cost_D$: Cost of deleting a flight

  The values of these cost parameters are provided in Table 5.2.

Table 5.2: Cost values for the optimisation problem.

$cost_j$	$cost_C$	$cost_R$	$cost_D$
$(j)^2$	15,000	8,000	30,000

Except the cost of the trajectory options - $cost_j$, all the costs are integer numbers. Regarding the $cost_j$, the longer an aircraft flies along a sequencing leg, the higher is its trajectory associated cost. A quadratic increase has been used to motivate the model to select trajectory options making the aircraft fly the less possible NM along the sequencing legs. The largest number of possible trajectory options of the investigated PMS is 66 - along the ORA and BLU leg of the PMS for runway 19, which results in a maximum $cost_j$ of 4356. For the $cost_R$, 8,000 has been chosen. Using a number almost twice as large than the maximum possible $cost_j$ was the strategy to best approximate reality. Furthermore, as it is the lowest cost of all the costs - except $cost_j$, it means that violating the FIFO principle is preferred than seeing a conflict rising between two aircraft or deleting flights from the traffic samples. Still, it is to be avoided when possible. The order of priority, as well as the ratio from one cost to another, has been derived following discussions with controllers. It is possible to play around with these parameters. However, to match reality as close as possible, this combination of cost values revealed to be appropriate.

OBJECTIVE FUNCTION

The final simulation results are such that the overall cost is minimised.

$$\text{Minimise: } \sum_{i\in F}\sum_{j\in S(i)}\Big[(cost_j\cdot x_{i,j})+\sum_{(m,n)\in C(i,j;m,n)}(cost_C\cdot c_{i,j;m,n})+\sum_{(m,n)\in R(i,j;m,n)}(cost_R\cdot r_{i,j;m,n})\Big]+\sum_{i\in F}(cost_D\cdot d_i) \tag{5.11}$$

CONSTRAINTS

The first constraint of the model, expressed in Equation 5.12, forces the model to select a single trajectory option j per flight i or to delete the flight i from the traffic sample if no satisfactory solutions can been found. The latter is performed at a high cost ($cost_D$).

Subject to:

$$\sum_{j\in S(i)} x_{i,j}+d_i=1 \quad \forall i\in F \tag{5.12}$$

The second constraint is there to make the model select pairs of flight trajectory options not conflicting with each other. This is done by imposing a high cost if not the case ($cost_C$).

And subject to:

$$x_{i,j}+x_{m,n}-c_{i,j;m,n}\leq 1 \quad \forall \text{ conflicting pairs (i,j) and (m,n)} \in \text{S(i,j;m,n), if S(i,j;m,n)} \neq \emptyset \tag{5.13}$$

Finally, to make sure the FIFO principle is always respected, a last constraint has been added to the model. If this constraint is not respected, a high cost is imposed ($cost_R$).

And subject to:

$$x_{i,j}+x_{m,n}-r_{i,j;m,n}\leq 1 \quad \forall \text{ pairs (i,j) and (m,n) violating the FIFO principle} \in \text{R(i,j;m,n), if R(i,j;m,n)} \neq \emptyset \tag{5.14}$$

After having run the optimisation problem for the different scenarios presented in Section 4.3 and prior to analysing the simulation results (Chapter 6), one can consult Section C.3 in Appendix C where the optimisation parameters (simulation time, MILP gap and problem matrix size) are presented.

5.2.6. VERIFICATION & VALIDATION

Verification and validation are tasks that have been continuously performed all along the simulation model development. Even before developing the model, validation tasks have been undertaken. To make sure the selected traffic samples presented in Section 5.1.2 were realistic data, a series of checks have been carried out. As a matter of fact, if the simulation model inputs are not correct, it is very unlikely that valuable outputs can later be gathered. Furthermore, each time a new module was added to the simulation model or a modification was made, the simulation outcomes have been carefully analysed. Adjustments of the model have been undertaken when required to approximate reality as best as possible.

5.3. MODEL ASSUMPTIONS

Any simulation tool has limitations preventing a faithful representation of the reality. From these limitations, a series of assumptions often emerge when developing a model. Being aware of them is primordial to understand and interpret the simulation results;

- Aircraft entering the PMS are pre-sequenced. A separation requirement of 5 NM has been imposed.
- All aircraft are sent to the PMS, irrespective of the traffic load and complexity. Controller flexibility has not been integrated in the model.
- Discrete turning points are used in the simulation. The aircraft are only able to turn towards the merge points when on top of one of these turning points. In reality, an aircraft can be sent towards the merge point irrespective of its location along the sequencing legs.
- With SAAM, only fly-over waypoints can be simulated. In reality, fly-by waypoints along the sequencing legs of the different PMS and at strategic locations are foreseen to increase the operational flexibility in case of low traffic density and allow feasible turn angles towards the merge points, as well as to the runway thresholds.
- Only nominal conditions are simulated. Non-nominal conditions, such as emergencies, technical failures, adverse meteorological conditions and sequencing leg run-offs, are not considered. All aircraft are kept on the designed PMS routes. There are no trajectory deviations.
- All aircraft are assumed to be equipped with the necessary technology, namely RNAV1.
- All ground equipment was assumed to be operating and all sectors and positions were assumed to be open and fully manned.
- Traffic mix (heavy, medium, light) has been ignored. Homogeneous traffic samples have been used to run the simulations. All aircraft of the traffic samples are considered to be Airbus A320.
- All aircraft are flying at the same speed at the same altitude levels. The aircraft behaviour is homogeneous in the systems.
- A constant, equal airspeed has been imposed along the sequencing legs of all PMS.
- The profile processing takes into account the aircraft performance stored in BADA, as explained in Section 5.1.1. As a single aircraft type has been selected to make all the aircraft of the simulation fly at the same indicated airspeed along the sequencing legs, all aircraft also have the same performance regarding the rate of descent.
- A separation of 4 NM has been set as criterion to detect conflicts in final.
- When two incoming streams are merged prior to being loaded on one common sequencing leg (e.g. PMS for runway 01 and 07L), distinct altitudes are assigned to each stream to ensure vertical separation when merging. The assigned altitudes have to be maintained all along the sequencing leg. Due to the model limitations in terms of altitude constraints and segment parity - one parity per segment, two different altitudes cannot be attributed to a single sequencing leg. Since SAAM can only provide an altitude to fly at or below and optimise the vertical profile when descending, the highest altitude of the two merging flows is considered in the simulation along the leg.

- When simultaneous dependent and independent approaches are simulated with the PMS for runways 25L/R, traffic crossing has not been considered. Aircraft coming from the east can only land on runway 25L and aircraft coming from the west on runway 25R only.
- The first in first out principle has been considered when developing the simulation model to best reflect reality. However, to give flexibility to the simulation, violation of this rule migh occur possible.
- To evaluate the optimum potential of the PMS designed for EBBR, arrivals only are considered.
- The major limitation of SAAM is undeniably the wind effects not possible to simulate. In reality, the wind has a major impact on the air traffic operations, in particular for departing and arriving traffic.

6

Result Assessment

While every precaution has been taken to approximate reality as best as possible, one cannot forget that the results presented in this chapter have been calculated by a computer model. Carefully analysing these results was therefore of utmost importance to best interpret them.

This chapter contains quantitative as well as qualitative analyses. In Sections 6.1 to 6.6, the results of the analysis on mileage, system capacity, sequencing time, vertical profiles, controller workload and track dispersion, are respectively discussed. Finally in Section 6.7, a preliminary safety check is provided.

6.1. Mileage

One of the analyses that could motivate the implementation of PM at EBBR was the impact on the track miles flown. To evaluate this impact, 2D comparisons have been carried out. Each scenario presented in Section 4.3 has been separately tested by comparing radar tracks - radar vectoring - to their corresponding calculated trajectories - PM. As PM only impacts the approach phase of the flights, focus for this analysis has been on the terminal airspace around EBBR. In Figures 6.1 to 6.4, the zones within which the NM comparisons between radar tracks and calculated trajectories have been undertaken are displayed. The zones extend from the ground upwards to FL245 - the upper limit of the airspace under the responsibility of *skeyes*. The radar tracks are represented in green while the calculated trajectories along the PMS are highlighted in red.

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Figure 6.1: NM comparison zone (PMS for RWY01).

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Figure 6.2: NM comparison zone (PMS for RWY19).

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Figure 6.3: NM comparison zone (PMS for RWY07L).

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Figure 6.4: NM comparison zone (PMS for RWY25L/R).

Table 6.1 provides, for each tested scenario, the average difference in NM between what has been flown with radar vectoring and what would be flown with a PMS.

Table 6.1: Average NM differences when comparing radar tracks to calculated trajectories.

PMS	**Average NM difference [NM/aircraft]**
RWY01	16.59
RWY19	6.94
RWY07L	2.92
RWY25L	6.56
RWY25L BATLNO	6.60
RWY25L/R SimDep	1.19
RWY25L/R SimIndep	1.55

The results presented in Table 6.1 have been highly criticised by controllers. The majority of the NM observed when comparing a radar track to its corresponding PMS trajectory is due to the lack of flexibility in the FTS. With the simulation model, any form of controller flexibility has been prohibited. All aircraft are sent to the systems, irrespective of the traffic load and complexity. In reality, in case of low traffic conditions and complexity, aircraft could be sent straight to final, without the need of overflying the system entry points. In Figure 6.5, an example is provided to illustrate this point. Instead of making all aircraft fly along the red trajectory, the green trajectory could be followed if the traffic situation allows it. Trajectory deviations from the standard PMS routes can only follow a controller instruction.

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Figure 6.5: Comparison of traffic routing.

The results presented in Table 6.1 are therefore not representative of what could be achieved in reality with the different PMS designed for EBBR. Based on this observation, PM at EBBR would only have an added value if used during periods of medium to high traffic load and/or complexity. Outside these periods, shortcuts along the PMS routes should be made available to give controllers the flexibility to direct aircraft straight to final without entering the systems. If flexibility is appropriately integrated to the concept of PM, mileage improvements could even potentially be obtained. To get better insight of what could be achieved at EBBR, RTS would need to be undertaken.

Note 1: The NM comparison for the PMS for runway 25L (nominal and balanced traffic distribution) reveals larger numbers than for the operational models of simultaneous dependent and independent approaches (25L/R). This difference directly comes from the operational model. Runway 25L is not a runway system commonly activated at the airport. It is usually activated in really low traffic conditions, and therefore all aircraft can be sent straight to final from the different IAFs. When comparing the PMS trajectories to these direct routes, it is logical that larger NM differences are obtained. When the traffic load increases, simultaneous dependent and independent approaches are allowed. Handling larger volumes of traffic inevitably results in less straightforward manoeuvres. Therefore, the difference in NM flown is less impacted when comparing the radar tracks to their corresponding calculated trajectories.

Note 2: From the results in Table 6.1, it can also be seen that there is only a slight difference between the results for the PMS for runway 25L with the nominal and balanced traffic distribution. This does not justify so far a traffic restructuration between the navigational points BATTY and LNO.

6.2. SYSTEM CAPACITY

EBBR, as numerous other airports all around the world, is likely to be impacted by the continuous growing of air traffic demands (193,300 TMA movements predicted at the airport in 2024 [26]). The feasibility of a PMS at EBBR therefore also depends on the system ability to handle large volumes of air traffic during long periods of time.

Before carrying out any analyses, a common understanding of what is meant by maximum system capacity is required. In this case, the maximum PMS capacity is defined as the maximum number of aircraft that can be handled by the system, in a specific period of time, without making use of conventional holding stacks.

The strategy used to evaluate the maximum system capacity of each PMS was to feed the simulations with traffic samples containing a number of aircraft equal or superior to the maximum runway capacity throughput - arrivals only (see Table 2.1). As a matter of fact, the maximum runway capacity throughput is considered as a hard upper limit regarding the number of aircraft that can land at an airport. Out of these inflated traffic samples, all flights for which no solution was found without violating one of the model constraints - presented in Section 5.2.5 - have been removed. Such a procedure is referred to as a stress test. Deleting flights has been made automatic by introducing the decision variable d_i in the constraint expressed by Equation 5.12. Furthermore, the value of the cost parameters introduced in Section 5.2.5 have been adjusted to ease the simulation efforts. The adjusted cost values for the stress tests are provided in Table 6.2.

Table 6.2: Cost values for the stress tests.

$cost_j$	$cost_C$	$cost_R$	$cost_D$
(j)	800	200	400

For the stress tests, the $cost_R$ remains the lowest cost with the exception of the $cost_j$. What has changed with respect to the cost values presented in Section 5.2.5 in Table 5.2 is that now the $cost_D$ is lower than the $cost_C$. This means that aircraft are more easily deleted than conflicting with another aircraft. The reason to keep the cost of violating the FIFO rule $cost_R$ lower than the one of deleting a flight $cost_D$ is to avoid the simulation model to delete flights to easily without investigating the best solution possible.

To obtain large, though realistic traffic samples, a traffic forecast has been generated. The time period selected is the Friday 5^{th} of September 2025 from 06:00 to 08:00 UTC. This forecast has been retrieved from the demand data repository (DDR) of *EUROCONTROL*. During this time period, a total of 92 arrivals have been identified. As the traffic demand during this specific period of time is larger than the maximum runway capacity throughput of all single runway operations (see Table 2.1), the maximum system capacity of the PMS for runway 01, 19, 07L and 25L has been tested with this traffic sample. Generating a traffic sample containing more flights than the maximum runway capacity throughput for runways 25L/R when simultaneously used was more challenging since such a traffic volume is not predicted for at least the next seven years [26]. For a two hour period, a traffic sample of 150 aircraft was required. To do so, a specific tool has been used. Based on a reference traffic sample and the percentage of extrapolation needed, a new traffic sample could be created. By using the previously forecasted traffic sample as baseline scenario and a percentage increase of 66%, a traffic sample of 153 flights has been established.

After having run the different scenarios with the adjusted cost values and inflated traffic samples, results about the maximum system capacity have been obtained. These can be found in Table 6.3. Hereafter, the parameters that have to be kept in mind when analysing the capacity results are listed;

- Only arrivals have been considered. This has been done in order to evaluate the maximum system capacity that could possibly be reached.
- Please note that the arrival declared runway capacity numbers - presented in Table 6.3 - have been theoretically derived and rely on optimal operational conditions. Variations are likely to happen in reality due to mixed operations and external factors (e.g. wind).
- The model assumptions of homogeneous traffic and constant/equal airspeed in the systems are other factors optimising the results compared to what could be achieved in reality.
- A finite number of segments connecting the sequencing legs to the merge points have been defined in the simulation (see Section B.1 in Appendix B). In reality, the possibilities to send an aircraft from the sequencing legs to the merge points is infinite. Although a large number of connecting segments has been created in the simulation, discrepancies might rise due to the discrete nature of the simulation.
- Aircraft enter the systems pre-sequenced, with a lateral separation of 5 NM.

Table 6.3: Maximum PMS capacity - arrivals only - Confidential data.

PMS	**Declared capacity (/2hrs) [7]**	**PMS maximum capacity (/2hrs)**
RWY01		
RWY19		
RWY07L		
RWY25L		
RWY25L BATLNO		
RWY25L/R		

Comparing the maximum PMS capacity numbers to their corresponding declared runway capacity, it can be seen that in all cases, the designed PMS are able to maximise the runway capacity throughput. This maximisation of the runway throughput directly comes from the way the landing sequence is organised. The procedure systematisation, as well as the traffic pre-sequencing performed at higher altitudes, facilitates the traffic flows and ultimately leads to the possibility to handle larger volumes of traffic during longer periods of time than nowadays the case. As a matter of fact, such arrival rates cannot be maintained during extended periods of time with radar vectoring as it is a highly demanding procedure - especially during peak periods.

Based on the above observations, it can be concluded that PM at EBBR has the potential to maximise the runway capacity throughput, as well as to maintain it during longer periods of time than nowadays possible with radar vectoring, with high accuracy and current staffing levels.

Note 1: Regarding the maximum system capacity for the PMS for runway 25L with the nominal and balanced traffic sample, there is a negligible difference in the results. It can therefore be concluded that the designed system for runway 25L is perfectly capable of handling a traffic volume with a distribution between BATTY and LNO as nowadays experienced.

Note 2: The results for runways 25L/R could be increased if traffic crossing was considered. In the simulation, aircraft coming from the east can only land on runway 25L and those coming from the west on runway 25R only. In reality, crossing is allowed. This means that if one of the two runways becomes saturated, the traffic coming to land on it can be sent onto the other runway, maximising the number of aircraft that can land in a given period of time.

6.3. SEQUENCING TIME

Another relevant criterion to analyse is how efficiently a continuous pressure can be maintained on the runway capacity throughput. In this case, efficiency is the average time the aircraft have to fly along the sequencing legs before being turned - at the most appropriate time - towards the merge point. Therefore, the average aircraft sequencing time has been looked at. In Table 6.4, the simulation results are presented.

Table 6.4: Average leg extension and sequencing time in nominal peak periods and with the stress tests.

PMS	**Nominal peak period**		**Stress test**	
	Average leg extension [NM]	**Average delay absorbed [min]**	**Average leg extension [NM]**	**Average delay absorbed [min]**
RWY01	6.4	1.7	8.5	2.2
RWY19	3.4	0.9	7.0	1.8
RWY07L	3.8	1.0	5.5	1.4
RWY25L	3.9	1.0	10.0	2.6
RWY25L BATLNO	2.4	0.6	9.3	2.4
RWY25L/R SimDep	8.1	2.1	4.5	1.2
RWY25L/R SimIndep	5.7	1.5	4.9	1.3

In nominal peak conditions, the largest average sequencing time has been observed for runways 25L/R with simultaneous dependent approaches. An average time of 2.1 minutes has been absorbed by the aircraft entering this PMS. Following this result, 1.7 and 1.5 average minutes of sequencing time have been absorbed by the PMS for runway 01 and 25L/R with simultaneous independent approaches. Out of the PMS for single landing operations, the PMS for runway 01 is the system that scores the less good. Respecting the airspace constraints at the south of the airport, the PMS has been positioned in a way which somehow jeopardises the system performances. A redesign could help improving this result. Regarding the impact of the traffic distribution on the performance of the PMS for runway 25L, a small decrease of the average delay absorbed is observed when the traffic coming from the east is evenly distributed between BATTY and LNO. Imposing new regulations to achieve in real life such a distribution is therefore not a must. 1 minute on average has been absorbed when the PMS for runway 07L and 25L has been tested.

Now, comparing the results obtained in nominal peak periods to those of the stress tests, the average time flown by the aircraft along the sequencing legs has increased. This is logical as more aircraft needed to be handled. They flown longer along the sequencing legs before being turned towards the merge points. However, two PMS violate this observation. These are the PMS for runways 25L/R with simultaneous dependent and independent approaches. The explanation for it is that the simulation runs for the stress tests have been stopped after a pre-defined period of time - 5,000 seconds (see Section C.3 in Appendix C). The solutions obtained, even if satisfying all simulation requirements, are suboptimal. When evaluating the maximum system capacity of the different PMS, the model had the possibility to delete flights from the traffic sample. It seems that, in these particular cases, the model has deleted more flights, allowing the others to be turned sooner to the merge points. However, still 126 and 136 aircraft have been handled which is more than the 67 aircraft of the traffic sample tested for the nominal peak period. This means that the traffic distribution of the sample used was also better.

Another parameter interesting to look at regarding sequencing time is the portion of the sequencing legs used. In Table 6.5, such information is provided for both sets of simulation runs - nominal peak periods and stress tests. In all cases, the majority of the aircraft have turned towards the merge points before having reached the half of the sequencing legs.

Table 6.5: Use of the sequencing legs in nominal peak periods and with the stress tests.

PMS	**Nominal peak period** **1st 1/2 Sequencing legs**	**Stress test** **1st 1/2 Sequencing legs**
RWY01	91%	74%
RWY19	96%	80%
RWY07L	96%	90%
RWY25L	100%	67%
RWY25L BATLNO	100%	66%
RWY25L/R SimDep	80%	100%
RWY25L/R SimIndep	94%	91%

The size of the traffic volume handled, the way the system is fed and the PMS structure - the number of sequencing legs and their length, are the parameters influencing the use of the first and second half of the sequencing legs. For instance, all aircraft that have flown along the sequencing legs of the PMS for runway 25L - with the regular traffic sample and the balanced one - only flew the first half of the sequencing legs. In these cases, the size of the traffic sample used is smaller relative to the other tested samples. Furthermore, four legs are available to handle the traffic coming from different directions. This unsurprisingly leads to good system performances. In comparison to that, the system for runways 25L/R with simultaneous dependent approaches displays the less good performances. This can be explained, first, by the larger traffic volume handled, secondly by the operational model of simultaneous dependent approaches. When simultaneous independent approaches are performed, the incoming traffic can be sent faster to the merge point than with dependent approaches. As a matter of fact, no separation between aircraft landing on different runways is required. For the PMS for runway 01, 19 and 07L, some aircraft also had to fly along the second half of the sequencing legs. In addition to the number of sequencing legs being 3, the size of the traffic sample is also larger than what has been tested for runway 25L. This can explain why some aircraft had to further extend their trajectory along the sequencing legs prior being sent towards the merge points. Since the sequencing leg MAT of the PMS for runway 01 approaches the TRA South Alpha at exactly 2.5 NM, it has been checked if the extreme end of the leg was used. In nominal peak periods, the closer an aircraft came to the extreme end of the leg was 2 NM.

To explain the results of the different stress tests, the same reasoning applies. The results for the PMS for runways 25L/R with simultaneous dependent approaches are in line with what has been previously discussed due to the suboptimal solution found with the stress tests. The other results reflect what is expected to happen in reality. If larger volumes of traffic have to be handled, the second half of the sequencing legs is likely to be used more. In only one case - runway 25L, an aircraft has flown up to the extreme end of the sequencing leg.

All in all, all systems display acceptable performances in terms of sequencing time. It can be said that the introduction of a PMS at EBBR could reduce the use of conventional holding patterns, if not outright delete it, since the sequencing legs of the different systems proved to be sufficient to absorb the sequencing time. Please note that the results presented in Table 6.4 and Table 6.5 are only valid for the traffic samples used assuming all aircraft had to extend their trajectory along the sequencing legs. They could vary if the traffic samples change in size and distribution. Finally, handling greater volumes of traffic would result in larger sequencing time values.

6.4. VERTICAL PROFILES

From an environmental point of view, the concept of PM in itself does not bring any specific benefits. The system becomes environmentally interesting when combined with the concept of CDO. The objective of the simulation regarding vertical profiles was therefore to verify the possibility to fly optimised descent profiles with the PMS designed for EBBR, and to subsequently assess the associated advantages in terms of noise, fuel consumption and pollutant emissions.

Comparing the vertical profiles flown with radar vectoring to those that could be flown with PM has been a real challenge, mainly due to the simulation tool limitations and the way the model has been built. While the vertical profiles of the radar tracks – radar vectoring - are perfect representations of what has been flown, the situation is far from being realistic when looking at the vertical profiles of the calculated trajectories - PM. Selecting a single aircraft type to run the simulations, as well as imposing airspeed restrictions at specific levels, are manipulations that somehow limited the quality of the generated vertical profiles. A detailed explanation of the consequences of these manipulations is provided in Section C.1 in Appendix C.

Although it was not possible to accurately estimate the delta in performance between a stepwise descent pattern with radar vectoring and a continuous one using a PMS, insight on the current use of CDO at EBBR has been gained by looking at the statistics published by *Brussels Airport* [27]. The airport uses two different indicators to present the CDO results; CDO noise and CDO fuel. CDO noise focuses on the altitude layer ranging from FL60 to 3,000 ft, while CDO fuel is measured from FL100 to 3,000 ft. Such indicators are evaluated through binary analyses. This means that an aircraft is considered to have flown a CDO only if no level off lasting more than 30 seconds occurred. As is later pointed out, such binary analyses have limits. A bad score obtained for these analyses might still result in considerable environmental benefits. Hereafter, the CDO noise and CDO fuel are separately discussed.

In Table 6.6, a high level comparison of what has been done in 2018 in terms of CDO noise to what could be performed with a PMS is provided. With PM, a CDO is theoretically performed from the sequencing legs to the merge point. As the sequencing legs of all designed PMS for EBBR are at FL60 or above, 100% CDO noise could therefore be achieved. In reality, this percentage is likely to be lowered due to special events, such as adverse meteorological conditions, system technical failures, airline policy and parallel runway operations.

Runway	**Radar Vectoring**	**PMS**
RWY01	77.85%	100%
RWY19	63.47%	100%
RWY07L	78.07%	100%
RWY25L/R	76.58%	100%
All	76.27%	100%

Table 6.6: Percentage of CDO noise per runway: radar vectoring (2018) [27] versus PM.

From the results presented in Table 6.6, using a PMS - especially to bring the incoming traffic onto runway 19 - is likely to improve the system performance in terms of CDO noise.

By translating these binary results in corresponding minutes of level off saved and noise reduction, the numbers presented in Table 6.7 are obtained.

Table 6.7: Impact on CDO noise at EBBR with PM - Confidential data.

In comparison with 2018	**CDO noise (FL60 to 3,000 ft)**
Minutes of level off saved	
Noise reduction	
Level off reduction	

Regarding the CDO fuel, the results for 2018 are compared to what could be achieved with a PMS in Table 6.8. In this case, a range from 0 to 55% is provided for PM. As the sequencing legs of the designed PMS have an altitude between FL60 and FL110, the analysis for the CDO fuel was less straightforward than for the CDO noise. 0% would be the binary result obtained if all aircraft are flying more than 30 seconds along the sequencing legs before being turned towards the merge point. This scenario is unlikely to happen as demonstrated by the analysis on sequencing time (Section 6.3). 55% has been derived by looking at the simulation results. On average, during peak periods, 55% of the aircraft have flown less than 30 seconds along the sequencing legs. The analysis only looks at what has been done along the legs – level off or no level off, and neglects what has happened upstream them.

Runway	**Radar Vectoring**	**PMS**
RWY01	44.18%	0-55%
RWY19	50.07%	0-55%
RWY07L	37.60%	0-55%
RWY25L/R	59.91%	0-55%
All	56.33%	0-55%

Table 6.8: Percentage of CDO fuel per runway: radar vectoring (2018) [27] versus PM.

When comparing this range – 0-55% - to the results of CDO fuel in 2018, no improvements can, a priori, be observed. However, a degradation of the binary indicator does not necessary means that no environmental benefits can be achieved. Previously, it have been demonstrated that 100% CDO noise could potentially be achieved with PM at EBBR. Therefore, even if all aircraft level off along the sequencing legs more than 30 seconds - 0% CDO fuel, minutes of level off can be saved when looking at the altitude layer FL100 to 3,000 ft.

A high level estimate has been derived for the saving in minutes of level off, fuel consumption and pollutant emissions. The assumptions taken into account to obtain the numbers presented in Table 6.9 are the following;

- With PM, 100% CDO noise (FL60 to 3,000 ft)
- 49 kg of fuel/minute of level off [28]
- Total number of descents in 2018 at EBBR: 114159 [29]
- Comparison with numbers from 2018 [6]
- Kg/kg of fuel burned: CO2: 3.15, H2O: 1.23, SO2: 0.00084, NOx: 0.0004 [28]
- Avgas: 0.445 €/litre [28]
- Avgas density (15°C): 0.721 kg/litre [28]

Table 6.9: Impact on CDO fuel at EBBR with PM - Confidential data.

In comparison with 2018	**CDO fuel (FL100 to 3,000 ft)**
Minutes of level off saved	
Fuel saving	
CO_2 saving	
H_2O saving	
SO_2 saving	
NO_x saving	
Level off reduction	

To give some additional weight to the fact that a CDO can be flown with a PMS and that it is rarely the case with radar vectoring, two case-by-case analyses have been carried out. Figures 6.6 and 6.7 present these analyses. Please note that in these figures, the vertical axis represents the altitude. It is expressed in FL, although below 4,500 ft - the transition altitude in the Belgium FIR, the altitude should be expressed in ft and not in FL. FL are based on the atmospheric pressure (QNH = 1013) and therefore the results presented are only valid in standard atmospheric conditions.

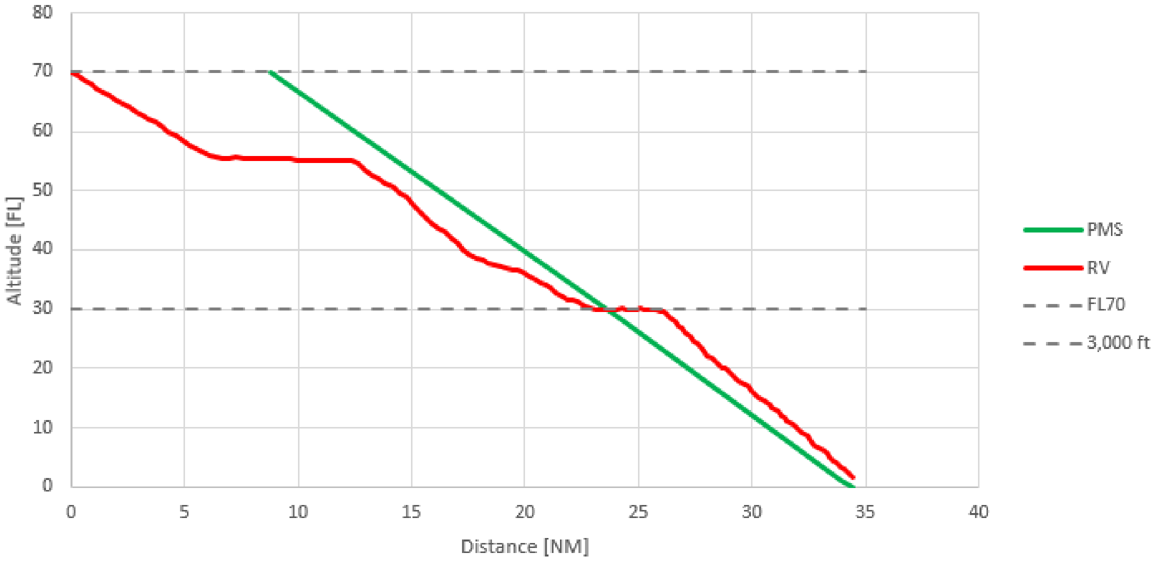

Figure 6.6: Vertical profile comparison (RWY 19, ADEP: LEMD, ADES: EBBR, date: 30/03/2018).

In Figure 6.6, the vertical profiles with radar vectoring (red curve) and PM (green curve) for a flight coming from the south west to land on runway 19 is presented. When radar vectoring is used, the vertical profile flown by the aircraft is discontinuous. In this particular case, one big level-off has been flown between FL70 and 3,000 ft. This altitude range corresponds to the one from the sequencing leg BLU of the PMS of runway 19 to the merge point. The level-off occurred at FL75. At 3,000 ft, another level-off occurred. However, this one is not considered as an interruption in the continuous descent profile since it corresponds to the stabilisation level prior intercepting the ILS localiser. When now looking at the green curve - the vertical profile flown with a PMS, the trajectory is continuous from FL70 to 3,000 ft. In this case, the CDO even extends from the sequencing leg to touch-down.

In Figure 6.7, another analysis for an arrival on runway 25R is presented.

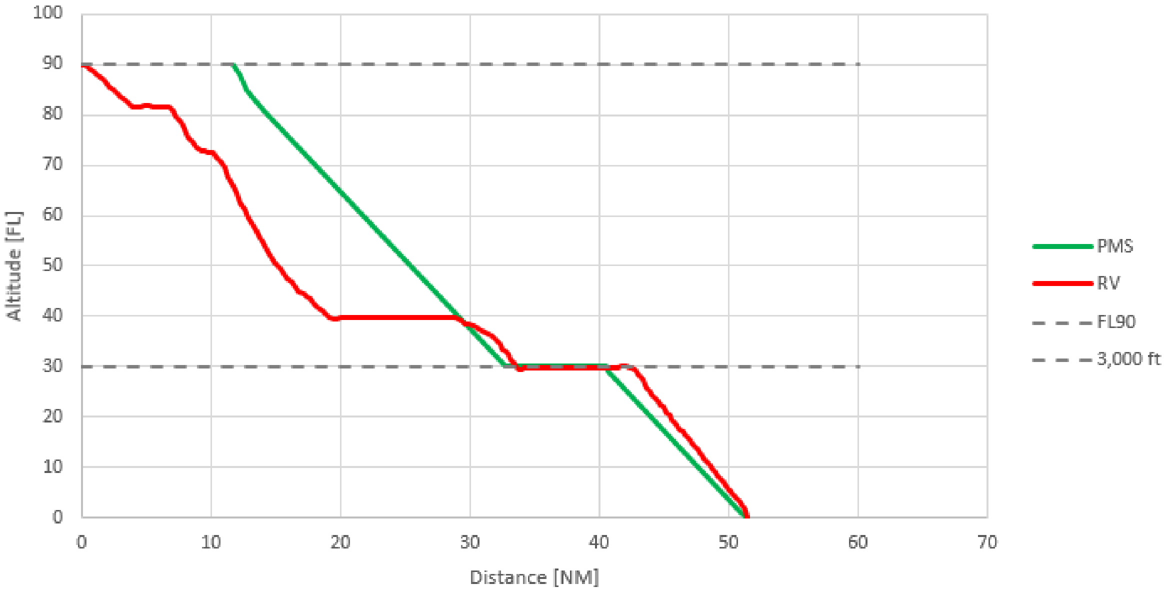

Figure 6.7: Vertical profile comparison (RWY 25R, ADEP: CYUL, ADES: EBBR, date: 18/06/2018)

Once more, a stepwise descent has been flown by the aircraft when guided with radar vectoring (red curve). Three level-offs can be distinguished between FL90 (WOD leg) and 3,000 ft (merge point). In this altitude layer, the PM trajectory is continuous within this altitude layer. Compared to the situation presented in Figure 6.6, the calculated trajectory interrupts its continuous descent at the merge point, instead of extending it to the runway threshold. It is interesting to see that levelling off at 3,000 ft is also something done with radar vectoring. In reality, to intersect the ILS localiser or the glide slope, the aircraft has to be at a specific altitude at a certain distance from the runway threshold. If kinetic energy has to be dissipated or the aircraft is too low too far from the runway threshold, a stabilisation level can be flown.

With PM, the concept of CDO can be further exploited than by limiting its application in a specific altitude layer. Three phases could eventually be designed to optimise its use. By initiating a CDO from the en-route segments to the entry points of the systems and allowing a CDO along the sequencing legs before descending towards the merge points could result in a CDO initiated at higher altitudes than the ones of the sequencing legs. The first extension of CDO would however require a lot of vertical and lateral airspace to give the possibility to the aircraft coming from high altitudes to descend along a smooth profile with a descent rate coherent to what would be flown in the system. This is hardly possible to implement at EBBR. Regarding a CDO along the sequencing leg, this is possibly achievable only on the most inner leg of the system for safety reason, negatively impacting the system capacity. It has therefore been decided for the PMS at EBBR to impose strict altitude constraints along the sequencing legs, with the possibility for the controllers to assign different altitude levels along the most inner leg of the system if judged appropriate.

In sum, environmental benefits are to be expected with the introduction of PM in the terminal airspace of EBBR due to the possibility to perform CDO from the sequencing legs to the merge points. At best, CDO can be extended to the interception with the ILS localiser or the glide slope. Following this fact, noise pollution, fuel consumption and noxious emissions can be lowered.

6.5. CONTROLLER WORKLOAD

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Figure 6.8: Controller workload level - approach & final sectors (date: 09/09/2016, RWY25L/R, MIL OFF).

6.6. TRACK DISPERSION & OVERFLOWN AREAS

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Figure 6.9: 2D comparison of radar tracks with calculated trajectories (RWY01, similar traffic conditions).

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Figure 6.10: Worst case scenario: complete PMS coverage (RWY01).

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Figure 6.11: 2D comparison of radar tracks with calculated trajectories (RWY19, similar traffic conditions).

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Figure 6.12: Worst case scenario: complete PMS coverage (RWY19).

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Figure 6.13: 2D comparison of radar tracks with calculated trajectories (RWY07L, similar traffic conditions).

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Figure 6.14: Worst case scenario: complete PMS coverage (RWY07L).

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Figure 6.15: 2D comparison of radar tracks with calculated trajectories (RWY25L/R, similar traffic conditions).

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Figure 6.16: Worst case scenario: complete PMS coverage (RWY25L/R).

6.7. SAFETY CHECK

In this section, a high level safety check for the use of PMS at EBBR is provided. Focus is on the impact of implementing such a strategy on controllers (Section 6.7.1), procedures (Section 6.7.2) and systems (Section 6.7.3). When applicable, safety barriers are provided. Please note that this safety check does not substitute in any case the safety assessment required before implementation.

6.7.1. IMPACT ON PEOPLE

Controllers are undoubtedly the stakeholders that will be the most reluctant to the introduction of this new strategy. Hereafter, the impacts of using a PMS on the controllers are listed. Actions to minimise the safety impact are also provided.

- The new procedure will provide the controllers with a structured and intuitive way of building and maintaining the landing sequence. This will ultimately lead to a standardisation of the controlling performances between controllers.

- The new procedure seeks to decrease the level of ATC intervention, and relies on straightforward clearances and instructions. In addition to reducing workload, this should diminish the risk of errors and misunderstandings, even in high density TMAs, and result in a better situational awareness for the controllers.

- With PM, the method is less demanding, possibly leading to a loss of vigilance, boredom and a rise in human errors. However, being able to handle bigger volumes of traffic could compensate for this decrease in satisfaction.
- The internal ATC units impacted are Brussels ACC and Brussels APP. A change in roles and task allocation between the controllers is required. Controllers will need to adapt to new working method. To end up with a clear, balanced and non-confusing task sharing model, a clear training of the controllers will have to be established. This training should cover the following operational aspects;
  - Traffic transfer from ACC to APP sectors
  - Traffic transfer from APP controller to final director
  - Transfer from radar vectoring to PMS and vice versa
  - New phraseology
  - Transfer from one runway system to another, from one PMS to another
  - Contingency procedures in case of non-nominal situations

6.7.2. IMPACT ON PROCEDURES

The ATC environment affected by the introduction of a PMS at EBBR is the terminal airspace around the airport. Hereafter, the main characteristics of the procedure with a PMS, as well as the implications for the controllers, are described.

- There will be no change with respect to the ATC goals, which are to enable a safe, expeditious and orderly flow of air traffic. It is expected that there will not be any regulatory issues, in particular regarding ICAO PANS-ATM (Doc 4444). Separation minima and spacing will still be based on distance.
- The objective is to effectively integrate the arrival flows, while keeping aircraft on lateral navigation, even at high traffic loads. In this context, radar vectors should only be used to recover from unexpected situations.
- PM is to be used during medium to high traffic loads and complexity.
- A clear coordination with the military will be required for an optimal use of the airspace according to the user needs.
- Involvement of the surrounding ATC units LVNL and DSNA might be required for pre-sequencing tasks and vertical profile optimisation.
- Delaying or expediting aircraft through path stretching or shortening will be performed in a more flexible manner than with current P-RNAV applications in TMA. The use of conventional holding stacks is minimised when a PMS is activated.
- Radar vectoring, together with speed control, remains a principal control strategy at EBBR after the introduction of PM, amongst others to maintain a certain level of flexibility, handle non-equipped aircraft, non-nominal situations and during low traffic conditions.
- The controllers will need to get used to the unusual situation where aircraft have to fly along legs vertically separated and possibly of opposite directions, and to merge on a point rather than an axis. Integration of arrival flows is achieved on a common point using the "Direct to" instructions. A close monitoring of the aircraft flying to this common point is required to ensure in all times lateral separation.
- In case of non-nominal situations, alternative routes and procedures are available to ensure undisturbed operations while maintaining satisfactory safety levels. These non-nominal situations, together with a high level description of their contingency procedure, are hereafter listed. In most cases, the use of alternative routes, radar vectoring, speed control and capture holdings are considered to deal with these situations.
  - Adverse meteorological conditions affecting the system

  - Technical failure such as RNAV equipment and aircraft FMS
  - Communication failure
  - Emergency including aircraft running low on fuel and technical issues
  - Non-equipped aircraft to fly RNAV1 routes
  - Handling of non-homogeneous traffic mix
  - Missed approaches
  - Sequencing leg run-off
  - Runway closure
  - Demand exceeds capacity

- To make sure the airline operators operating at EBBR are aware of these procedures, as well as the nominal procedure when a PMS is used, information sessions will have to be organised.

- All the changes in procedures will be documented in the following documents;

  - Belgium and Luxembourg Aeronautical Information Publication
    - Flight procedures
    - Instruments Approach Charts
    - Standard Arrival Charts
  - Operations and supervisor manuals for Brussels ACC and APP (WIGU 0249, 0132, 0140 & 0133)
  - Letters of Agreement describing standard working method between Brussels ACC and Brussels APP for the arrivals on the different runways (special procedures a01, a02, a03 and a04)

- Suggested best practices and lessons learnt acquired from existing applications have been referred to during the development process.

6.7.3. IMPACT ON SYSTEMS

The proposed new procedure associates a dedicated route structure with a systemised operating method to integrate arrival flows with extensive use of RNAV. Hereafter, the requirements in terms of equipment and systems for the different interfaces impacted by the introduction of a PMS at EBBR are discussed.

- The introduction of a PMS would require the introduction of new waypoints defining the new RNAV routes.

- The structure of the new RNAV routes is compliant with safety guidelines specifying realistic turns, minimum lateral and vertical separation requirements and other design specifications, as higher altitudes on the inner legs than on the outer ones and no head-to-head convergence.

- No investments in new equipment are required for neither the airport, the ground operators or the airline operators.

- For an optimal use of the system, a new arrival manager should be acquired by *skeyes*.

- Hereafter are listed the systems that would be impacted by the implementation of a PMS at EBBR;

  - Aircraft FMS
  - AMAN
  - Controller display screen
  - Short-term conflict alert (STCA)
  - AMS
  - EUROCAT
  - Re-categorisation of wake turbulence separation minima (RECAT)

7

CONCLUSIONS, DISCUSSIONS & RECOMMENDATIONS

The conclusions on the applicability of PM at EBBR are provided in Section 7.1. In Section 7.2, the conditions for optimised system performances, as well as for a successful implementation, are discussed. Finally, recommendations for future work are elaborated in Section 7.3.

7.1. CONCLUSIONS

In order to efficiently accommodate the future, continuously growing air traffic demands at EBBR, as well as to avoid an impending saturation of the terminal airspace, the concept of PM revealed to be a potential solution. The characteristics of PM that made it at first glance an interesting arrival procedure for the airport are the embedded CDO, the procedure systematisation, the possibility to maximise the runway capacity throughput and to decrease the controller workload, while maintaining - if not improving - current levels of safety, punctuality and efficiency. To verify if all these elements could be achieved in the dense and complex operational environment of EBBR, a feasibility study has been carried out.

Conclusions on the applicability of PM at EBBR have been drawn by comparing the system performances that could potential be achieved with PM to those nowadays achieved with radar vectoring. To do so, FTS have been undertaken and focus has been on system capacity, sequencing time, vertical profile, controller workload, impact on mileage and environment. At the end, it has been concluded that introducing the concept of PM in the terminal airspace of EBBR was feasible and an attractive solution for several reasons. Hereafter, the study findings are summarised;

- The PMS at EBBR should be introduced and published as RNAV transition routes in the terminal airspace.
- The PMS are to be used during medium to high traffic loads and complexity. Outside these periods, shortcuts should be possible to minimise the track miles flown by each aircraft.
- Radar vectoring and speed control would remain available tactical control strategies. Mainly, these strategies would be used during non-nominal conditions, as well as to avoid and resolve conflict infringements.
- The use of conventional holding stacks could be decreased, resulting in better flight predictability and minimised arrival delay.
- Direct RNAV routes along the PMS should be available as reference routes for an optimal fuel planning and management.
- The possibility to maintain current runway throughput during longer periods and with high accuracy rises. Runway throughput maximisation with current staffing levels and low sequencing delay could be achieved.

- Flight efficiency and predictability could be increased by keeping the aircraft on FMS trajectories. Minimising the uncertainties in aircraft trajectories would enable better anticipation of the traffic evolution by the controllers.
- Safety would be maintained, possibly enhanced. Reduction in controller workload in TMA sectors, decreased frequency occupancy, as well as a better situational awareness of the controllers and flight crews, are all factors contributing to a safe handling of the air traffic.
- The system structure and procedure systematisation are likely to lead to standardisation of the controller performances.
- Using a PMS at EBBR is expected to lead to environmental benefits in terms of noise and noxious emissions at low levels due to the concept of CDO embedded in the system design. CDO is guaranteed in the altitude layers ranging from the sequencing legs to the merge points.
- Introducing PM as main arrival strategy would not result in the overflight of new or dense populated areas. Flight trajectories are contained in path envelopes covering approximately the same areas as currently done with radar vectoring.

These conclusions are in line with the findings of the first feasibility study on PM at EBBR carried out in 2009. During this study, RTS have been carried out, validating to another extent the present study findings.

7.2. DISCUSSIONS

To optimise the operational benefits claimed to be achievable with a PMS at EBBR, some conditions are necessary, most of the time requiring modifications of the current operational systems and procedures;

- Arrival manager

  It has been claimed, amongst others, after the *ENAV* prototyping sessions for the implementation of a PMS in the Rome terminal area [23] and in the IATA position on PM [21] that combining a PMS with an adequate AMAN would lead to optimised system performances. Furthermore, at any airports where PM has been implemented, it is always used in combination of an AMAN with tailored functionalities. The possibility to optimise the use of a PMS when combined with an adequate AMAN has also been highlighted by the airspace design experts and controllers of *skeyes*. Introducing an XMAN at EBBR would further increase the system efficiency and flight predictability.

- New military airspace sharing strategies

  Given the large portion of the Belgian airspace dedicated to military activities, an optimal use of the PMS for runways 25L/R and 19 designed for EBBR can only be ensured if a better share of the airspace based on the user needs is established. As a matter of fact, these systems are penetrating the TRA North Alpha, Two and Three. Negotiations should be opened. As the PMS are likely to be more exploited during the morning (07:30-09:30 LT) and evening (18:00-20:00 LT) peak periods, excluding these periods from the currently established flying windows is considered the best action to take.

- Involvement of the neighbouring ATC units

  Due to the proximity of some of the PMS entry points with the boundary of the Belgium FIR, the working methods nowadays in place to pre-sequence and descend the traffic coming to land on the different runways need adaptations. Coordination with the neighbouring ATC units injecting traffic to land at EBBR would be required. In particular, Paris ACC, Amsterdam ACC and Maastricht Upper Area Control Centre (MUAC), would be impacted. The new methods of coordination will be documented in the corresponding LoAs.

- PMS design modifications

  Validation of the different designed PMS is primordial to make sure the best systems are implemented at EBBR. The PMS designed for runway 19 and 25L/R seems to be efficient designs since their direct routes closely match what is nowadays flown with radar vectoring. The less optimal system is the PMS for runway 01. To achieve better operational performances, its design should be revised. A smoother integration of the incoming flows, an alignment of the merge point along the runway axis and the possibility to perform right-hand circuits, are measures that could help reach this goal. Improvements could also be reached for the PMS of runway 07L. Anyway, a clear assessment and verification by a team of airspace procedure design experts will be required. RTS are means to support the concept validation process.

- Adjustment of current operational environment

  Modifications will need to be brought to the EBBR STARs to ensure a smooth connections with the different PMS. New IAFs, as well as other specific navigation elements, will need to be redesigned to best fit the new arrival strategy. Airspace adaptation of the terminal airspace to include the entire PMS structure will also be required. For the moment, this modification would only be required for the PMS designed for runways 25L/R and 19 which are going out of the Brussels TMA.

- Route network modifications

  The introduction of PM in the terminal airspace of EBBR is likely to impact the structure of the current, highly intertwined route network above Belgium. Not only the SID and STAR network of EBBR will be impacted, the departures and arrivals of the other controlled airports of Belgium might be affected. Although the different PMS have been designed in a way as to minimise route interference, a careful assessment of the complete SID and STAR network is still required. The identification of hotspots where the traffic interactions are complex is crucial, and new procedures and routes must be established if necessary.

- Standard working methods

  While the basic working principle of PM is easy to grasp, the operational procedures in nominal and non-nominal conditions for EBBR need finalisation regarding specific operational scenarios;

  - Task repartition between ACC and APP
  - Traffic transfer from ACC to APP sectors
  - Traffic transfer from APP controller to final director
  - Transfer from radar vectoring to PMS and vice versa
  - Transfer from one runway system another, from one PMS to another
  - Alternative and contingency procedures in case of non-nominal conditions
  - Use, design and location of conventional holding stacks
  - Airspeed and separation requirements

To give prospective to the study, the steps required for a successful implementation are hereafter listed. Accomplishment of these tasks is only required if PM is launched as a project at EBBR.

- Implementation plan

  A detailed implementation plan has to be derived, including the strategy during the transition period, the planning of the controller training, the adaptation phase and the official date of introduction into operations.

- Real time simulation

  So far, only FTS have been carried out. Although it was possible to draw high level conclusions on the feasibility of a PMS at EBBR, deeper analyses and validation works are required. Performing a RTS is the next logical step. This will allow to demonstrate the feasibility of a PMS at EBBR taking into account, to some extent, all operational aspects of ATC. Controller flexibility, weather conditions, traffic mix and demand, as well as changes in the operational model, are some of the elements that can be accurately simulated with a RTS.

- System updates

  A series of systems will need to be updated (EUROCAT, controller display screen, aircraft FMS) or acquired (appropriate AMAN) to support the use of PM at EBBR.

- Safety assessment

  Following the preliminary safety check highlighting the impacts on ACC and APP controllers, procedures and systems, a complete and detailed safety assessment has to be carried out before implementation. This is required in order to analyse the safety acceptability of the change, and to indicate whether and in which areas it needs improvement with respect to safety. Mitigation measures, if needed, will also be identified during this assessment. This task has to be carried out by the change leader, which will be supported by a safety practitioner. A state approval will be required.

- Controllers training programme

  A clear and detailed training programme has to be established for the controllers. This training programme has to cover all possible scenarios that could possibly happen when using a PMS. Not only the standard procedures for nominal conditions have to be trained, all alternative and contingency procedures for non-nominal conditions must be mastered.

- Communication to stakeholders

  Controllers, neighbouring ATC units and all stakeholders possibly impacted by the implementation of a PMS at EBBR have to be involved from an early stage in the procedure design and implementation process. Inputs from all parties involved have to be considered to make sure all important operational aspects are considered, as well as all necessary system updates are carried out.

7.3. RECOMMENDATIONS

In this section, recommendations for future work are provided. Actions regarding the thesis work, as well as possible future research topics, are discussed;

- Model optimisation

  Although the developed simulation model allowed to draw high level conclusions on the feasibility of PM at EBBR, some actions could be taken to optimise its performances. In particular, the simulation time and effort could be lowered. One possible way to do so is to reduce the matrix size to solve. This can be done, for instance, by only generating time and trajectory options when needed, instead of generating them all at first.

  Regarding the overall model performance, the concept of multiple objectives could have been referred to. With such as concept, instead of solving a single objective function, several objective functions are established. A priority order is then imposed to make sure the accomplishment of one objective does not degrade the solution obtained at a higher level.

- Noise study

  Further study could be on the noise impact of using a PMS at EBBR. Being able to accurately quantify the noise reduction that could be achieved in the airport vicinity would definitely complete the present study outcomes. One possible tool is the integrated aircraft noise and emissions modelling platform developed by *EUROCONTROL*, IMPACT.

- Time-based separation

  To increase the efficiency and accuracy when handling the air traffic with PM, the operational concept of time-based separation could be used. Instead of measuring the distance between two aircraft to determine if sufficient lateral separation exists, a time-based separation system could provide the controllers with the exact time at which aircraft have to be sent towards the merge points. This would lead to optimised and compact landing sequences.

- Automation

  Over the last years, automation has became an important part in our everyday life. In the aviation industry, studies and research have already been launched to evaluate to which extent automation could be used. Regarding the complex and high-responsibility mission of the air traffic controllers, a complete substitution of physical persons by systems is unlikely. However, automating some steps of the process could facilitate the work of the controllers, while providing optimised services. For instance, regarding the use of PM, allowing the systems of the controllers to communicate with the aircraft systems without human interventions could enhance the operational efficiency. To do that, a controller-pilot data link communication (CPDLC) could be introduced.

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A

POINT MERGE SYSTEMS - DETAILED DESCRIPTIONS

This appendix contains all waypoint coordinates of the different PMS investigated for EBBR (Table A.1 to A.4), as well as the detailed maps of the different systems (Figure A.1 to A.4). In Figure A.5, an alternative design for the PMS for runway 01 is presented. This design would only be possible if the political restrictions over the area at the south east of the airport are dropped and if more flexibility is obtained with the military to better organise in time the Belgian airspace according to the user needs. A complete assessment of the design remains primordial if it is considered for future investigations.

Table A.1: Waypoint coordinates (PMS for RWY 25L/R) - Confidential data.

Table A.2: Waypoint coordinates (PMS for RWY 19) - Confidential data.

Table A.3: Waypoint coordinates (PMS for RWY 07L) - Confidential data.

Table A.4: Waypoint coordinates (PMS for RWY 01) - Confidential data.

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Figure A.1: Detailed design of the PMS for runways 25L/R. Distances are expressed in NM.

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Figure A.2: Detailed design of the PMS for runway 19. Distances are expressed in NM.

This figure is switched off for confidentiality reasons.

Figure A.3: Detailed design of the PMS for runway 07L. Distances are expressed in NM.

This figure is switched off for confidentiality reasons.

Figure A.4: Detailed design of the PMS for runway 01. Distances are expressed in NM.

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Figure A.5: Alternative design for the PMS for runway 01 [first feasibility on PM for EBBR (2009-2011)].

B

SIMULATION MODEL CONSTRUCTION

In this appendix, information on the simulation model construction is provided. First, the importance of using a large number of segments connecting the system sequencing legs to the merge points is explained (Section B.1). Next, the pre-sequencing areas (Section B.2) and the conflict zones (Section B.3) of each designed PMS are presented.

B.1. NETWORK DEFINITION

The number of points defined along the sequencing legs is a parameter influencing the PMS overall performances when tested through FTS. Different simulations with more or less points resulted in significantly different results. Initially, only the waypoints defining the segments of the sequencing legs have been taken into account in the simulation. As aircraft can only fly along segments connecting two points of the network, the number of possible trajectories was rather limited. Not allowing the aircraft to turn towards the merge point as soon as the minimum separation distance was reached unsurprisingly resulted in loss of capacity. To match reality as closely as possible, the number of points along the sequencing legs has been increased. Intermediate points have been added in a way as to increase the number of possible trajectories from the sequencing legs to the system merge point. Table B.1 summarises this modification.

Table B.1: Total number of possible trajectories from the sequencing legs to the merge point of each PMS.

PMS	Waypoints only	With intermediate points (per leg)
RWY01	15	146 (46 + 50 + 50)
RWY19	18	166 (34 + 66 + 66)
RWY07	14	138 (38 + 50 + 50)
RWY25	19	188 (38 + 50 + 50 + 50)

B.2. PRE-SEQUENCING AREAS

In Figures B.1 to B.4, the pre-sequencing areas for each designed PMS are displayed. There is one area for each sequencing leg. The areas extend from the ground surface upwards to FL245.

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Figure B.1: Pre-sequencing areas (PMS for RWY01).

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Figure B.2: Pre-sequencing areas (PMS for RWY19).

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Figure B.3: Pre-sequencing areas (PMS for RWY07L).

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Figure B.4: Pre-sequencing areas (PMS for RWY25L/R).

B.3. CONFLICT ZONES

In Figures B.5 to B.10, the conflict zones for each different scenario tested are displayed. These areas extend from the ground surface upwards to FL245.

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Figure B.5: Conflict zone (PMS for RWY01).

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Figure B.6: Conflict zone (PMS for RWY19).

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Figure B.7: Conflict zone (PMS for RWY07L).

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Figure B.8: Conflict zone (PMS for RWY25L).

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Figure B.9: Conflict zones (PMS for RWY25L/R SimDep).

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Figure B.10: Conflict zones (PMS for RWY25L/R SimIndep).

To simulate simultaneous dependent and independent approaches with runways 25L/R, different conflict zones had to be established. With simultaneous dependent approaches (Figure B.9), the aircraft have to be separated by 4 NM when landing on the same runway, and by 2 NM when landing on different runways. For this reason, three conflict zones have been designed; two for the 4 NM separation requirement along each runway, and one for the 2 NM separation requirement between aircraft landing on different runways. With simultaneous independent approaches, aircraft can simultaneously land on the parallel runways. Only the separation requirement of 4 NM between aircraft landing on the same runway is required. Therefore, only two conflict zones for each runway was necessary (Figure B.10).

C

SIMULATION PARAMETERS

In this appendix, some elaboration on BADA are provided (Section C.1). The outputs of the pre-sequencing problems (Section C.2), as well as the optimisation parameters obtained after each simulation run (Section C.3), are presented.

C.1. BADA

BADA is the reference model used to generate 3D trajectories with SAAM. It indicates, through tables, at which speed the aircraft have to fly at what altitude when cruising, as well as the optimal rate of descent as a function of the distance to the runway threshold. This information is stored in two distinct tables, and depends on the aircraft type. Different aircraft type have different speed and descent performances.

To satisfy, in the simulation, the operational condition of an equivalent and constant speed along the sequencing legs, several manipulations have been performed. First, a single aircraft type has been considered to ensure an homogeneous traffic evolution along the systems. The Airbus A320 has been selected as a good candidate to represent the majority of medium traffic coming to land at EBBR (88.4% in 2018). Next, speed constraints have been imposed at certain levels. In the altitude layer ranging from 6,000 ft to FL110, an indicated airspeed of 230 kts has been set. This has been done by modifying the table of the A320 containing the aircraft cruise performances. By doing so, a discontinuity rose when switching from one table to another, from cruise to descent. Depending on the sequencing leg flown, some aircraft needed to perform some manoeuvres to catch up the pre-established optimal rate of descent. In Figures C.2 to C.4, the three possible trajectory descent profiles are presented. Figure C.1 gives an overview of all the vertical profiles calculated.

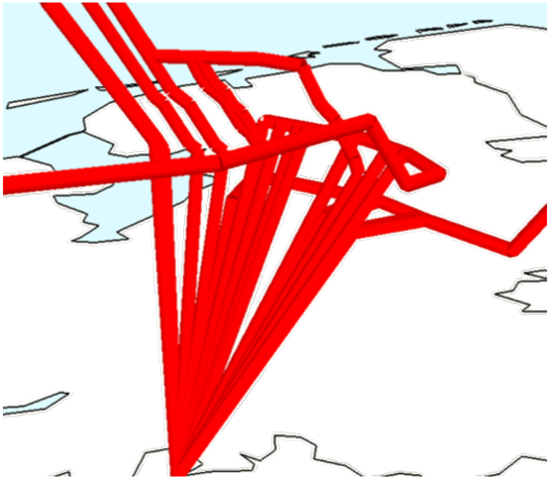

Figure C.1: Vertical profiles (RWY19, FL60, FL70, FL80).

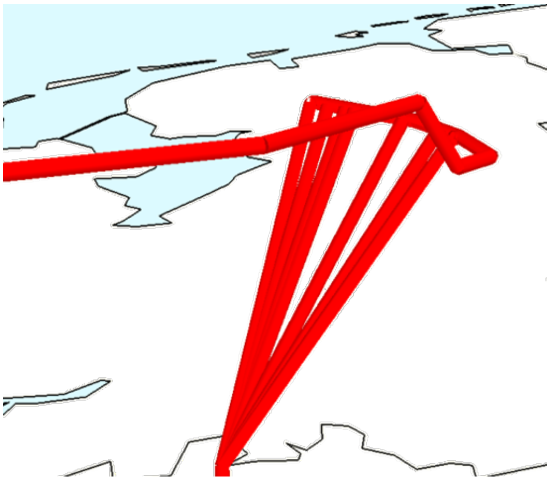

Figure C.2: Vertical profiles (RWY19, FL70).

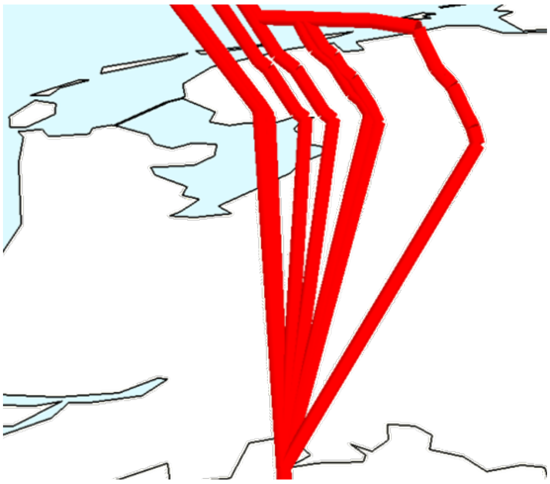

Figure C.3: Vertical profiles (RWY19, FL80).

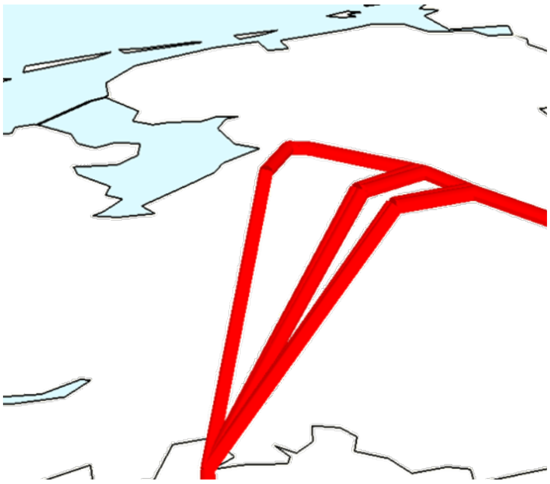

Figure C.4: Vertical profiles (RWY19, FL60).

In case the altitude of the sequencing leg is too high too close from the runway threshold (see Figure C.3), the aircraft have to descend along the leg before turning towards the merge point in order to intercept the optimal descent profile established by BADA. If the altitude along the leg is too low (see Figure C.4), the aircraft flying along it, after having turned towards the merge point, have to maintain their altitude until they intersect the optimal descent slope. In Figure C.2, the aircraft start descending as soon as they turn towards the merge point. This means that the altitude along the leg matches what was defined by the BADA profile for cruising.

In reality, the cases illustrated in Figures C.3 and C.4 would never occur. Descents would be initiated as soon as the aircraft leave the sequencing legs to fly in direction to the merge point. The rate of descent would be adjusted appropriately in function of the altitude and distance to the point merge or to the intersection with the glide slope.

C.2. PRE-SEQUENCED TRAFFIC SAMPLES

As explained in Section 5.2.1, the first part of the model consists of organising the traffic of the selected samples so that aircraft enter the PMS with at least 5 NM in between them. In Table C.1, the number of flights of the samples that have been shifted in time to satisfy the condition of pre-sequencing are presented. The absolute value of the minimum and maximum time shift is also provided.

Table C.1: Pre-sequencing results.

PMS	Number of arrivals	Number of shifted flights	Minimum absolute time shift [sec]	Maximum absolute time shift [sec]
RWY01	49	13	60	180
RWY19	47	9	60	180
RWY07L	49	15	60	540
RWY25L	33	3	60	120
RWY25L BATLNO	32	2	60	120
RWY25L/R SimDep	67	10	60	120
RWY25L/R SimIndep	67	10	60	120

At most, a flight has been shifted by 9 minutes when testing the PMS for runway 07L. For the other PMS, the maximum time shift is 2 or 3 minutes depending the runway system in use.

To run the optimisation problem - second part of the simulation model, these pre-sequenced traffic samples have been considered.

C.3. OPTIMISATION PARAMETERS

It has been observed that the size of the traffic samples, as well as their distribution, directly influences the optimisation time and MILP gap. This is easily understandable by looking at the size of the matrix to be solved, whose columns correspond to the number of variables and the rows to the number of constraints.

In Table C.2, a summary of the matrix size, the optimisation time and the gap is provided for each tested scenario.

Table C.2: Optimisation parameters.

PMS	**Time [sec]**	**Gap [%]**	**Matrix size [row x column]**
RWY01	16.61	0.00	120,136 x 122,493
RWY01 Boost	5000	94.90	399,111 x 403,495
RWY19	3.12	0.00	139,961 x 142,728
RWY19 Boost	5000	93.32	607,676 x 612,920
RWY07L	2.86	0.00	89,350 x 91,559
RWY07L Boost	5000	93.82	284,660 x 288,724
RWY25L	2.06	0.00	66,206 x 67,811
RWY25L Boost	5000	94.22	391,838 x 396,274
RWY25L BATLNO	1.74	0.00	53,743 x 55,299
RWY25L BATLNO Boost	5000	87.80	296,870 x 300,918
RWY25L/R SimDep	5000	86.31	203,444 x 206,667
RWY25L/R SimDep Boost	5000	95.18	876,389 x 883,790
RWY25L/R SimIndep	23.12	0.00	169,558 x 172,781
RWY25L/R SimIndep Boost	5000	93.69	732,978 x 740,379

The MILP gap, expressed in %, is the difference between the current optimal solution (value of the objective function for current incumbent) and the best bound (value of the minimum of the objective values of all current leaf nodes of branch and bound tree). The value of the upper bound is expecting to decrease, while the value of the best bound should increase during the optimisation process. When the gap is 0, this means the upper bound and best bound are equals, and therefore that the optimum solution has been found. Mathematically, the MILP gap is expressed as in Equation C.1.

$$\text{MILP gap} = \left|\text{upper bound - best bound}\right| / \left|\text{upper bound}\right| \tag{C.1}$$

A maximum simulation time of 5000 seconds has been set after having observed that if the simulation gap was not lower than 50% at that time, it started to stagnate as from that moment on.