Improved Flexible Runway Use Modeling

A Multi-Objective Optimization Concerning Pairwise RECAT-EU Separation Minima, Reduced Noise Annoyance and Fuel Consumption at London Heathrow

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Master of Science Thesis in Aerospace Engineering

TU Delft

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Executive Summary

A minimization of disturbance caused by aircraft noise events and a reduction of fuel consumption during the initial and final phase of flight. These are the two objectives that play an important role in current research on runway allocation models. Over the past few decades, models have been developed that put their focus on the minimization of noise annoyance in the airport's vicinity. As a result, the aviation industry moved away its focus from other important elements that affect airport's daily operations, airline companies and human well-being.

With the techniques developed in the last decades, it is still impossible to imagine flight operations without any noise generation. However, several research areas, such as aircraft performance and aircraft noise effects, have proven multiple techniques that reduced aviation noise dramatically [30]. Noise generation is found to be one of the major contributors to the limitation on flight operations at certain airports. This limitation has to do with several factors that relate to human well-being as well as environmental issues. These are prescribed by regulations to control external factors, such as human health, that are affected by flight operations. However, only concerning noise annoyance as a major limitation to flight operations results in an incomplete picture of the actual airport operation process.

To further improve the current runway allocation models, additional factors should be incorporated. The call for such next generation runway allocation models has resulted in a model with multiple objectives. This new type of model concerns noise annoyance as well as fuel consumption during the departure and arrival phase of flight. It could be of great importance to consider this additional objective in the runway allocation process. This importance is strongly related to increments in fuel consumption as a result of extended approach an departure trajecories. These extensions are result of noise optimized arrival and departure tracks in which overflying densely populated areas is minimized.

When concerning fuel consumption in the allocation process, runway allocation can take place more efficiently in terms of fuel cost as well as noise annoyance. This has been initiated by the initial version of the flexible runway allocation model. In this research, the focus is on the development of this model in order to make its calculations, that are used in the simulation, more refined. Moreover, the improvements conducted in this research relate to the methodologies to compute the cost of the decision variables and the level of complexity of specific linear programming constraints in the optimization model. Consequently, the aim of this research is to answer the following research question:

Can the performance of Standard FLEX be further optimized by applying pairwise flight dependencies, while ensuring and contributing to a valid trade-off between runway capacity, noise emission, fuel burn and safety based on a specific demand of flights?

Besides the two objectives of the optimization model, runway capacity is an important factor in the runway allocation process. Runway capacity defines the runway throughput in a given period of time. The throughput capacity of a runway depends on the traffic mixture. The traffic mixture identifies the aircraft pairs that can occur in a landing or departure sequence. Depending on the aircraft type, a minimum separation time is defined to allow safe operations between two consecutive aircraft in a sequence. Safety in this case relates to the impact of wake turbulence that is caused by the preceeding aircraft on its succeeding aircraft in the sequence. In the past, the minimum separation time was based on a categorization related to the maximum take-off weight of the leading and following aircraft in the flight pair to be analyzed (ICAO WTC). In recent research it is found that wing span also has an influence on the generation of wake turbulence. As a result, a new methodology to categorize aircraft according to their relative wake turbulence generation has been introduced. This methodology, named European Wake Vortex Recategorization (RECAT-EU), allows aircraft to be categorized more accurately according to their design characteristics.

The pairwise flight dependency as described by RECAT-EU is implemented in the flexible runway allocation tool by means of an inequality constraint. This constraint describes the availability of a specific runway at a

certain time. Besides the categorization of aircraft, the availability of the runway depends on the type of operations of the leading and following aircraft in the operational sequence. Moreover, this constraint enables the airport to operate in single as well as opposite direction mode in cases weather conditions allow to do so. The model examines all possible flight pairs that can occur in a specified time frame. It does so for each unique runway end, and, for each operation mode. As a result, a dependency matrix is generated per unique aircraft pair. This depency matrix indicates the minimum occupancy time of a certain runway based on a specific flight operation. This information is then used as a constraint by the optimization model in order to ensure that no conflicts can occur with respect to separation minima. The runway occupation inequality constraint is defined in Equation 7.14.

The improvements made to the initial model have resulted in a refined flexible runway allocation model. This model is able to assign a runway to a specific flight based on weighted importance of the two objectives fuel consumption and noise annoyance. The allocation takes place by allowing a certain delay in order to assign aircraft to the preferred runway. Based on the objective function and constraints, the model presents the optimal solution by means of a runway allocation and occupation scheme. This scheme comes with a visualization of locations in the vicinity of the airport at which a specified cummulative noise exposure limit is exceeded. In this way one can analyze the utilization of the runway set as well as the noise impact of the operation strategy that is found.

To test the effectiveness of the model, it is applied to a day of operations at London Heathrow Airport. This major airport in the global aviation network is an airport with limited capacity. Furthermore, the airport has to deal with a large amount of noise annoyance complaints as the airport is situated in a densely populated area west of the metropolis of London. Flexible runway allocation at London Heathrow is applied in multiple scenarios as weather conditions can play a dominant role which can limit the number of options in terms of available runway configurations. The first scenario reflects calm weather conditions. In this scenario both runways can be operated in both directions. This enables the runway capacity to be utilized in the most efficient way.

In order to find the most optimal set of objective weights, the scenario is initiated 21 times to generate a Pareto front. This Pareto front concerns both optimization objectives and aims to find the best trade-off between the objective weights. The Pareto front is illustrated in Figure 8.1. The results obtained in this figure are compared to a reference scenario in which the standard runway alternation strategy is simulated. The Pareto optimal solution results in a reduction of 0.7% of the number of exposed households to a L_{DEN} noise level higher or equal to 55 dB between 10 a.m. and 11 a.m. A larger contribution is made to the reduction of fuel consumption (11.4%) within the TMA.

The remaining two scenarios define cases in which weather conditions are dominant. In these cases runway can only be operated in west and east directions, respectively. For the west configuration, flexible runway allocation proves to be less efficient in terms of fuel consumption (+9.7%) and more efficient in terms of reduced noise annoyance (-5.0%), compared to the full flexible case. For the east configuration both objectives face an increase. The number of exposed households to a L_{DEN} noise level higher or equal to 55 dB is increased by 3.7%, whereas the fuel consumption is increased by 8.8%.

Based on the results obtained from the Pareto front together with a weather analysis on London Heathrow, an annual saving has been estimated. This saving reflects the reduction in terms of fuel cost throughout an entire year. The potential fuel savings that have been estimated show a reduction of over 60,000 tonnes of fuel. Based on the current fuel price, this yields a saving of over 34 million U.S. dollars on a yearly basis. The overall number of exposed households to a L_{DEN} noise level higher or equal to 55 dB is reduced by at least 2.1% on a yearly basis.

The implementation of opposite direction operations comes with an increased safety concern. This is because of the fact that missed approach procedures as well as opposite departure and arrival operations might cause additional conflicts in the operation process. To account for these additional conflicts, missed approach, departure and arrival procedures must be adapted in order to comply to safety regulation regarding minimum separation between aircraft inside the TMA. As the aim of this research is to identify the possible gains of implementing flexible runway allocation, the model is based on some well-based assumptions.

However, further development of this model would need additional resources on the investigation of safety impacts of opposite direction runway operations.

In conclusion, the research question of this research is answered positively. By means of this research, the flexible runway allocation has been improved on many aspects. The computation strategy of both objectives has moved from a reference aircraft based computation strategy to an analysis based on each unique aircraft on its own. This refined computational approach has resulted in a better understanding and modeling strategy of the operations that take place at an airport. Finally, the implementation of RECAT-EU separation minima has resulted in a reduction of 5-10% in overall separation times with respect to the regular ICAO WTC strategy, based on multiple air traffic demand mixture scenarios.

Preface

Aviation has triggered my curiosity for such a long time. Since I attended primary school about 21 years ago, my interest in aviation has increased extremely over the years. A strong interest in something specific makes you a passionate individual aiming for an ultimate goal. Pursuing such goals in life lets you live your life the most optimal. I am very happy to have found my interest in the aviation industry. For sure, I know this industry will outline my future life and career, which even makes me more curious about the days to come. I am therefore very grateful of being able to conclude this degree by means of this thesis.

This thesis concludes my Master of Science degree in Aerospace Engineering at Delft University of Technology. The attainment of this MSc degree marks a milestone in my life. I feel very thankful for the opportunities I have had during my study period in Delft. Before you start reading this thesis I would like to thank some people who played an important role during this thesis project.

Ir. Paul Roling, thank you for being my supervisor during this thesis. I highly appreciate the time you have spent on my work. You were always available for a short brainstorm in cases I needed some expert advice. After our meetings, I always felt extra motivated. Furthermore, I would like to thank dr. ir. Dries Visser for being my second supervisor during the several meetings we have had during the research project. Your visions on this project definitely contributed to the outcome of this research. I would also like to acknowledge the role of dr. ir. Joost Ellerbroek as external member of the exam committee.

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S.A. van der Meijden
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List of Abbreviations

09L	Northern runway end in east direction
09R	Southern runway end in east direction
27L	Southern runway end in west direction
27R	Northern runway end in west direction
A320	Airbus A320 as part of the Airbus A320 Family
A333	Airbus A330-300
A346	Airbus A340-600
A359	Airbus A350 XWB
A388	Airbus A380-800
AA	American Airlines
AA	Arrival-Arrival consecutive flight pair
AC	Air Canada
AD	Arrival-Departure consecutive flight pair
ADS-B	Automatic dependent surveillance – broadcast
AEL	Acoustic Energy Level
AGC	Airport Ground Chart
AIP	Aeronautical Information Package
AN-124	Antonov An-124 Ruslan
ANSP	Air Navigation Service Provider
APM	Aircraft Performance Model
APP	Approach phase of flight
AROT	Arrival Runway Occupancy Time
AT45	ATR-42-500
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
B738	Boeing 737-800
B744	Boeing 747-400
B763	Boeing 767-300(ER)
B772	Boeing 777-200
B77W	Boeing 777-300ER
B788	Boeing 787-800 Dreamliner
B789	Boeing 787-900 Dreamliner
BA	British Airways
BADA	Base of Aircraft Data
BIG	Biggin VOR/IAF
BILP	Binary Integer Linear Programming
BNN	Bovingdon VOR/IAF
BPK	Brookmans Park VOR
CAS	Calibrated Airspeed
CO	Carbon Monoxide
CPT	Compton VOR
CX	Cathay Pacific
DA	Departure-Arrival consecutive flight pair
DBS	Distance-based Separation
DCAP	Declared Capacity
DD	Departure-Departure consecutive flight pair
DEN	Day-Evening-Night

DENL	Day-Evening-Night Average Level
DET	Detling VOR
DL	Delta Airlines
DM	Dependency Matrix
DME	Distance Measuring Equipment
DMS	Degree/Minutes/Seconds Geographic Coordinates Format
DOC	Direct Operating Cost
DROT	Departure Runway Occupancy Time
E190	Embraer 190 as part of the Embraer E-Jet family
EEA	European Environment Agency
EGLL	London Heathrow International Airport
EPNdB	Effective Perceived Noise level in decibels
EW	Eurowings
FA10	Dassault Falcon 10
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FCFS	First-Come-First-Served
FDOC	Fixed Direct Operating Cost
FICAN	Federal Interagency Committee on Aviation Noise
FICON	Federal Interagency Committee on Noise
FIR	Flight Information Region
FL	Flight Level (vertical altitude per 100 feet at standard pressure)
GRUMP	Global Rural-Urban Mapping Project
GS	Ground Speed
HA	Highly Annoyed
HC	Hydrocarbons
HKG	Hong Kong International Airport
IAF	Initial Approach FIX
IAIP	Integrated Aeronautical Information Package
IAS	Indicated Airspeed
IAT	Inter-Arrival Time
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IDT	Inter-Departure Time
IFR	Instrument Flight Rules
IMC	Instrument Metheorological Conditions
INM	Integrated Noise Model
IOC	Indirect Operating Cost
JNB	Johannesburg O.R. Tambo International Airport
KUL	Kuala Lumpur International Airport
LAM	Lambourne VOR/IAF
LH	Lower Heavy RECAT-EU Category
LHR	London Heathrow International Airport
LJ35	Learjet 35
LM	Lower Medium RECAT-EU Category
LOS	Level of Service
LOS	Lagos Murtala Muhammed International Airport
LP	Linear Programming
MAY	Mayfield VOR
MD11	McDonnell Douglas MD-11
MH	Malaysia Airlines
MID	Midhurst VOR
MILP	Mixed Integer Linear Programming
MTC	Maximum Throughput Capacity
MTOW	Maximum Take-off Weight
MVA	Minimum Vectoring Altitude

NADP	Noise Abatement Departure Procedure
NAT	North Atlantic Tracks
NATS	UK Aeronautical Information Service
NDB	Non-Directional Beacon
NOC	Non-Operating Cost
NOx	Nitrogen Oxides
NPR	Noise Preferred Route
OCK	Ockham VOR/IAF
O/D	Origin/Destination
ODE	Ordinary Differential Equation
ODO	Opposite Direction Operations
ORD	Chicago O'Hare International Airport
PANS-ATM	Procedures for Air Navigation Services - Air Traffic Management
PHCAP	Practical Hourly Capacity
POP	Population in number of households
QC	Quota Count
RECAT-EU	European Wake Vortex Recategorization
RNAV	Area Navigation
ROC	Rate of Climb
ROD	Rate of Descent
ROT	Runway Occupancy Time
RPK	Revenue Passenger Kilometer
RUH	Riyadh King Khalid International Airport
RWY	Runway
SCAP	Sustained Capacity
SDO	Single Direction Operations
SEL	Sound Exposure Level
SF34	Saab 340
SH	Super Heavy RECAT-EU Category
SID	Standard Instrument Departure
SIN	Singapore Changi International Airport
SN	Smoke Number
SPL	Sound Pressure Level
SQ	Singapore Airlines
STAR	Standard Terminal Arrival Route
TAS	True Airspeed
TBS	Time-based Separation
TC	Total Cost
TFB	Total fuel burn
TFU	Total amount of consumed fuel
TMA	Terminal Manoeuvring Area
TOC	Total Operating Cost
TSFC	Thrust Specific Fuel Consumption
UA	United Airlines
UH	Upper Heavy RECAT-EU Category
UK	United Kingdom
UM	Upper Medium RECAT-EU Category
US	United States
UTC	Coordinated Universal Time
VDOC	Variable Direct Operating Cost
VMC	Visual Metheorological Conditions
VOR	VHF Omni Direction Radio Range beacon
VS	Virgin Atlantic
WHO	World Health Organization
WTC	Wake Turbulence Category

List of Symbols

Alphabetic Symbol	**Description**	**Unit**
AEL	Acoustic Energy Level	$dB(A)$
$AROT$	Arrival Runway Occupancy Time	s
c	Communication buffer	s
$C^F_{f,r,d}$	Cost value related to fuel burn objective	-
$C_{L_{\max}}$	Maximum lift coefficient	-
C^P_{xy}	Cost value related to noise annoyance objective	-
d	Delay	-
dt	Time step	s
D	Delay set	-
D	Distance	nm
D	Drag	N
$DROT$	Departure Runway Occupancy Time	s
E	Expected average service time	s
f	Flight	-
F	Flight set	-
ff	Fuel flow	kg/s
g	Gridpoint	deg
G	Grid set	-
g_{xy}	Decision variable gridpoint with coordinates x and y	-
h	Altitude	ft
i	Leading aircraft in flight pair	-
j	Following aircraft in flight pair	-
L	Lift	N
L_{DEN}	Day-Evening-Night Average Level	dB
L_A	A-weighted sound pressure level	$dB(A)$
$\dot{m}_f$	Fuel Flow	kg/s
n	Common approach path length	nm
n_f	Normalization factor fuel burn objective	-
n_n	Normalization factor noise annoyance objective	-
p	Probability of specific pair of successive aircraft	-
p_e	Effective free field sound pressure	N/m^2
p_{e_0}	Reference sound pressure	N/m^2
POP_{xy}	Population count at gridpoint	$Households$
r	Runway	-
R	Runway set	-
ROT	Runway Occupancy Time	s
s	Separation distance	nm
s	Flight segment	-
S	Flight segment set	-
S	Wing surface	m^2
SEL	Sound Exposure Level	$dB(A)$
SPL	Sound Pressure Level	dB
t	Average time interval between consecutive operations	s
t	Time	s
T	Time-based separation	s
T	Length of measuring period	s
T	Thrust	kN

T_{ref}	Length of reference period	s
T_0	Reference time of one second	s
TFB_s	Total fuel burn per flight segment	kg
TFU	Total Fuel Used	kg
$TSFC$	Thrust Specific Fuel Consumption	$g/(kN \cdot s)$
V	Airspeed	kts
V_{APP}	Approach Speed	kts
V_{corr}	Speed correction	kts
V_{REF}	Reference Landing Speed	kts
V_{stall}	Stall Speed	kts
V_{TAS}	True Airspeed	kts
w_i	Weight factor related to noise event in DENL	dB
W	Weight	N
$x_{f,r,d}$	Decision variable flight with defined runway and delay step	-
X	Decision variable flight with defined runway and delay step in LP	-

Greek Symbol	**Description**	**Unit**
α	Weight factor related to fuel consumption	-
β	Weight factor related to noise annoyance	-
ΔL_A	Corrected frequency band level	$dB(A)$
μ	Minimum time separation	s
μ_r	Maximum runway throughput rate	ac/hr
ρ_∞	Air density at sea level according to ISA	kg/m^3
$\mathbb{Z}$	Integer	-

1 Introduction

Decreasing oil prices, the rising middle class in China and India and the emergence of low-cost and Gulf carriers. A modest selection of geopolitical situations, macro-economical conditions and societal trends that directly impacts the airline industry, making it a continuously changing branch. Over 6,500 billion Revenue Passenger Kilometers (RPKs) along with the intensification of world passenger traffic (+6.8%) and world freight traffic (+2.2%) in 2015 [32], shows the airline industry has evolved to a major world-wide industry.

Home to legacy carrier British Airways, Heathrow is centered in a network comprising 194 destinations in 82 countries. With over 80 airlines and 75.7 million passengers transported in the year 2016, Heathrow belongs to Europe's busiest airports [37]. Thanks to the growing industry, airports like Heathrow have reached their maximum capacity. As shown in dynamic and prosperous cities such as Dubai [14] and Abu Dhabi [1], this should lead to extensive projects increasing the airport's landside and airside capacity to the needs of the near future. However, this type of expansion is not always possible from legal and geographic perspective.

Heathrow can be considered as one of those airports for which geographic limitations are a limiting factor. With the airport located in a densely populated area, the airport's expansion plans have been restrained by government as well as residents in the vicinity of the airport for a long time. This hold back is due to the fact that the expansion of Heathrow will result in an increase of noise exposure in this noise-sensitive area. Despite the fact that some progress with respect to the expansion of Heathrow has been made at the end of 2016, the airport is predicted to suffer a capacity and noise annoyance problem for a number of years.

Together with airport capacity, noise annoyance [15], human well-being [26] and legal regulations form a cycle that affects the airport's daily operations. Since noise annoyance is one of the major limitations in airport operations, runway capacity optimization models mainly focus on minimizing noise at, and in the vicinity of, the airport. Doing so, results in Noise Preferred Routes (NPR) which circumnavigate certain densely populated areas in the vicinity of the airport. As a result, noise emissions, and, therefore observed noise annoyance is managed more effectively as the amount of affected people is reduced. Moreover, the airport decision maker in this case sets a high cost on the impact of noise annoyance in the area around the airport which is benificial from the community perspective.

However, such noise-optimized routings often come with an increased flight trajectory length over sparsely populated areas such as seas or countrysides. Therefore, the concept of NPR may lead to benificial contributions with respect to noise annoyance, but can cause an increase in fuel burn as the trajectory length increases. From both an environmental perspective as well as the perspective of an airline company, the concept of NPR comes with multiple negative factors; the most important being additional fuel burn and delay.

The last decade shows a situation in which noise annoyance has obtained an increased importance in the aviation industry. Airports have to deal with more strict regulations regarding noise exposure in the vicinity of the airport and therefore put a high cost on decreasing noise footprints around the airport. Consequently, within the aviation industry the point of focus has moved away from other important elements that affect airport's daily operations, airline companies and human well-being. Fuel burn is one of those important elements. For this reason, this research puts fuel consumption on the agenda and aims to bridge the gap between maximum noise reduction and efficient fuel consumption in the departure and arrival phase of flight. A balanced level of fuel consumption and noise annoyance are set to be the two objectives in the multi-objective optimization model presented in this research. Involving a more efficient level of fuel consumption in the runway allocation process leads to an extension in the variety of stakeholders that can find their interest in this next generation model. This proves the model's relevance in daily operations.

1.1. Research Framework

The need for designing and implementing an improved multi-objective optimization model for noise annoyance and fuel burn in the airport runway allocation process has been touched upon in the introduction of this chapter. This research will be a continuation on the research performed by Delsen [11]. His research, to be referred to as Standard Flex, focused on the development of an optimization model that is able to allocate runways to arriving and departing traffic operating at a complex airport. The capacity of a runway system, being the set of active runways at an airport, is dependent on the layout of this system. Inclined or crossing runways drastically affect the capacity as an increased safety margin should be applied to ensure safe operations at the airport and in the airspace around the airport. Taking into consideration Air Traffic Control (ATC), communities and airline opinions, an optimized trade-off based on the following three key parameters can be made: i) runway capacity, ii) noise annoyance, and iii) fuel burn.

Moreover, this research will investigate the existing gap with respect to noise annoyance and fuel burn modeling in airport runway allocation management. A primary concern of the existing allocation model is the level of detail that has been built-in. According to Delsen [11], the applicability of the existing model is limited in terms of multiple parameters and size of the data available. To decrease the degree of uncertainty in the outcome of the model, this research, to be referred to as Improved Flex, will focuss on implementations which are expected to contribute to the accuracy and thereby the credibility of the runway allocation model. To define the framework of this research, the research objective and research question will be discussed in the following paragraphs, respectively.

1.1.1. Research Objective

The research framework as described above identifies the gap between regular runway allocation and flexible runway allocation. Additionally, a gap has been identified between Standard Flex and what should become Improved Flex as an outcome of this research. This gap can be translated to the following research objective:

The objective of this research (Improved Flex) is to improve the overall flexible runway allocation tool (Standard Flex), by defining pairwise flight constraints instead of single aircraft separation constraints. Additionally, the estimation of the model's cost factors of both objectives should be improved by modeling aircraft specific operational characteristics instead of generalization of aircraft types.

In accordance to the objective described above, the model should be able to assign flights to a certain optimal runway end. This should be done by taking into account the following factors:

- Implementation of delay.
- Aircraft specific noise emission and fuel burn.
- Effect of cummulative noise annoyance on the ground.
- Operation type (arrival/departure).
- Wind direction and strength.

The model should evaluate the effects of allocating flights in a flexible manner given a relative set of weights to both objectives. The outcome should be in the form of a Pareto front, showing the trade-off between noise annoyance, fuel burn and runway capacity.

1.1.2. Research Question

Following the research objective that defines the boundaries of what should become Improved Flex, leads to the following research question:

Can the performance of Standard Flex be further optimized by applying pairwise flight dependencies, while ensuring and contributing to a valid trade-off between runway capacity, noise emission, fuel burn and safety based on a specific demand of flights?

Having defined the fundamental research question of this research, the following sub-questions have been defined.

RQ1 Which elements affect airport runway capacity?

RQ2 How can dependency matrices be transformed such that they account for multiple aircraft types?

RQ3 Can the incorporated optimization techniques also be used for pairwise flight dependencies?

RQ4 How can noise annoyance, as a result of aircraft noise events, be modeled?

RQ5 Which key performance parameters define the fuel costs within airline's economics? And, how can these be modeled in a more refined way?

RQ6 What parameters and variables in the optimization model are dependent on aircraft type?

RQ7 How is the model applicable to a case study of London Heathrow Airport?

RQ8 In what way should the results of the model be visualized?

RQ9 Can the model outcome be related to a certain safety measure?

RQ10 To what significance has the model been improved?

1.2. Research Relevance

In order to make this research useful it should contribute to scientific as well as practical purposes. The relevance with respect to both perspectives is made visible in the following two paragraphs, respectively.

1.2.1. Scientific Relevance

This research aims to explain the impact of improvements made in pairwise flight separation modeling, noise modeling and fuel burn modeling to the existing runway allocation model. The impact of these improvements can either be positive or negative with respect to the overall runway capacity, noise annoyance, fuel burn and delay. The improved model enables the visualization and analysis of key performance parameters which describe operational processes within the runway allocation process. Although this research focuses on London Heathrow Airport, the model is designed to be applicable to a broad scale of complex airports.

1.2.2. Practical Relevance

The practical relevance of this research is based on the alternatives with respect to air traffic management operations at and around airports. This research aims to investigate the possibilities that can arise from putting runway operations in a new perspective. By enabling airports to operate in opposite direction operation modes, benefits can arrise with respect to runway capacity, noise annoyance as well as fuel consumption. To do so, operation restrictions have to be redefined as is part of this research. Furthermore, a new pairwise aircraft separation strategy is implemented in order to obtain a more accurate estimation of real life operations. As this research focuses on London Heathrow, the effects of creating a new operational Air Traffic Management (ATM) structure can be analyzed as the airport contains two independent runways resulting in increased posibilities with respect to opposite direction operations.

1.3. Report Structure

This research identifies the improvements that can be made with respect to the initial Standard Flex model. As a continuation of this, these improvements are applied to Standard Flex which results in an improved model that is being referred to as Improved Flex in this thesis. To analyze the impacts of the improvements, Improved Flex is applied to a busy day in August at London Heathrow Airport, located in the United Kingdom.

This thesis intents to provide a guideline through all the processes that have been made in order to establish Improved Flex as it is now. At first, this introduction has given an overview of the research framework. The rest of this thesis is constructed as follows. The following chapter provides background information with respect to runway capacity modeling, aircraft noise modeling and the airline's cost structure. This is done by means of a summary of the literature study that has been performed prior to this research. The background information is followed by Chapter 3, providing an overview of a regular day of operations at Heathrow. This is done by performing a flight schedule analysis.

With this in mind, the process of developing and improving the separate modeling methods is being discussed. The discussion of these modeling methods is being done using a general structure concerning the theory, metrics and the modeling process. In the first place, Chapter 4 covers the improvements that are made with respect to aircraft separation modeling. This chapter discusses the recently designed methodology named RECAT-EU by Eurocontrol. This methodology is used in Improved Flex to improve the level of detail in modeling the separation of consecutive aircraft. Just in the same way, Chapter 5 concerns the improvements with respect to noise modeling, being one of the two objectives in the optimization process which is discussed later on. This chapter is followed by Chapter 6 which concerns the latter objective in the optimization process, fuel consumption.

Having discussed the improvements that are made with respect to the model's objectives as well as the constraints, the following chapter combines the strategies and methods described in Chapters 4, 5 and 6. This next step is discussed in Chapter 7 providing information on the linear programming approach that is being applied in this research. This chapter concerns the explanation of the Multi-Integer Linear Programming strategy as well as all objectives and constraints that are used in the model.

In the final analysis, Chapters 8 and 9 discuss the results of Improved Flex with respect to Heathrow's daily operations. Furthermore, the results as well as the improvements are synthesized in order to analyze the impact of certain decisions that are made. Eventually, the model is verified and validated.

This thesis concludes with Chapter 10 providing a general conclusion of this research. The conclusion is accompanied by a set of limitations that are found during the development of the model. From this set of conclusions and limitations a recommendation has been written in order to identify the gaps that still need to be bridged. By identifying these shortcomings, Improved Flex can be further developed into a model of increased value.

2

Background: Objectives in the Runway Allocation Process

The majority of large international hubs contain a multiple runway system. This system enables the Air Navigation Service Provider (ANSP) to distribute flights over different runways. However, such a complex runway system can potentially cause conflicts. Often an airport of such dimension has runways that are preferred over others. This preference can take multiple forms. Among others, four major reasons for having a certain runway preference relate to either runway capacity, noise exposure, third-party risk or weather conditions. This research covers all these reasons to some extent.

Central to the airport operations process is the strategy behind the allocation of flights to a certain runway. Much literature can be found about the development of runway allocation over the years [22] [24] [42]. In the first place, airport capacity was modeled as a function of permitted delay on a single runway. Research on multiple runway allocation strategies also originates decades ago. The fundaments of this research area mainly concern multiple runway allocation from an operational perspective. Bolender & Slater [9] investigated the impact of aircraft demand mixture on the capacity of a runway. They found that delay can be significantly lowered by creating an efficient aircraft sequence regarding the weight class of each aircraft. Regarding arrival traffic management, Isaacson et al. [34] developed a knowledge-based runway assignment tool. Based on a decision logic and a set of rules, this tool evaluates performance as well as workload.

Development in recent decades shows the importance of noise annoyance as a consequence of maximized capacity [26] [39] [51]. Nowadays, several noise models are used to optimize flight operations near airports regarding noise annoyance on the ground. Moreover, aircraft are vectored around certain densely populated areas in order to minimize noise annoyance. As a result, airlines can be forced to burn additional fuel to comply to these noise preferred routes [25]. Recent studies have shown the emergence of a multi-objective model that concerns all major stakeholders in the runway allocation process [11]. These stakeholders comprise the airport operator, residents around the airport as well as the airlines themselves. As a result, airport decision making concerns more than the operational level only.

Going back to the aim of this research, capacity should be combined with the noise annoyance problem as well as fuel consumption. To do so, the flight phases to be analyzed must be defined. A regular flight can be divided into five operational phases. These phases account for the departure, cruise and arrival of the flight. Moreover, these operational phases are defined as:

(i) Taxi-out and departure

(ii) Climb

(iii) Cruise

(iv) Descend

(v) Landing and taxi-in

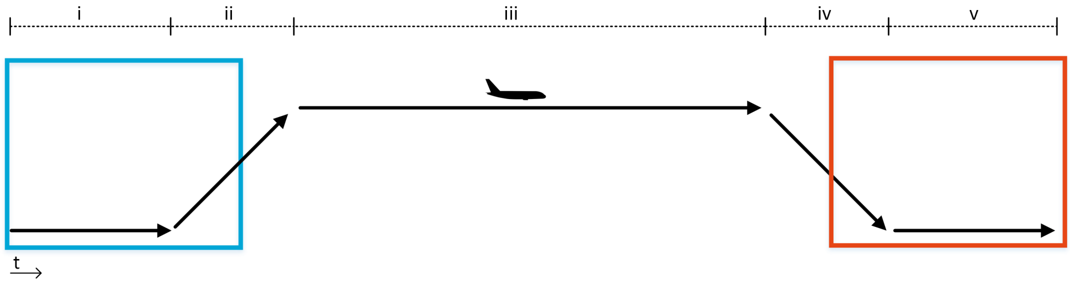

Figure 2.1: Flight profile of a regular flight.

The phases described above are illustrated in the flight profile of a regular flight as shown in Figure 2.1. As the research objective, as described in Section 1.1 makes clear, this research concerns phases i and v as well as phases ii and iv, partially. That is, the optimization model concerns decision variables that relate to ground as well as departure and arrival operations as being part of the airport operations process.

This chapter discusses four objectives that form the basis of the multi-objective optimization model concerning runway allocation at complex airports. These objectives comprise: i) airport runway capacity & delay, ii) Optimal sequencing strategies, iii) noise annoyance around airports, and iv) airline fuel economics. The coming sections summarize the information obtained from the literature study that preceeded this research. Thereby, the analysis of the identified objectives forms the basis of understanding of the runway allocation process.

2.1. Airport Runway Capacity & Delay

Capacity and delay are two driving factors in airport strategic and tactical planning. These two parameters define the amount of traffic that can be served in a certain time permitting a certain operational delay. As both parameters concern the operational service level of the airport, it can be said that these parameters form a major constraint if it comes to an increase in demand. As a result, demand and capacity should be efficiently distributed over a certain period. Failing to do so, causes increased delays and might even lead to diversions or cancellations [42].

The capacity of an airport depends on many factors. Besides the terminal and apron factors, such as the amount of gates and the available taxiway system, the runway lay-out plays an important role in the capacity definition of an airport. Namely, the lay-out of runways directly affects the capacity that can be guaranteed in certain configurations. Furthermore, the separation and possible intersection of runways have its effects on safety and, hence, the runway capacity.

This section defines four major capacity definitions that are commonly used in airport strategic planning. Furthermore, important factors that influence runway capacity are identified and analyzed. Consequently, the effects of a certain runway lay-out and configuration are assessed. This section concludes with an assessment of remaining factors that can impact the capacity of a runway.

2.1.1. Measures of Runway Capacity

Neufville and Odoni [42] prescribe four runway capacity definitions that are commonly used in airport strategic planning. The Maximum Throughput Capacity (MTC), as defined in Equation 2.1, forms the basis of most capacity parameters. The MTC, or Saturation Capacity, defines the expected number of aircraft movements that can be performed hourly on either one runway or the entire runway system of an airport [42]. These aircraft movements comprise departures and arrivals. Aircraft can be categorized in several groups related to their weight class. Each group has its own safety-related minima with respect to pairwise separation intervals. As a result, aircraft need to be separated according to these constraints. Section 2.1.3 discusses the impact of this constraint in more detail. The expected value, as defined in Equation 2.2, is defined as a function of the time interval between a certain flight pair and its related probability of occurence. Throughout this research, the term capacity will refer to the maximum throughput capacity.

$$\mu_r = \frac{1}{E(t)} \tag{2.1}$$

$$E(t) = \sum_i \sum_j p_{ij} t_{ij} \tag{2.2}$$

Based on the defined relations in Equations 2.1 and 2.2, the remaining three capacity derivatives are defined [42]:

(i) **Practical Hourly Capacity**
This capacity parameter relates to the concept of Level of Service (LOS). The LOS defines a standard for processing traffic with a specified delay that is found to be acceptable. The Practical Hourly Capacity (PHCAP) defines the expected number of aircraft movements that can be performed hourly on either one runway or the entire runway system of an airport, with an average delay per movement of four minutes.

(ii) **Sustained Capacity**
This capacity parameter relates to the workload of the ATM system and its Air Traffic Controllers (ATCo). The Sustained Capacity (SCAP) defines the number of aircraft movements that can be performed hourly on either one runway or the entire runway system of an airport, and, be reasonably sustained over a period of several hours.

(iii) **Declared Capacity**
This capacity parameter relates to the LOS in terms of delay. The Declared Capacity (DCAP) defines the number of aircraft movements that can be performed hourly on either one runway or the entire runway system of an airport, based on a reasonable LOS.

The above described capacity derivatives constrast with the capacity parameter defined in Equation 2.1. Each derivative approaches reality to a larger extent by accounting for external factors such as the human-in-the-loop effects. Doing so, results in a more accurate representation of reality.

2.1.2. Runway Configuration

The geographic position of an airport has major impact on its operations. Besides the fact that the airport must be accessible from a landside perspective, the geographic position influences the operations in terms of meteorological aspects. The positioning of the runway system of an airport mainly depends on the weather conditions that are predominantly active during the year. In ideal cases airports design their runway systems in such a way they can ensure headwind operations, within crosswind limits, throughout the entire year. Nevertheless, the geograpic position of certain airports does not have predominant wind conditions throughout the year. In such cases, the airport has to design its runway system in multiple directions, to ensure operations when facing different wind conditions.

At airports with a dense traffic demand, simultaneous operations are a daily routine. Simultaneous operations encompass increased separation minima to compensate for the dependency of specific runway sets with respect to safety. PANS-ATM Doc. 4444 [29] states the interdependence between specific runways can be categorized in two major dependencies: i) the parallel runway dependency, and, ii) the intersection runway dependency. Next to the parallel case, the latter can cause an extensive reduction in capacity. Within the intersection runway dependency, three classifications are defined: i) physical runway crossings, ii) diverging runways with the projections of their centerlines crossing each other, and, iii) converging runways with the projections of their centerlines crossing each other [42]. However, this dependency does not apply to the airport analyzed in this research and will therefore not be further discussed.

Parallel Runway Dependency

Airports located in areas in which specific wind conditions are predominantly active throughout the year often make use of a parallel runway system. Operating such a runway configuration in most cases contributes to the number of operations that can be allowed throughout the day. In periods of high demand, also known as peak hours, multiple runways in the runway system can be operated simultaneously. The interdependence of parallel runway operations can be classified in three categories as shown in Figure 2.2: i) dependent close parallel operations, ii) dependent medium spaced parallel operations, and, iii) independent operations. The impact of operating a certain runway set is discussed below.

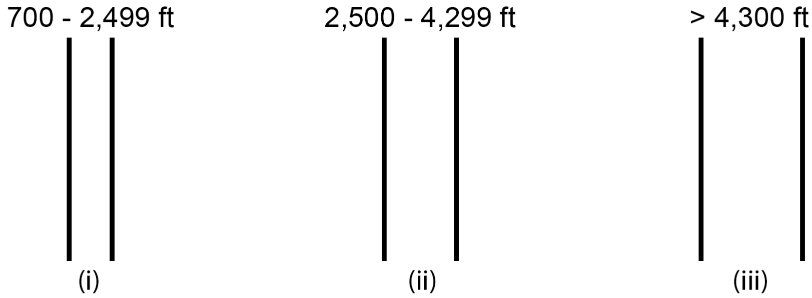

Figure 2.2: Parallel runway spacing categories: i) dependent close parallel, ii) dependent medium spaced parallel, and, iii) independent parallel operations.

(i) **Close parallel operations**
This configuration concerns parallel runways closely spaced with respect to each other. That is, the runways are located with a spacing between 700 and 2,499 feet. The close spacing causes a dependency between both runways. Operations on both runways at the same time could lead to cases in which safety minima are exceeded. As a result, to ensure safe operations, both runways must be operated in single runway mode when concerning two arrival flights. Most airports using such runway configurations operate each runway in one operation mode only, i.e. departure or arrival. However, doing so would need the departure to be timed such that a possible go around for the arrival flight is taken into account. By having one runway for departures, whereas the other runway is used for arrivals, the theoretical capacity of such a runway set can be utilized as much as possible.

(ii) **Medium spaced parallel operations**
This configuration concerns parallel runways medium spaced with respect to each other. That is, the runways are located with a spacing between 2,500 and 4,299 feet. The spacing causes a limited dependency between both runways. Consecutive arrivals landing on both runways must have a diagonal separation of at least 1.5 nautical mile (nm). By applying this separation, one ensures the trailing aircraft, j, will not get in conflict with the wake vortices created by the leading aircraft, i, on the parallel runway. The creation of such diagonal separation can be solved by the use of staggered runways as has been analyzed in the literature review that preceeded this research.

(iii) **Independent parallel operations**
This configuration concerns parallel runways largely spaced with respect to each other. That is, the runway are located with a spacing of at least 4,300 feet. The spacing results in an independence of both runways with respect to each other. Moreover, this type of operation is the most ideal case in parallel runway operations as aircraft can land and depart independently with respect to operations on the other runway. This configuration is often found at airports located in areas where winds are predominantly active from specific directions during the year. This configuration can also be found at London Heathrow Airport (ICAO: EGLL; IATA: LHR). The criticism over the last years in terms of noise annoyance as well as capacity makes this airport an interesting case study to apply the flexible runway allocation model to. Therefore, Heathrow is used as reference airport in this research. Accordingly, the operations on both runways are set to be independent. A more detailed analysis on Heathrow is provided in Chapter 3.

2.1.3. Regulatory Separation Minima

In order to ensure safe airborne operations, several regulations with respect to separation minima between consecutive flights have been established. These separation minima incorporate safety buffers related to the weight and size of aircraft. The ANSP applies these separation minima to ensure safe and efficient operations within the controlled airspace. An important document describing these regulations is PANS-ATM Doc. 4444 [29]. This document describes the separation categories as defined by the International Civil Aviation Organization (ICAO).

ICAO Wake Turbulence Categories

One of the major hazards in flight operations is the occurence of wake turbulence. Wake turbulence originates from the fact that high pressure air from the lower surface of the wings flows around the aircraft's wingtips to the lower pressure region on the upper side of the wings. As a result, the generated flow causes a pair of counter-rotating vortices. These vortices make the area behind the wings an area of unsmooth air. The impact of this hazard correlates with the wing size and weight of the aircraft. Moreover, an aircraft having a large Maximum Take-off Weight (MTOW) will cause a more heavy wake turbulence compared to an aircraft with a lower MTOW. To classify the impact of wake turbulence, aircraft are being categorized in four Wake Turbulence Categories (WTC) as described in Table 2.1.

Table 2.1: ICAO wake turbulence categories [29].

Identifier	WTC	MTOW [kg x 1,000]	Example Aircraft
J	SUPER	MTOW ~ 560	AN-124, A388
H	HEAVY	MTOW ≥ 136	B763, A346
M	MEDIUM	7 < MTOW < 136	AT45, B738
L	LIGHT	MTOW ≤ 7	SF34, LJ35

European Wake Vortex Re-categorization

The example aircraft mentioned in Table 2.1 give an indication of aircraft types that are classified within a certain ICAO WTC. However, when analyzing the group of aircraft that belong to the H class, a broad span of MTOW and wingspan can be found as illustrated in Figure 2.3.

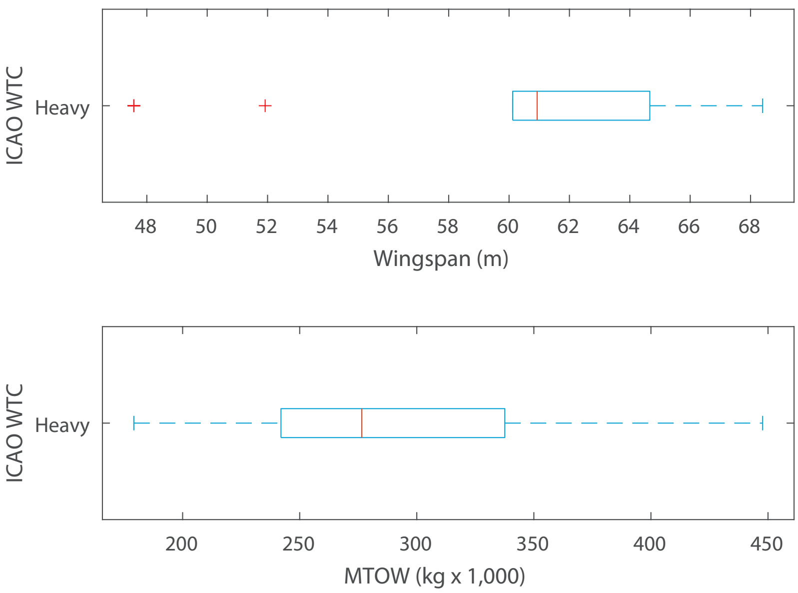

Figure 2.3: Boxplot of wingspan and MTOW of ICAO WTC Heavy.

Moreover, category H contains the B767-300 (B763) as well as the A340-600 (A346). Comparing these two aircraft in terms of design characteristics, shows the MTOW of the A346 is more than twice as large compared to the B763, whereas its wingspan is about 15 meters larger. The same kind of correlations can be found in category M. As a result of this type of generalization, the impact of wake vortices on trailing aircraft is in some way under-/overdesigned. In order to improve this conservative approach, Eurocontrol designed a new categorization methodology for aircraft with respect to their impact on wake turbulence [46]. This project was named Wake Turbulence Re-categorization for Europe (RECAT-EU). Comparing the RECAT-EU scheme with the orignal WTC scheme, shows that the impact of wake vortices is caused not only by MTOW but also by the size of the wingspan. The implementation of the size of the wingspan enables a more detailed categorization of different wake vortex characteristics. The RECAT-EU scheme can be found in Table 2.2.

Table 2.2: RECAT-EU wake turbulence categories [46].

Identifier	**WTC**	**MTOW [kg x 1,000]**	**Wingspan [m]**	**Example Aircraft**
A	SUPER HEAVY	MTOW ≥ 100	72 < Wingspan < 80	AN-124, A388
B	UPPER HEAVY	MTOW ≥ 100	60 < Wingspan < 72 [1]	B744, A346
C	LOWER HEAVY	MTOW ≥ 100	Wingspan < 52 [1]	MD11, B763
D	UPPER MEDIUM	15 < MTOW < 100	Wingspan > 32	B738, A320
E	LOWER MEDIUM	15 < MTOW < 100	Wingspan < 32	AT45, E190
F	LIGHT	MTOW ≤ 15	-	SF34, LJ35

Figure 2.4: RECAT-EU symbols used in this thesis.

Within RECAT-EU, six categories are defined. These categories are named Super Heavy, Upper Heavy, Lower Heavy, Upper Medium, Lower Medium and Ligt. The first five categories are applicable to the airport analyzed in this research. Figure 2.4 visualizes the symbols used for these categories in this thesis. According to the defined wake turbulence categories in RECAT-EU, specific separation minima have been established to ensure aircraft are not affected by wake turbulence caused by their successor in the operation sequence. Aircraft on a common approach path are separated by a certain distance. This type of separation is called Distance-based Separation (DBS). By applying a DBS minimum, the demand on a certain route or approach path can be optimized by ensuring the required safety separation. Optimization strategies that are commonly used for aircraft sequencing are discussed in Section 2.2. The DBS minima according to the RECAT-EU scheme can be found in Table 2.3.

Table 2.3: Distance-based standard separation minima (nm) for arrivals according to RECAT-EU [46].

	Trailing Aircraft					
Leading Aircraft [2]	*SUPER HEAVY*	*UPPER HEAVY*	*LOWER HEAVY*	*UPPER MEDIUM*	*LOWER MEDIUM*	*LIGHT LIGHT*
SUPER HEAVY	3	4	5	5	6	8
UPPER HEAVY	(2.5)	3	4	4	5	7
LOWER HEAVY	(2.5)	(2.5)	3	3	4	6
UPPER MEDIUM	(2.5)	(2.5)	(2.5)	(2.5)	(2.5)	5
LOWER MEDIUM	(2.5)	(2.5)	(2.5)	(2.5)	(2.5)	4
LIGHT	(2.5)	(2.5)	(2.5)	(2.5)	(2.5)	3

[1] Aircraft over 100 tonnes MTOW and having a wingspan larger than 52 meters and smaller than 60 meters will undergo a specific analysis after which it will be categorized in either group B or C.

[2] The bracketed values indicate minimum radar separation (MRS), set at 2.5 nm, as is applicable per current ICAO doc 4444 provisions [29] [46].

2.1.4. Other Sources of Capacity Limitation

Besides the elements described in Sections 2.1.2 and 2.1.3, the capacity of a runway system is limited by several other factors. These factors comprise operational, environmental and human-related aspects. The mixture of inbound and outbound traffic is one of the major operational factors that significantly influences the capacity. Aircraft characteristics like MTOW, speed profile and climb rate differ to large extent for specific aircraft types. Therefore, the mixture of aircraft types in an arrival or departure sequence increases the complexity of efficient operations. In order to adhere the separation minima as described in Section 2.1.3, the speed profile of aircraft must be carefully taken into account. Looking at the approach phase, multiple cases can be defined related to the speed profile of two consecutive aircraft. The application of such cases is further discussed in Chapter 4.

Another type of capacity limitation is caused by certain operational restrictions prescribed in the Aeronautical Information Package (AIP). These particular operational restrictions regarding Heathrow can be found in EGLL AD 2.22 Flight Procedures of Heathrow's AIP [40]. This document defines several airport specific restrictions in terms of altitude constraints, speed limits and initial climb constraints. These constraints are designed to structure the operations within the controlled airspace. However, speed and altitude restrictions can have an impact on the overall efficiency of operations.

Weather conditions are one of the most predominant factors that influence the runway configuration and thereby the capacity to a large extent. Meteorological conditions related to airport operations can be categorized in three groups: i) cloud ceiling, ii) visibility, and iii) wind direction and speed. Cloud ceiling and visibility define the situational awareness of pilots as well as air traffic controllers. Reduced vertical and/or horizontal visibility can dramatically affect the safety at and around an airport. To classify the visibility at an airport, two categories have been defined: i) Visual Meteorological Conditions (VMC), and ii) Instrument Meteorological Conditions (IMC). The latter defines reduced meteorological conditions in terms of cloud ceiling and visibility. Accordingly, pilots must operate under Instrument Flight Rules (IFR). Appendix F provides an annual weather analysis of Heathrow.

Among weather conditions, wind direction and speed can cause a major impact on airport operations. Preferably, aircraft take-off and land into the wind for operational and safety reasons. The headwind can be used to obtain an increased True Airspeed (TAS) versus Ground Speed (GS), enabling the aircraft to lift-off with a shorter take-off roll during departure, or, helping the aircraft slow down during the landing phase. However, (extreme) headwind conditions reduce the capacity of a runway. In some cases, airports are not able to operate in headwind conditions. Such cases force the airport operator to select the most suitable runway configuration which can lead to cross-/tailwind landings and/or departures. The use of such alternative configurations comes with certain operational limits from the airport's as well as the airline's perspective.

Nowadays, humans are integrated in the process of airport operations. Humans contribute and influence the system from multiple perspectives. Two major perspectives are related to the role of the pilot and the ATCo. The communication between these two agents in the system causes a certain inefficiency as a result of the human factor. To compensate for this, a human-related safety buffer must be applied to ensure safe operations.

2.1.5. Applicability of Airside Delay

The airport runway system can be typically seen as a queuing system as part of a queuing system network. A general queuing system consists of three major parts: i) a user source, ii) a queue and iii) a service facility with 1+ parallel servers. Important parameters in the queuing theory range from demand rates and Inter-Arrival Times (IAT) to service rates and times. The server in this case is the ANSP providing the ATC within the region of a specific airport.

There are two types of behaviour related to demand and capacity that are currently being adopted in research into runway capacity by Neufville and Odoni [42]. One is the situation in which the demand rate continuously exceeds the service rate (capacity). This situation will lead to an increasing delay as the demand rate will never be met in a specific time frame. The other is a situation in which the demand rate is lower than the overall service rate. But the inter-arrival times of the demand fluctuates as such that peak moments lead to delays. This type of delay is defined as probabilistic or stochastic delay. Delays of this kind, may lead to an extreme increase in delay once the demand rate approaches the service rate. The expected probabilistic or stochastic delay depends on the history of the queue and therefore lags behind the peak that can be observed in the demand rate.

Generally speaking, delay can have two effects on airside operations. The first, lack of capacity, has a negative influence on the overall operations at an airport. However, delay can also be used in order to smoothen operations and make the overall operational runway utilization more efficient. This type of controlled delay plays a major role in the flexible runway allocation process. As controlled delay can offer the availability of a preferred runway at a certain time, it will contribute to noise annoyance as well as the fuel consumption during the flight. In essence, aircraft will be consiously delayed in order to enable a more efficient overall approach or departure trajectory with respect to noise annoyance and fuel burn. The applicability of this type of delay is further discussed in Section 6.3.

2.2. Multi-Runway Aircraft Sequencing

When dealing with an airport as Heathrow, escape from complexity is never possible. The complexity at Heathrow is a result of the limited amount of runways and the extreme airspace density within the TMA. The conditions at this airport in terms of traffic demand has reached its maximum. To handle this high amount of traffic requires a well structured ATC organization. One of the major considerations in this ATC organization concerns the scheduling of aircraft on the runways the airport offers. At Heathrow this is limited to two runways only, enabling aircraft to land and depart on four runway ends. This section introduces the traditional "First-Come-First-Served" strategy to order aircraft in a given period of time. With this in mind, a modified strategy is introduced to optimize the aircraft sequence and thereby make it more efficient in terms of runway capacity.

2.2.1. First-Come-First-Served Ordering

The traditional "First-Come-First-Served" (FCFS) strategy has been used since the early years of ATC. This is obvious since ATC years ago was limited to aerodrome control only. In the years that past the ATC system has grown and now comprises terminal control and en-route control as well [42]. FCFS defines the sorting of aircraft based on their earliest landing or departure time as shown in Figure 2.5. That is, this strategy provides a fair and easy way of scheduling aircraft in an approach or departure sequence. However, this sequencing policy is not optimal anymore when aircraft of different categories arrise in the time frame to be analyzed. As a consequence, the FCFS sequence can lead to a loss in capacity, because of pairwise separation standards.

2.2.2. Optimal Ordering

To find a more optimal aircraft sequence, more efficient use should be made of the pairwise separation minima that have been defined by Eurocontrol [46]. At the first sight of complexity, when multiple aircraft are scheduled in a small time frame, an optimal sequence should be constructed in order to minimize the average runway occupancy time. Figure 2.5 gives a clear overview of the modifications that can be made with respect to a FCFS sequence upon arrival. The model that is concerned in this research, in theory, does not optimize the aircraft sequence as this objective is not included in the model's objective function. However, the constraints regarding the pairwise separation minima somehow influence the model such that it orders aircraft optimally within the bounds of the model's objectives.

Table 2.4: Minimum pairwise separation time over the entire operation sequence.

	Pairwise Separation (s)			**Total**
Strategy	*1-2*	*2-3*	*3-4*	**Separation (s)**
Optimized	60	60	60	180
FCFS	100	60	60	220

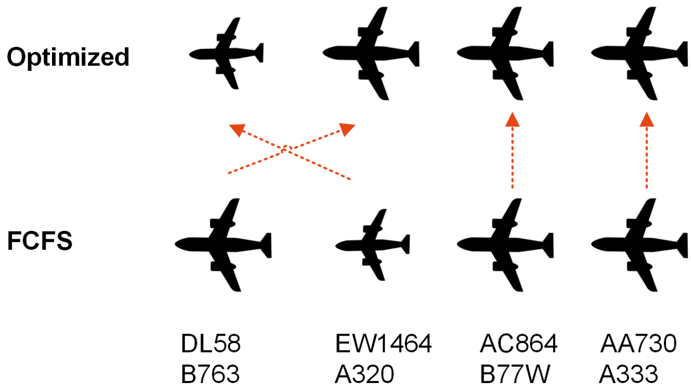

Figure 2.5: Typical FCFS and optimized arrival sequence.

2.3. Noise Exposure

The second objective in the flexible runway allocation process concerns noise annoyance in the vicinity of the airport. In fact, legally, this objective might be the most important in the entire process of flight operations at an airport. At major airports, the government has restricted the maximum amount of noise that may be emitted in a certain time frame. Multiple reasons can be stated as the logic behind this boundary. One of the most important, is the fact that a high amount of (continuous) noise events may lead to noise annoyance which can cause sleeplessness among residents in the airport's surroundings [26].

2.3.1. Noise around Airports

In the early 1970s, The Noise Advisory Council [49] published a report to express the causal of aircraft noise. In their report, the council describes that most people in the United Kingdom are subject to some level of aircraft noise. The intensity of the noise nuisance caused by aircraft increases in areas near airports. The primary goal of the research conducted by the council was to demonstrate whether it would be better to concentrate air traffic near airports or to spread it in order to mitigate noise disturbance in those areas. The answer to this problem could be one of ethical judgement. As of now, growing economies, passenger and cargo traffic, force airports such as Heathrow to be fully utilized in terms of capacity and its related noise budgets.

In his research, Halperin [21] investigates the impact of environmental noise and sleep disturbance on the well-being of human beings. He analyzes the categories of adverse health and social effects as documented by the World Health Organization (WHO) [26]. Among others, he states that healthy sleep contributes to the consolidation of memory in the human brain. From the research it can be concluded that there is a relation between sleep disturbances and health. Therefore, the need of minimizing noise caused by aircraft is of high importance. Halperin's research, among others, supports the statements made by the World Health Organization [26] in their report on the effects of night-time noise on health and well-being.

As London Heathrow is located in an area which is densely populated, evening and night operations will cause a high impact on the well-being of the residents living in the area around the airport. When analyzing the flight schedule of Heathrow [19], it can be clearly seen that the latest scheduled flight is set around 11:00 p.m. local time, whereas the first flight of the day is scheduled around 05:00 a.m. local time. That is to say that the airport has to comply to the regulated night curfew that is applied by the UK government. Therefore, at night times, the airport is only opened for non-scheduled emergency operations.

Moreover, to further decrease the annoyance that is caused by the flights operated to and from Heathrow, the airport has established a runway alternation scheme. This scheme has been set-up in order to equally distribute noise exposure throughout the entire year. That is to say that the airport operates a certain runway configuration according to a pre-established scheme. However, this scheme can only be used in cases weather conditions do not interfere the operations flow. Section 3.2 elaborates further on the runway alternation strategy at Heathrow.

2.3.2. Sources of Aircraft Noise

Aircraft noise annoyance as observed by residents on the ground can origin from several sources that are related to an aircraft. Most noise that origins from aircraft has low frequency components or is accompanied by vibrations. This type of noise is often observed as more annoying compared to other noise events [26]. In recent years, noise levels around airports have decreased as relatively old noisy aircraft are being replaced by modern next generation aircraft such as the Airbus A380, Airbus A350 XWB and the Boeing 787 Dreamliner.

According to Bertsch et al. [8], sources that cause aircraft noise can be categorized in three groups: i) interaction between object and flow, ii) interaction between flow and flow, and iii) entropy fluctuations. Noise annoyance is caused by pressure fluctuations which can be observed as noise. The human perception of sound is defined by the Sound Pressure Level (SPL). This logaritmic metric defines the effective sound pressure p_e, relative to a reference sound pressure, p_{e_0}. The mathemetic relation of the SPL can be found in Equation 2.3

$$\mathrm{SPL} = 10 \log \left(\frac{p_e^2(t)}{p_{e_0}^2(t)} \right) \tag{2.3}$$

The first source of noise defines a situation in which a pressure fluctuation is generated as a result of an interaction between flow and an object. An obvious example of this is the interaction between air and an airframe. The second source of noise defines an interaction between two flows of air. In several phases in flight, certain flow regimes often don't have equal velocities. As a consequence, a shear layer can exist. This shear layer causes an area of turbulent air as two flow regimes are mixing flows [2]. The last noise source is related to entropy fluctuations. These fluctuations originate from turbulent combustion in the aircraft's engine. The flow of air that runs through the engine is turbulent as it passes through several stages inside the engine. The interaction of turbulent air and the flame in the combustor of the engine causes pressure fluctuations which can be observed as noise [48].

Bertsch [8] states that commercial aircraft contain two primary noise sources. The majority of noise generated by the operation of aircraft is related to either engine noise and/or airframe noise. Engine noise comprises jet noise, fan noise and compressor noise. Noise emissions related to airframe noise are often caused by aerodynamic phenomena like bending of air flows and boundary layer control. Looking at noise annoyance in airport's vicinities, the reduction of noise emissions in aircraft operations is of high importance. This importance if reflected in the large amount of optimization studies that have been performed in last decades. These studies have led to multiple techniques that contribute to the reduction of noise annoyance around airports.

2.3.3. Noise Mitigation Techniques

The need for mitigating noise around airports is of high importance when it comes to maximizing operations at the airport. As stated by ICAO [30], four pillars are defined that should contribute to the balanced approach to aircraft noise management. These pillars are shown in Figure 2.6.

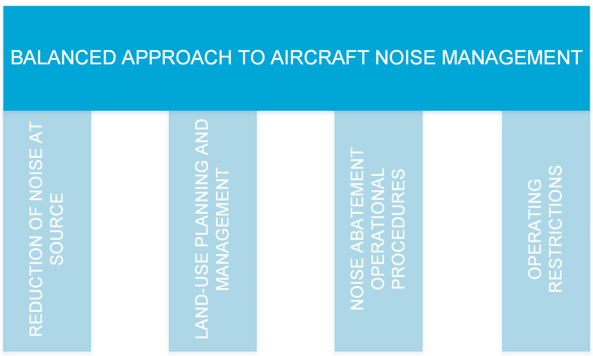

Figure 2.6: Pillars identifying the balanced approach to reducing the impact of aircraft noise defined by ICAO [30].

When concerning the first pillar, it can be stated that in recent years a high level of progress has been made with respect to the development of aircraft noise from the structural perspective. That is, engines as well as the airframe are optimized with respect to generation of noise. The second pillar, land-use planning and management, concerns the introduction of land-use zoning in the vicinity of the airport. However, this principle has no direct relation with this research. On the contrary, principles three and four definitely relate to this research.

Multiple regulations and solutions enable airports and airlines to operate under reduced noise emissions. The necessity of reduced noise emissions is based on the protection of the human well-being and annoyance observed by humans. As operations at an airport mainly consists of departures and arrivals, two types of mitigation techniques have been designed. Additionally, major airports have specified regulations during nighttime periods. That is, to minimize annoyance and awakening by residents, most airport operate a special noise optimized noise scheme.

Departure Procedures
Obviously, departure operations cause the most noise annoyance among residents on the ground. As the departure segment of flight contains a certain climbing profile, the aircraft is accelerating in the first stages of this segment. Moreover, the acceleration phase requires a high thrust setting, which results in an increased noise emission profile. To reduce noise exposure, Noise Abatement Departure Procedures (NADP) have been designed named NADP-1 and NADP-2 [31]. The difference in these two profiles lies in the fact where the closest residential area is located. NADP-1 prescribes a noise-optimized procedure for noise-sensitive areas in the close vicinity of the airport's departure runway, whereas NADP-2 is based on noise-sensitive areas that are located further away from the runway.

To further reduce noise disturbance caused by departure operations, most airports make use of Standard Instrument Departure (SID) profiles. By assigning an SID to a certain flight, the aircraft is forced to fly a certain ground track, towards the entry point of the upper/lower Air Traffic Service (ATS) route as part of their flight plan. Predefining these tracks results in the fact that aircraft can be circumnavigated around densely populated areas in order to minimize noise annoyance on the ground. However, as these tracks are the same per SID fix, the number of noise events concentrates around these tracks.

Arrival Procedures
Besides departures, arrival operations come with noise emission as well. During the approach procedure, aircraft gradually reduce its velocity while descending towards the destination airport. By doing so, several parts of the aircraft emit noise which may be observed by the human ear.

To minimize noise exposure caused by arriving aircraft, certain lateral and logitudinal flight trajectories can be designed. These trajectories are defined as Area Navigation (RNAV) trajectories specifying altitude, navigational and sometimes even speed constraints. These type of trajectories can be found at airports with a high airspace density and/or strict evening and night noise regulations.

Night Procedures
Focusing on the specific regulations at Heathrow, it is interesting to analyze the regulations for night operations at the airport. As prescribed by the Department for Transport [12], night operations at Heathrow are heavily regulated. The airport is surrounded by multiple populated areas, making its location noise-sensitive. As a result, the government prescribed a maximum amount of yearly flight operations that may be operated in night time periods. The limits for night operations have been defined in terms of flight movements as well as a noise quota. Section 3.3 elaborates on the application of the noise quota system at Heathrow.

2.3.4. Sleep Disturbance as a Consequence of Aircraft Noise
The noise mitigation techniques together with certain noise regulations have been designed in order to minimize noise exposure and annoyance on the ground. Next to the disturbance impact of aviaton noise to households, offices, hospitals and schools, noise annoyance during night times is experienced even higher. In 1992, the Federal Interagency Committee on Noise (FICON) has introduced a computational method to predict the percentage of awakings among the exposed population as a function of single event noise levels.

In the years after, a large area of research arised in which several studies have been performed on the effects of aviation noise on awakenings and human well-being [26] [43]. In 1997, the Federal Interagency Committee on Aviation Noise (FICAN) presented an adapted version of the recommended sleep disturbance dose-response relationship as shown in Equation 2.4 [18]. The percentage of awakenings among residents exponentially grows for an increasing level of noise related to a certain noise event as illustrated in Figure 2.7. As a result, an increase in noise exposure has a drastic influence on the number of awakenings in the region.

$$\text{Awakenings} = 0.0087 \cdot (\text{SEL} - 30)^{1.79} \tag{2.4}$$

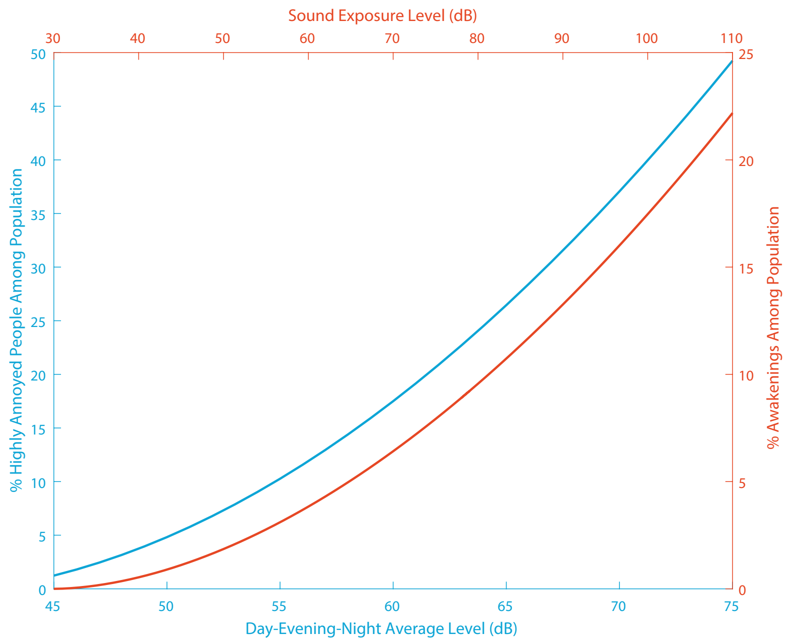

Figure 2.7: Recommended disturbance dose-response relationships [4] [18].

2.3.5. Noise Annoyance as a Consequence of Aircraft Noise

Besides the effects that noise exposure can have on the sleeplessness of human beings, it can also cause annoyance throughout the rest of the day. A study on exposure-response relationships performed by the European Environment Agency (EEA) [4] has resulted in a metric to estimate the percentage of people that get annoyed or even highly annoyed by a certain level of noise exposure. In the research performed by the EEA, distinction is made between noise annoyance caused by road traffic, railway traffic and aircraft. The latter is of high importance when concerning the noise reduction objective in this research. Equation 2.5 identifies the relationship between the level of noise exposure and the percentage of people that get highly annoyed (HA) by this exposure. The level of annoyance is a result of a combination of emotional as well as physical factors that contribute to the observation of noise. This relation is visualized in Figure 2.7. In this thesis a noise exposure limit of 55 dB L_{DEN} is used unless otherwise defined. According to the curve shown in Figure 2.7 a 55 dB L_{DEN} noise exposure would lead to 10.3% of the exposed population to be highly annoyed.

$$\%\text{HA} = -9.100 \times 10^{-5} \cdot (L_{DEN} - 42)^3 + 3.932 \times 10^{-2} \cdot (L_{DEN} - 42)^2 + 0.2939 \cdot (L_{DEN} - 42) \tag{2.5}$$

2.4. Airline Fuel Economics

The implementation of NPRs contributes to a reduction of noise annoyance around airports. Moreover, these routes ensure reduced noise emissions over densely populated areas. In order to establish such routes, substitutional flight tracks need to be designed. These tracks often have lateral, longitudinal and speed restrictions to reduce noise emissions. However, these noise-optimized tracks do not account for additional fuel usage. Moreover, these routes circumnavigate densely populated areas, and, thereby may cause an increase in fuel consumption. Logically, this increase in fuel burn is not favored by the airlines themselves.

This section discusses the airline's cost structure in terms of different cost divisions which have been defined within the aviation industry. From this generic economical overview the coming paragraphs zoom into the cost division which is related to fuel consumption of an airline. Consequently, the factors that play an important role in the determination of the fuel-related cost are being analyzed.

2.4.1. Airline Cost Structure

Airline expenditure can be categorized in different cost divisions. These cost divisions are used to structure airline cost, enabling decision makers to make operating and pricing decisions. The total cost of an airline comprises Non-Operating Cost and Total Operating Cost (TOC). The latter incorporates Direct Operating Cost (DOC) and Indirect Operating Cost. DOC is related to operational costs within the airline. These costs range from cleaning costs up to fuel costs. Fuel costs are of high importance in airline economics as fuel is one of the major contributors to Variable Direct Operating Cost (VDOC) within the DOC. VDOC is defined as costs that are allocated to individual flights or routes. According to Doganis [13] and IATA [28], fuel costs cover over one-fourth of the VDOC of an airline.

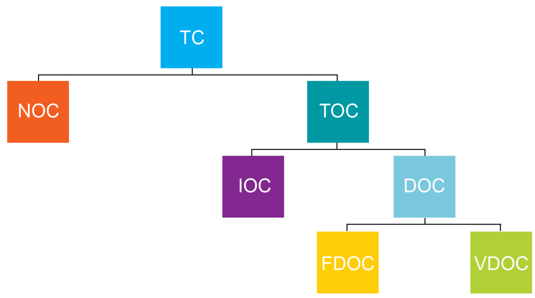

Figure 2.8: Fuel economics structure airline.

2.4.2. Variable Direct Operating Costs

As fuel costs are directly dependend on the type, size and weight of the aircraft as well as on the route it flies, a minimization in distance of the track to be flown results in reduced VDOC. Having described the essence of fuel costs, a fuel-optimized flight track will contribute to the airline's operating costs. Therefore, taking fuel consumption as an objective in the runway allocation optimization process is benificial for airlines, and, in some sense for the airport as well. Namely, reduced fuel emissions will contribute to the environment in terms of emitted exhaust gasses.

2.4.3. Jet Fuel Trend

The total fuel cost of an airline depends on two factors. These factors include total fuel consumption and fuel price. Recent years have shown, the latter is a topic of high interest. Because of several economic and geopolitic events that have taken place in the last decades, the oil and fuel price can be called unstable. Recent years have shown a dramatic drop in oil and fuel price. The decrease in oil price is expected to stimulate the global economic growth. In some way, this growth can be translated to the airline's economics. One of the major inputs in the airline's cost system is jet fuel. As Figure 2.9 shows, aviation fuel nowadays reflects 16% of the airline's total cost allocation. A decade ago, this component even reflected over 26% of the total admistrative costs [7]. Together with labor costs and rent & ownership costs, fuel costs is one major drivers in the airline administrative cost allocation structure.

As Figure 2.10 shows, the trend in oil and fuel price has been fluctuating a lot in the past two decades. The peak in 2008 reflects Asia's growth spurt which resulted in an increased demand of oil. Thereafter, the oil and fuel price have dropped and have now reached a minimum over the last decade. It can be stated that the decrease in price is a result of the continuously increasing global oil supply. Because of these variations, the airline's fuel economics are quite unstable and can have a major impact on the overall cost structure.

The majority of airlines tries to avoid uncertain situations like these. In order to be on the safe side, in cases the fuel price is expected to rise, airlines aim to lock in fuel purchases. This means, the airline establishes a contract with the fuel provider to lock the fuel price. This is also known as fuel hedging. By this way, the airline bets that jet fuel prices are rising in the near future. This should then result in a benificial situation

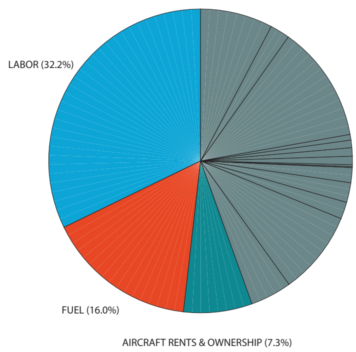

Figure 2.9: Average US airline total cost allocation in 2016 [3].

with respect to the overall fuel costs of the airline. However, in cases expectation and reality do not coincide enough, fuel hedging could lead to drastic loses for large airlines. This is wat occured during the unexpected trend in jet fuel price in the last years.

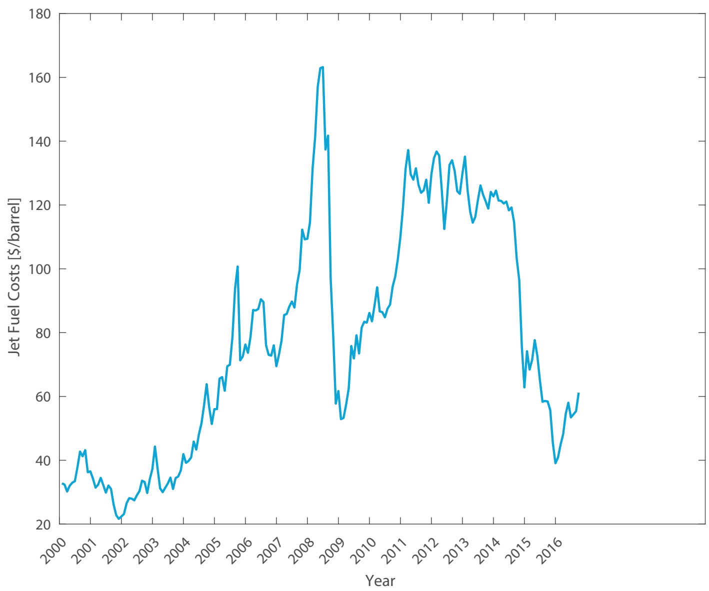

Figure 2.10: Trendline aviation fuel price over the past 16 years [3].

3
Flight Operations at Heathrow

To travel to or from London's largest airport, London Heathrow (ICAO: EGLL; IATA: LHR), means the possibility to encounter terminal and/or ground delays. One of the most dense Terminal Manoeuvring Areas (TMA) is the one above London, servicing multiple large airports surrounding the city of London. The amount of traffic at Heathrow, located in the metropole of the United Kingdom, is quite remarkable for the amount of runways the airport has. The airport faces limitations in terms of capacity. These limitations are reflected in the number of operations that is allowed at the airport throughout the day and night [12].

This chapter provides an analysis of the airport as well as its flight schedule on a regular day during summer at Heathrow. Based on the operations defined in this schedule, the existence of peak periods is identified. In the first place, the number of operations is related to certain operational factors which may have an influence on the outcome of the optimal solution of the flexible runway allocation model. As this model concerns both noise annoyance and fuel burn including taxi fuel, the assignment of a certain runway to a specific flight can be somehow related to the terminal the flight operates to or from, the direction, the origin/destination airport and so on. The correlation of these factors is analyzed in the coming sections.

3.1. Airport Characteristics

London Heathrow (LHR) is one of the busiest airports in the world. Despite the fact that it is not the largest airport in size, the airport handled 473,231 air transport movements and 75.7 million passengers in the year 2016 [37]. This makes it Europe's most busy airport in terms of passenger handling. The airport was founded in the first halve of the 20th century and has expanded into an airport of high importance from global perspective.

The airport consists out of a two-runway system in which both runways are parallel and facing in East-West configuration as shown in Figure 3.1. Heathrow comprises five terminals of which T1 is currently being renovated. The airport is home to UK's legacy carrier British Airways (BA) as well as Virgin Atlantic (VS).

Having the airport located in an area which can be marked as highly noise-sensitive, further expansion of the airport is limited by the Government as well as the population surrounding the airport. With the contiously growing demand, only two options could lead to acceptance of an increased amount of passengers traveling through Heathrow. These options include an increase in capacity in terms of flights, or an increase in capacity in terms of larger aircraft. As during the last decade the airport was not allowed to expand by adding a third runway. Instead, the growing demand was handled by large aircraft operating at Heathrow. This is what can be clearly seen in the aircraft mixture at LHR, as is discussed in Section 3.4.

The following paragraphs comprise analyses on the flight operations at Heathrow. In the first place, a peak hour analysis is performed in order to identify peak periods throughout the day. By knowing these periods, the aircraft demand mixture defines the variety of aircraft types that are being operated, which helps investigating the impact of certain peak periods. Furthermore, the flight schedule is analyzed in terms of origin and destination airports and the influence of British Airways' operations at its hub airport Heathrow.

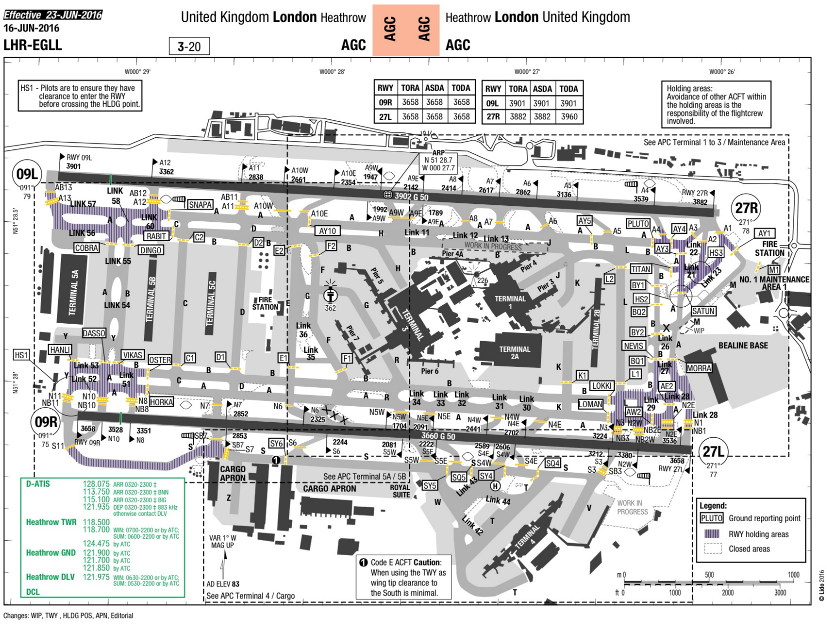

Figure 3.1: Airport Ground Chart Heathrow [38].

3.2. Runway Alternation Strategy

Heathrow's daily operations, are restricted to the runway alternation scheme that has been set-up in cooperation with surrounding residents and the UK Government. This alternation scheme defines a strict way of operation concerning the configuration of the airport during calm and moderate weather conditions. The scheme simply divides the day in two halves, starting at 07:00 a.m. to 03:00 p.m. and the second half being from 03:00 p.m. until the last departure of the day. At 03:00 p.m., the airport switches operations between the northern runway and the southern in order to equally divide noise emission over the populated area in the vicinity of the airport. However, this strict operational strategy limits operations from being fuel and noise efficient. It might even be considered that this strategy is not the most suitable for all stakeholders in this case.

3.3. Peak Hour Identification

Establishing a timetable consisting of flight operations requires a trade-off between multiple factors. These factors, of which runway capacity is one of the most important [6] [42], somehow influence the flow of operations at the airport. Even if airlines have established their timetables, they have to comply to operational restrictions of the airport they are operating to or from. One of these operational restrictions at Heathrow prescribes the night curfew that is active between 11:30 p.m. and 06:00 a.m. local time. Obviously, this restriction limits the scheduling flexibility of operations and capacity at Heathrow.

When analyzing the operational flight schedule of Heathrow, some important parameters are taken into account. The schedule used in this research, dated from August 3, 2016 [19], comprises the following parameters:

- Flight number
- Scheduled departure/arrival time
- Aircraft type
- Destination and origin airport

Because of this limited dataset several assumptions have to be made in order to create a set of data which satisfies the requested input for the model. The consequences of this data limitation continues in the analysis of the model outcome as well as the validation of the outcome. These limitations are emphasized on in the following chapters.

In order to simulate the fact of uncertainty in flight operations, and thereby make the schedule more representative, a random variable is added to the scheduled operation time. That is, by adding a random integer value between -15 and 15 minutes to the operation time, the stochastic effects of operational delay, weather conditions and other operational factors are taken into account.

Having defined the flights in a regular summer season schedule [19], the hourly distribution of operations can be analyzed in order to identify connecting banks and peak periods. As Heathrow operates a two-runway system only, the capacity at the airport is limited. This, together with the fact that London is one of the most economically active cities in the world [53], the utilization ratio of both runways is extremely high. However, when looking at Figure 3.2, some peak periods can be identified with respect to the type of operations, departures and arrivals, respectively. An interesting fact is that in the first hour of operation, between 05:00 a.m. and 06:00 a.m. local time, only arrivals are scheduled into Heathrow. This is due to the rules that define the night curfew that is active until 06:00 a.m. and only allow a reduced amount of traffic before that time.

Table 3.1: Hourly flight operations on 3 August 2016.

	Local Time (hrs)					
	05:00-06:00	**06:00-07:00**	**07:00-08:00**	**08:00-09:00**	**09:00-10:00**	**10:00-11:00**
Departures	0	25	41	42	43	36
Arrivals	13	41	40	35	38	37
	11:00-12:00	**12:00-13:00**	**13:00-14:00**	**14:00-15:00**	**15:00-16:00**	**16:00-17:00**
Departures	42	40	42	40	43	40
Arrivals	25	39	37	40	38	41
	17:00-18:00	**18:00-19:00**	**19:00-20:00**	**20:00-21:00**	**21:00-22:00**	**22:00-23:00**
Departures	40	38	41	45	31	26
Arrivals	41	43	40	36	40	21

As prescribed by the Department of Transportation [12], limited operations are allowed during the night curfew period. In order to classify aircraft related to noise emissions, Quota Counts (QC) are introduced as shown in Table 3.2. These quota counts represent a certain noise band reflecting the noise emission of a certain aircraft during departure and arrival, separately. This system enables individual noise count against an overall noise quota. With this in mind, the noisiness of aircraft has a direct influence on the number of flight operations that can be allowed during night periods. As described in Chapter 2, the noisiness of aircraft is larger for departures compared to arrivals. Therefore, it is more benificial to use the noise budget by operating arrival flights as their QC is lower with respect to a departure of the same aircraft type. This effect can also be seen in Figure 3.2 and Table 3.1. All operations in the night curfew period are arrivals. Besides, the aircraft operated within this period are modern aircraft, having a low QC, which leads to a maximized amount of flights to be eligible to operate.

Table 3.2: Quota Count per noise classification at Heathrow.

	Noise Classification (EPNdB)						
	84.0-86.9	**87.0 - 89.9**	**90.0 - 92.9**	**93.0 - 95.9**	**96.0 - 98.9**	**99.0 - 101.9**	**> 101.9**
Quota Count	0.25	0.5	1	2	4	8	16

3.4. Aircraft Demand Mixture

In order to set up aircraft specific fuel burn profiles, a set of aircraft that are operated at the airport must be defined. A set of unique aircraft that are being operated at an airport is often used to describe the aircraft

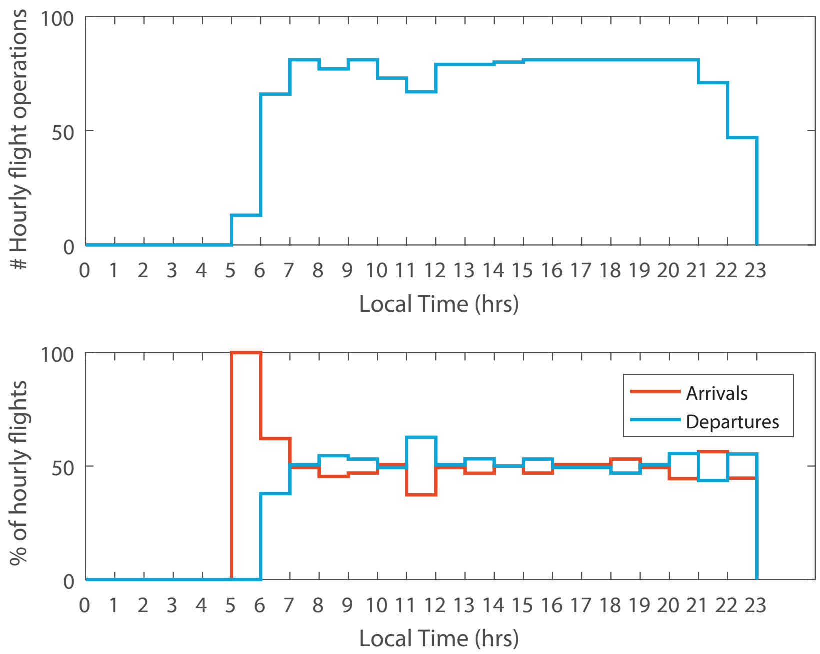

Figure 3.2: Relative frequency of occurrence of arrival and departure operations at Heathrow on 3 August 2016.

demand mixture. This definition is used to define the variety of aircraft types at an airport. The distribution of these aircraft over a certain time frame may impact the capacity of the airport to some extent. Moreover, by applying the RECAT-EU categorization, it can be stated that a high amount of aircraft categorized as RECAT-EU A can cause a decrease in runway capacity compared to a high amount of aircraft categorized as RECAT-EU D which need less separation distance.

From the flight schedule, a list of unique aircraft types can be extracted. Throughout the day a total amount of 1,300 flight operations have been observed by Flightradar24 [19]. All of these flights can be categorized in either RECAT-EU category A, B, C, D or E. As Heathrow deals with capacity problems, aircraft of RECAT-EU category F can generally not be found at the airport. These aircraft regularly operate at other airports in the vicinity of London. The total amount of 1,300 flight operations can be reduced to 27 unique aircraft types as shown in Figure 3.3. In this figure one aircraft type family stands out with respect to the remaining aircraft. This is because BA has its hub at Heathrow. The majority of BA's European narrow body fleet exists out of aircraft of the A320 Family. The overall spreading and categorization of all flights are further discussed in the coming paragraphs.

3.5. RECAT-EU Categorization Spreading

With the new categorization scheme, aircraft can now be categorized into five different categories which reflect the impact of aircraft on wake turbulence generation. These relative presence of aircraft within these categories is visualized in Figure 3.4. Compared to the presence of other RECAT-EU categories, the Upper Medium category is predominantly active throughout almost the entire day. This is obvious, as the aircraft types that relate to this category are often used by European carriers to transport their passengers within Europe. The increased presence of wide body aircraft in the early morning can be supported by the fact that Heathrow operates as a hub for British Airways, being part of the **one**world alliance. Accordingly, the early morning identifies a clear example of hub operations. First, intercontinental aircraft arrive at the hub after which the narrow body fleet of the hub carrier distributes the passengers over the European continent. This pattern continues throughout the entire day as Figure 3.4 clearly identifies some sort of inverse proportionality between the Upper Medium and Upper Heavy categories. These categories represent the majority of narrow body and wide body aircraft, respectively.

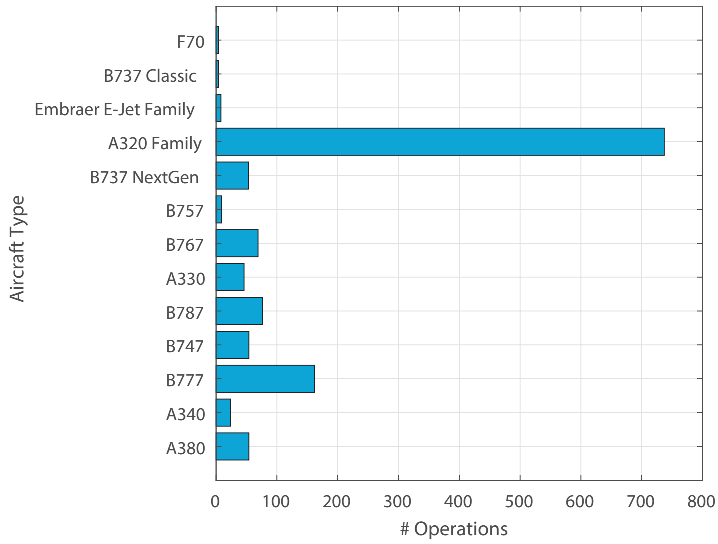

Figure 3.3: Heathrow's traffic mixture on 3 August 2016.

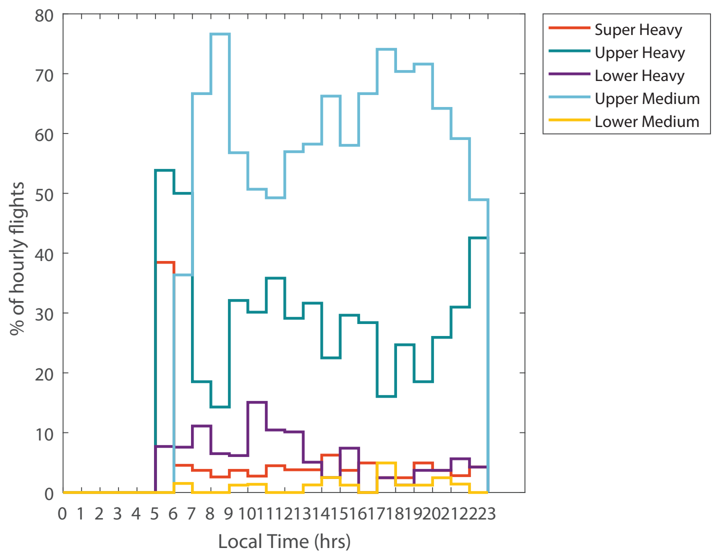

Figure 3.4: Relative frequency of occurrence of different RECAT-EU categories at Heathrow on 3 August 2016.

3.6. Origin & Destination Analysis

Focusing on the directions of flight with respect to the origin or destination airports leads to a clear insight in preferred runway configurations over the day. That is, a certain runway configuration can be preferred as this configuration leads to a reduced air or taxi time, resulting in reduced fuel burn for most aircraft operating within a certain time frame. At Heathrow, two types of configurations can be defined. Namely, the western (RWY 27L/R) and eastern (RWY 09L/R) configuration. The directional dependency of flight operations at Heathrow is visualized in Figure 3.5, showing the percentage of operations to a certain continent over the entire day. The figure shows a clear relation with Figure 3.4 which was analyzed in the previous paragraph. This is obvious as narrow body aircraft usually operate flights within the European continent. As the figure shows, flights with origin in Asia arrive in the early morning at Heathrow.

North America, the other important continent in terms of number of flights, comes with additional regulations relating to ATC. Flights operating to and from the North American continent have to cross the Atlantic Ocean. As this ocean spans over thousands of kilometers, the area lacks in terms of available land-based navigational aids and communication relays. As a result, cockpit crew and ATC are only able to communicate by means of position reporting. In order to manage the enormous amount of traffic that is passing this region, use is made of the North Atlantic Tracks (NAT) system. This system consists out of a dynamic set of airways which change location and direction twice daily. Accordingly, this organized track system has different operation hours in each direction:

- Eastbound operations: 01.00 - 09.00 UTC
- Westbound operations: 11.30 - 19.00 UTC

The entry and exit points on the European side of the ocean are located near the shore of Ireland. This area is located about 500 nm from Heathrow. This means that the average flight time between Heathrow and the entry/exit of the NAT takes about one hour (FL360/M085). The average eastbound NAT spans 2,200 nm which takes about four hours (FL370/M085) taking into account the jet streams over the Atlantic Ocean. Applying this information to a regular flight operating to or from Heathrow, the most obvious time of operation for North America flights is:

- Arrivals: 06.00 - 13.00 UTC
- Departures: 10.30 - 18.00 UTC

The estimated time frames support the validity of the flight schedule as illustrated in Figure 3.5. This figure shows an increase in the number of North America flights around 06:00 a.m., whereas the number of flights drops at the start of the evening.

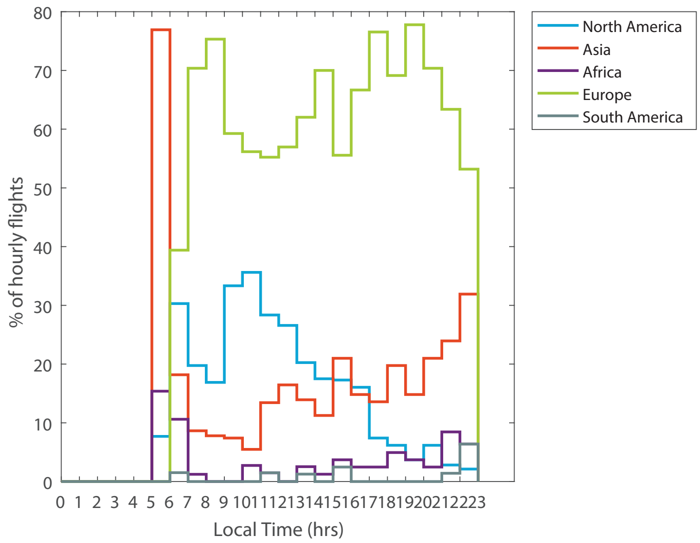

Figure 3.5: Relative frequency of occurrence of operations in different directions at Heathrow on 3 August 2016.

The directional dependency as analyzed above is related to a certain preferred runway configuration at the airport. Arrivals from the East along with departures to the West will generally have a preferred western runway configuration, excluding the effects of taxi times at the airport itself. Conversely, arrivals from the West and departures to the East prescribe the preferred eastern runway configuration. As Figure 3.6 shows, the west configuration is predominant throughout almost the entire day.

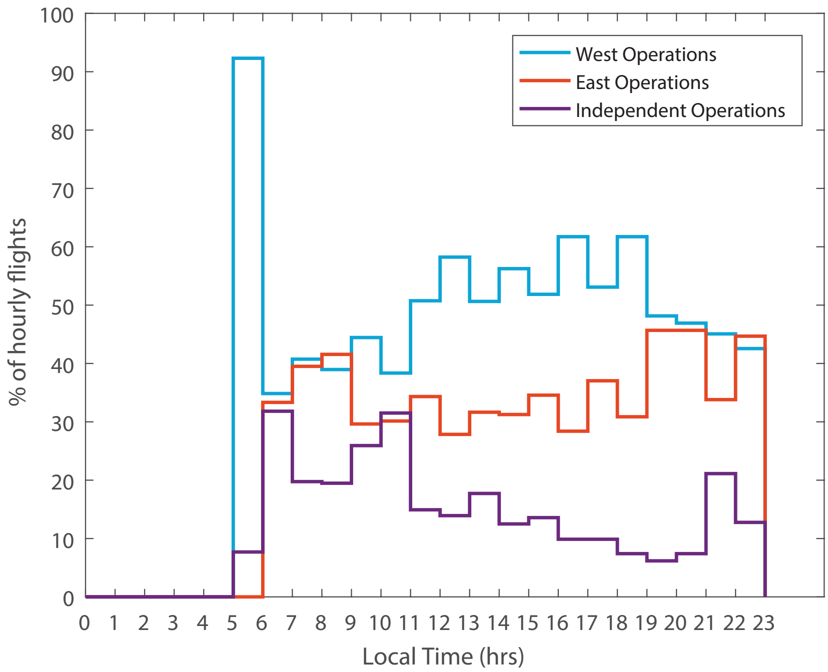

Figure 3.6: Relative frequency of occurrence of preferred runway configuration at Heathrow on 3 August 2016.

3.7. Terminal 4 Operations

Heathrow's Terminal 4 is the outlying terminal situated south of RWY 09R/27L. Since its position is remote to the other terminals, operations to and from this terminal come with additional effects. As Figure 3.1 illustrates, aircraft can only access Terminal 4 by using the taxiways that cross Heathrow's southern runway. These taxiways comprise perpendicular runway crossing taxiways as well as high speed exit taxiways. Remarkable is the fact that there are no taxiways designed that go around the southern runway. Obviously, this has to deal with the limited space available within the airport's property.

The limitation with respect to the reduced number of options in available taxiways can have an impact on the throughput rate of RWY 09R/27L. That is, in cases aircraft are supposed to land or depart on RWY 09L/27R, they need to physically cross the southern runway in order to get to the runway or Terminal 4. Doing so results in an increased separation time between two consecutive operations on RWY 09R/27L created by ATC in order to allow aircraft to safely cross the southern runway. This increased separation results in a reduced runway throughput rate as defined by Equation 2.1. Consequently, less aircraft are able to operate to and from the southern runway within the specified time frame.

It is therefore recommended to have flight operations from and to Terminal 4 operated on the southern runway. This runway can be accessed and vacated from and to the south, creating a direct taxiway connection to the respective terminal. Additional to the capacity perspective, the taxi time from and to RWY 09R/27L is less compared to the northern runway for airlines operating at Terminal 4. As a result, operations on this runway would contribute to the reduction in fuel consumption of the airline. Consequently, in terms of the fuel burn objective in this research, the southern runway is preffered as is confirmed by Tables 6.5 & 6.6 later on.

Having described the impact of Terminal 4 flights operations, the flight schedule can be further analyzed in terms of this aspect. This is done by means of Figure 3.7. The figure shows continuous activity at Terminal 4 throughout the entire day. This is obvious as multiple types of airlines operate at this terminal as is elaborated on in Appendix B. The European and intercontinental airlines that are situated at this terminal operate flights to almost all continents. As a result, the impact of operations at this terminal will be active throughout the enitre day. The impact of this factor is further analyzed in Section 8.2.1.

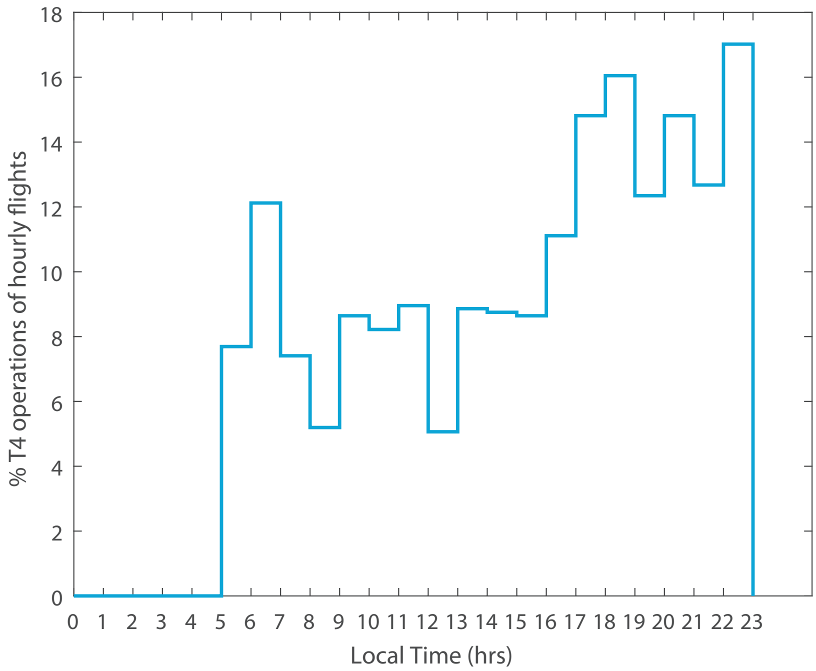

Figure 3.7: Percentage of hourly flights operating to and from T4.

4 Separation Modeling

One of the major limitations in the flexible runway allocation tool is the degree of detail that has been built in with respect to modeling wake vortex separation minima. As the research objective in Chapter 1 defines, this research aims to improve the modeling of runway capacity in terms of improved separation minima. To do so, the process of improving the separation modeling module of the flexible runway allocation tool is analyzed in three phases.

The first phase describes the conceptualization of the problem that has been identified with regard to the previous model. The problem comprises the limitation in ability to model and categorize aircraft such that they are being modeled in the correct sense. That is, in the old situation aircraft are being categorized as either Super, Heavy or Medium. Despite that this type of categorization is officially defined by ICAO [29], this methodology is rather aged. A recently published methodology by Eurocontrol [46] enables to categorize aircraft in a more accurate manner by the weight as well as the wingspan. By applying this methodology for modeling pairwise flight dependencies the old model is improved. A more detailed description of this RECAT-EU methodology can be found in Section 2.1.3.

The conceptualization of the model with respect to the RECAT-EU methodology is defined in the second phase. The implementation of RECAT-EU starts by defining the respective RECAT-EU category for each flight in the flight schedule as defined by Flightradar24 [19]. Then, the pairwise time-based separation minima should be defined in dependency matrices that can be used to identify the availability of a certain runway at a specific time. The TBS data is obtained from Eurocontrol.

Phase three comprises the modeling of the problem in terms of writing constraints that can be used in the opzimization process to allocate a runway to a specific flight. The availability of a runway is defined by a constraint according to the respective dependency matrix generated in the previous phase. By writing the constraint in such a way, the model is able to identify the availability of a certain runway and can thereby select the most optimal available runway at a specific point in time.

The process as described above comes with several calculations, theories and assumptions. Section 4.1 describes the methodology behind the RECAT-EU categorization. This is done in terms of theory as well as a practical visualization. Secondly, Section 4.2 describes the impact of runway occupancy on the runway capacity. Next, Section 4.3 elaborates on the possible runway operation modes that are suitable for Heathrow. Furthermore, the translation of separation dependencies into a dependency matrix is described in Section 4.4. After all, the findings in this chapter regarding the separation constraints in the flexible runway allocation process, are implemented in the linear programming module as described in Chapter 7.

4.1. RECAT-EU Separation Minima

With the introduction of the RECAT-EU categorization, an enhanced methodology for categorizing aircraft based on their wake vortex impact has arisen. This new methodology enables ATC to further optimize the runway capacity of an airport, by applying improved separation minima. As shown in Table 2.2 the categorization of aircraft is based on the wingspan as well as the Maximum Take-off Weight (MTOW). Since RECAT-EU prescribes six categories, aircraft can now be categorized more efficiently, which will contribute to the sequencing strategy by the ATCo. The sixth category, however, is excluded in this research as Heathrow primarily operates a flight schedule without RECAT-EU category six aircraft.

A more recent application of separation minima is Time-based Separation (TBS). The distance-based separation minima as described in Section 4.3 can be translated into time-based separation minima. The conversion from distance to time enables modeling of separation minima on a time scale. Besides, modeling TBS compared to DBS minima gives a better representation in strong headwind conditions. That is, maintaining a set separation time significantly improves the capacity of the runway as wake vortices dissipate more quickly in certain headwind conditions. As a result, the distance between consecutive aircraft can be reduced. The TBS minima can be found in Table 4.1. This table provides a clear insight in the correlation of all aircraft categories with respect to their wake vortex impact. Figure 4.1 visualizes the data from this table to improve the understanding of the wake vortex impact of a leading aircraft to its trailing aircraft on the same approach path.

Table 4.1: Time-based separation minima (s) for departures according to RECAT-EU [46].

	Trailing Aircraft					
Leading Aircraft [3]	*SUPER HEAVY*	*UPPER HEAVY*	*LOWER HEAVY*	*UPPER MEDIUM*	*LOWER MEDIUM*	*LIGHT*
SUPER HEAVY	(60)	100	120	140	160	180
UPPER HEAVY	(60)	(60)	(60)	100	120	140
LOWER HEAVY	(60)	(60)	(60)	80	100	120
UPPER MEDIUM	(60)	(60)	(60)	(60)	(60)	120
LOWER MEDIUM	(60)	(60)	(60)	(60)	(60)	100
LIGHT	(60)	(60)	(60)	(60)	(60)	80

4.2. Runway Occupancy Time

With the introduction of the RECAT-EU categorization, an enhanced methodology for separation minima has emerged. The separation time between two consecutive aircraft is dependent on multiple factors. The first describes the effect of wake turbulence as described by the values in Table 4.1. The second is related to the occupancy time of aircraft on a runway. This occupancy time is referred to as Runway Occupancy Time (ROT). Within the ROT definition, a distinction can be made. The first, being the Arrival Runway Occupancy Time (AROT), and, the second being the Departure Runway Occupancy Time (DROT). These ROT are dependent on several factors. Many of them are related to aircraft characteristics such as landing weight, brake setting, flap setting, approach speed etc. However, a correction for the human factor in the operational process needs to be taken into account. This correction reflects several human factors that may negatively influence the process in terms of time. Table 4.2 shows the DROT and AROT for each RECAT-EU category, respectively.

Table 4.2: Departure and arrival runway occupancy time for RECAT-EU categories [35].

RECAT-EU Category	DROT (s)	AROT (s)
SUPER HEAVY	51.7	47
UPPER HEAVY	50	47
LOWER HEAVY	50	45
UPPER MEDIUM	40	45
LOWER MEDIUM	35.3	45

[3] The bracketed values indicate minimum radar separation (MRS), set at 60 s, as is applicable per current ICAO doc 4444 provisions [29] [46].

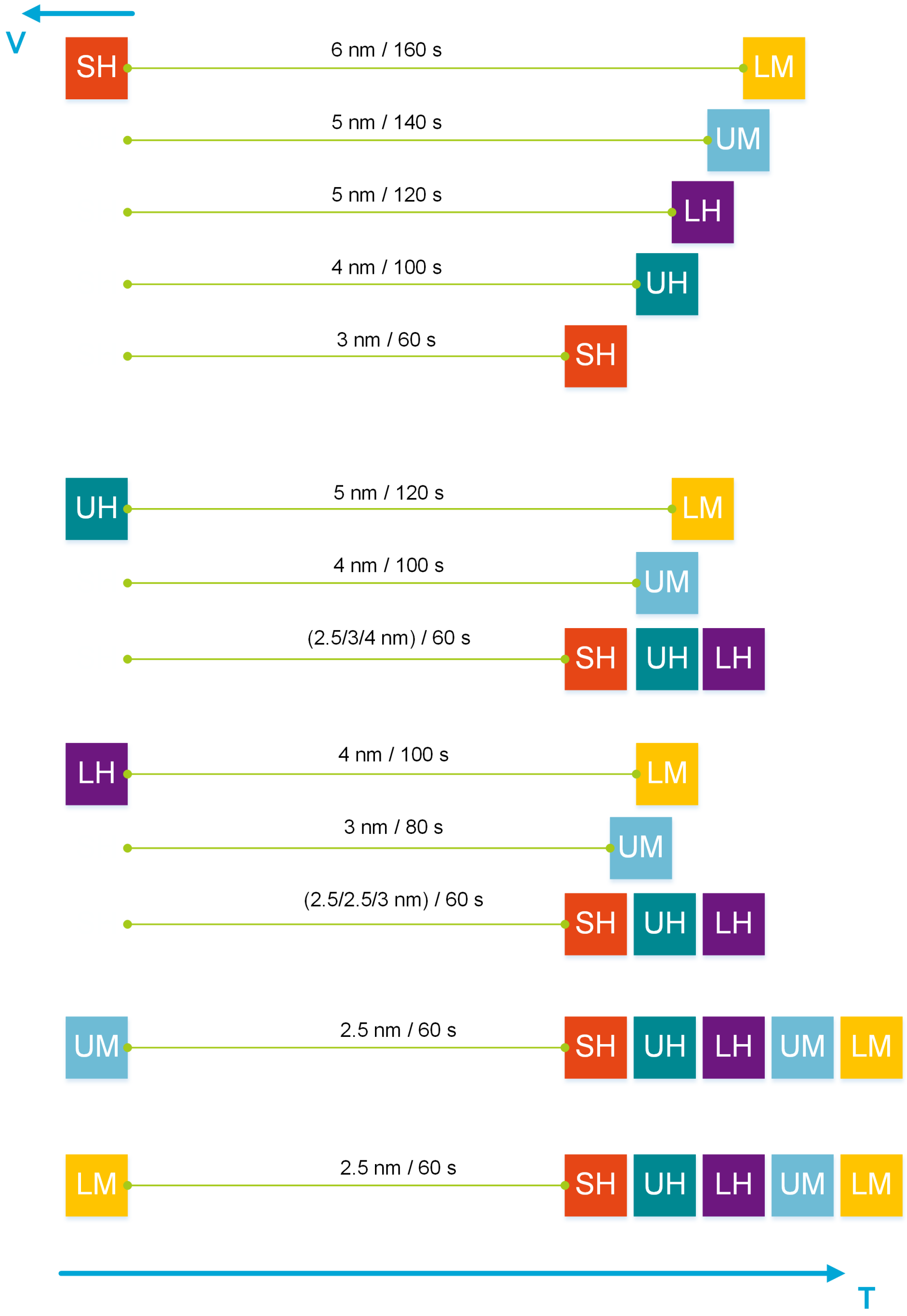

Figure 4.1: RECAT-EU distance-based (arrivals) and time-based (departures) separation minima scheme.

4.3. Runway Operation Modes

In association with independent parallel runways as described in Section 2.1.2, several operation modes can be defined. These modes comprise i) simultaneous independent parallel approaches, ii) simultaneous independent parallel departures, and iii) segregated parallel approaches/departures. The latter can be used in several ways. For example, one runway is exclusively used for approaches, while the other runway is being used for approaches as well, or, is being used for departures only. The same yields for the opposite, in which one runway is exclusively used for departures, while the other runway is being used for departures as well, or, is being used for approaches only. However, both cases are referred to as semi-mixed parallel operations. In contradiction to this type of operation, runways can also be operated as mixed parallel operations. That is, this operation type comprises a combination of the above describes operation types.

When zooming in on the single runway, as yields for Heathrow's independent parallel runway set, four types of operation modes can be defined. These operation modes are visualized in Figure 4.2 and comprise the Arrival-Arrival (AA), Departure-Departure (DD), Departure-Arrival (DA) and Arrival-Departure mode (AD).

The four types of operation modes can be operated in two manners. The first, being referred to as the regular operation, defines operations in a single direction. Operations of this type are illustrated in Figure 4.2. In contradiction to single direction operations, runways can also be operated in opposite direction. Opposite direction operations can be benificial in case flight origins/destinations are in multiple directions. For example, an arrival aircraft from the east and a departure to the east. However, this type of operation comes with an increased safety buffer in order to ensure operational safety. The four types of opposite direction operations are discussed in Section 4.3.4 and visualized in Figure 4.5.

4.3.1. Arrival Mode

Operations in the arrival mode are dependent on certain aircraft characteristics. As described in Section 2.1.3, separation minima are defined either distance-based or time-based. For this research, time-based separation minima are used to define certain separation constraints. The TBS minima according to RECAT-EU can be found in Table 4.1.

This section elaborates on the establishment of time-based separation minima. Separation minima are defined by the approach speed, approach path distance and runway occupancy time of two consecutive aircraft on approach. To define the dependency of such an aircraft pair, some definitions are used. The first aircraft in the approach sequence pair is named the leading aircraft, whereas the second aircraft is named the trailing aircraft. In mathematical form, these aircraft are referred to as i and j, respectively.

Equation 4.1 defines how the minimum separation time can be obtained from the aircraft characteristics of the two consecutive aircraft in the approach pair. This separation time is often referred to as Inter-Arrival Time (IAT). The IAT is set to be the maximum of the separation time on the approach path and the arrival runway occupancy time of the leading aircraft. The arrival runway occupancy time is defined as the time interval between the threshold crossing and the the aircraft's tail vacating the runway. The AROT is described by five elements. These elements include: i) the threshold crossing, ii) the touchdown, iii) the decelaration, iv) the runway exit maneuver, and v) the tail-off runway point. Upon approach three cases can occur in which the aircraft's speed plays an important role. These are referred to as the i) equivalent case, ii) closing case, and iii) the opening case.

$$\begin{aligned} \mu_1 &= \frac{s_{ij}}{V_j} \\ \mu_2 &= AROT_i \\ T_{ij} &= \max\left(\mu_1, \mu_2\right) \end{aligned} \tag{4.1}$$

Equivalent case
In the first case aircraft of the same type, and thereby having the same approach speed, are in the approach sequence to be analyzed. For this case $V_i = V_j$ yields.

Closing case
The second case defines a situation in which the leading aircraft in the approach pair is approaching a certain runway at a lower speed compared to its trailing aircraft ($V_i < V_j$). In this case, the separation between the two successive aircraft decreases. To prevent both aircraft from exceeding the separation minimum, both aircraft should be separated with an increased buffer to cope with the closing separation distance.

Opening case
The latter case defines a situation in which the leading aircraft in the approach pair is approaching a certain runway at a higher speed compared to its trailing aircraft ($V_i > V_j$). In this case, the separation between the two successive aircraft decreases. To efficiently use this fact, the separation distance between both aircraft should be adapted for the difference in approach speed as shown in Equation 4.2.

$$\mu_1 = \frac{n + s_{ij}}{V_j} - \frac{n}{V_i} \tag{4.2}$$

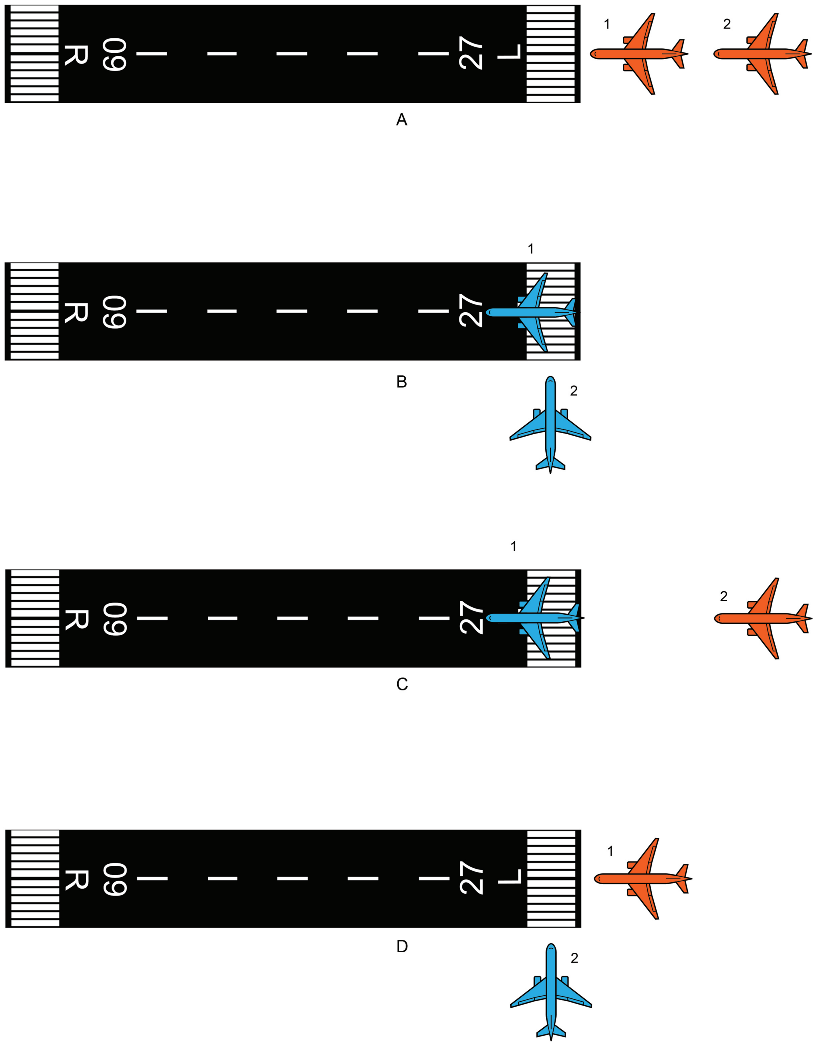

Figure 4.2: Four possible profiles for operations in single direction (blue = departure; red = arrival).

4.3.2. Departure Mode

Departures are managed by using minimum separation times. To define the Inter-Departure Time (IDT), use is made of Table 4.1. For this type of operation, the IDT is defined as the maximum of the TBS minimum and the departure runway occupancy time of the leading aircraft in the departure sequence pair to be analyzed. The DROT defined as the time interval between the line-up clearance by ATC and the aircraft commencing a positive climb rate on departure. This parameter is described by five elements. These elements include i) the flight crew reaction time to the line-up clearance, ii) the line-up maneuver, iii) the waiting time on the runway, iv) the flight crew reaction time to the take-off clearance, and v) take-off roll.

$$\mu_1 = TBS_{ij}$$
$$\mu_2 = DROT_i \tag{4.3}$$
$$T_{ij} = \max(\mu_1, \mu_2)$$

4.3.3. Mixed Mode

In case a runway is operated in mixed mode, two special types of situations can occur. The first, being the case in which a departure is followed by an arrival. The second comprises the opposite. In order to ensure safety and comply to the separation minima, Equations 4.1 & 4.3 should be rewritten. For the first case, this yields to the relation described by Equation 4.4. The latter case is described by Equation 4.5. The only dependency in this case is the AROT of the leading aircraft in the operations pair.

$$\mu_1 = TBS_{ij}$$
$$\mu_2 = DROT_i \tag{4.4}$$
$$T_{ij} = \max(\mu_1, \mu_2)$$

$$T_{ij} = AROT_i \tag{4.5}$$

4.3.4. Opposite Direction Mode

According to ICAO [29], opposite direction operations (ODO) are defined as operations conducted to the same or parallel runway where an aircraft is operating in a common direction of another aircraft arriving, departing, or conducting an approach. ODO can be used to operate a certain runway in both directions. That is, both runway ends will be active for operations. However, during such operations, increased safety measures take place in order to ensure safe operations. As indicated in Figure 4.5, four types of opposite approaches exists. These four types will be discussed in this section.

Opposite Arrival-Arrival

Situation A, in Figure 4.5, describes a situation in which two consecutive aircraft, i and j, approach the same runway, but in opposite direction, respectively. Since both aircraft are approaching during ODO, aircraft i is supposed to land on RWY 27L, whereas aircraft j is supposed to land on RWY 09R. In order to comply to safety regulations, both aircraft need to be separated sufficiently. This separation buffer includes the option in which aircraft i needs to make a go around and follow a missed approach procedure as illustrated in Figure 4.3. In this case, aircraft i might cause a conflict with the approach path of aircraft j. Therefore, both aircraft need to be separated both laterally as well as in a longitudinal sense. To ensure safe operations, a safety buffer has been built in as obtained from Equation 4.6. This safety buffer is independent of RECAT-EU category as this time frame does not reflect any factors that might be affected by the MTOW or wingspan of aircraft. This safety buffer enables the ATCo to safely separate the traffic in case of a go around procedure. Doing so, leads to a time interval between the two consecutive aircraft, in which aircraft j can be turned away from the opposite glidepath with respect to the trajectory of aircraft i. In order to change aircraft's heading in the vicinity of airports, the ATCo and the pilot should ensure the aircraft is at or above the minimum vectoring altitude (MVA). This altitude is defined as the altitude at or above aircraft are safe to adapt their headings with respect to height obstacles in their close vicinity. The MVA in the close vicinity of Heathrow is set to be equal to 1,600 feet. By assuming a rate of descend (ROD) of 700 feet per minute and a communication buffer (c) of 20 seconds, the total safety buffer regarding opposite arrival-arrival operations is set to be 160 seconds.

$$T_{ij} = \frac{\text{MVA}}{\text{ROD}} + c \tag{4.6}$$

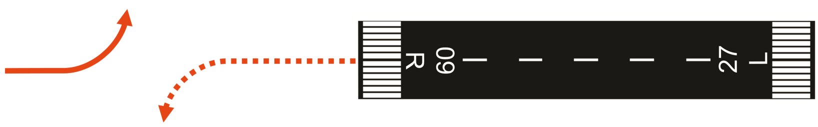

Figure 4.3: Opposite direction operations A-A separation.

Opposite Departure-Departure

Situation B, in Figure 4.5, describes a situation in which two consecutive aircraft, i and j, depart from the same runway, but in opposite direction, respectively. Since the aircraft are operating under ODO, aircraft i is supposed to depart from RWY 27L, whereas aircraft j is supposed to depart from RWY 09R. Opposite departure operations don't cause any major conflict with respect to wake turbulence on the runway itself. Therefore, the separation time between the two consecutive departures equals to the DROT of aircraft i as described by Equation 4.7.

$$T_{ij} = \mathrm{DROT}_i \tag{4.7}$$

Opposite Departure-Arrival

Situation C, in Figure 4.5, describes a situation in which two consecutive aircraft, i and j, depart from and approach the same runway, but in opposite direction, respectively. Since the aircraft are operating under ODO, aircraft i is supposed to depart from RWY 27L, whereas aircraft j is supposed to land on RWY 09R. In order to create a conflict free approach path towards RWY 09R, the departing aircraft i out of RWY 27L should turn away from the centerline of the runway as soon as possible as illustrated in Figure 4.4. However, to make a turn the aircraft should be above the MVA as defined in the paragraph above. The MVA is set to be equal to 1,600 feet in the close vicinity of Heathrow. The average rate of climb of aircraft upon the first segment of departure is set to be equal to 1,800 feet per minute. For the departure aircraft to turn away from the centerline, it takes 54 seconds after the aircraft establishes a positive climb rate upon departure, as obtained from Equation 4.8. Moreover, to enable ATC to apply ODO, the departure and arrival procedures should be adapted accordingly.

$$T_{ij} = \frac{\mathrm{MVA}}{\mathrm{ROD}} + \mathrm{DROT}_i + \frac{\mathrm{MVA}}{\mathrm{ROC}} \tag{4.8}$$

Figure 4.4: Opposite direction operations D-A separation.

Opposite Arrival-Departure

Situation D, in Figure 4.5, describes a situation in which two consecutive aircraft, i and j, approach and depart from the same runway, but in opposite direction, respectively. Just like the situation described in the opposite departure-departure mode, the opposite arrival-departure mode is quite simple. The only dependency in this situation is related to the occupancy of the arrival aircraft i on the runway after landing. Once aircraft i has vacated the runway, aircraft j can start its take-off roll from the opposite runway end. However, it should be aware of the possible wake turbulence that has been generated on the approach path of aircraft i. Nevertheless, departing aircraft are supposed to have a larger climb rate compared to the descend rate of an arrival aircraft. This results in the fact that the departure aircraft will not notice any major wake turbulence as it rotates at some distance from the end of the runway. As a consequence, the departure aircraft's trajectory will be above the glide slope of the opposite runway end all the time. Therefore, the separation time of the consecutive aircraft i and j in the opposite arrival-departure mode is set as defined in Equation 4.9.

$$T_{ij} = \mathrm{AROT}_i \tag{4.9}$$

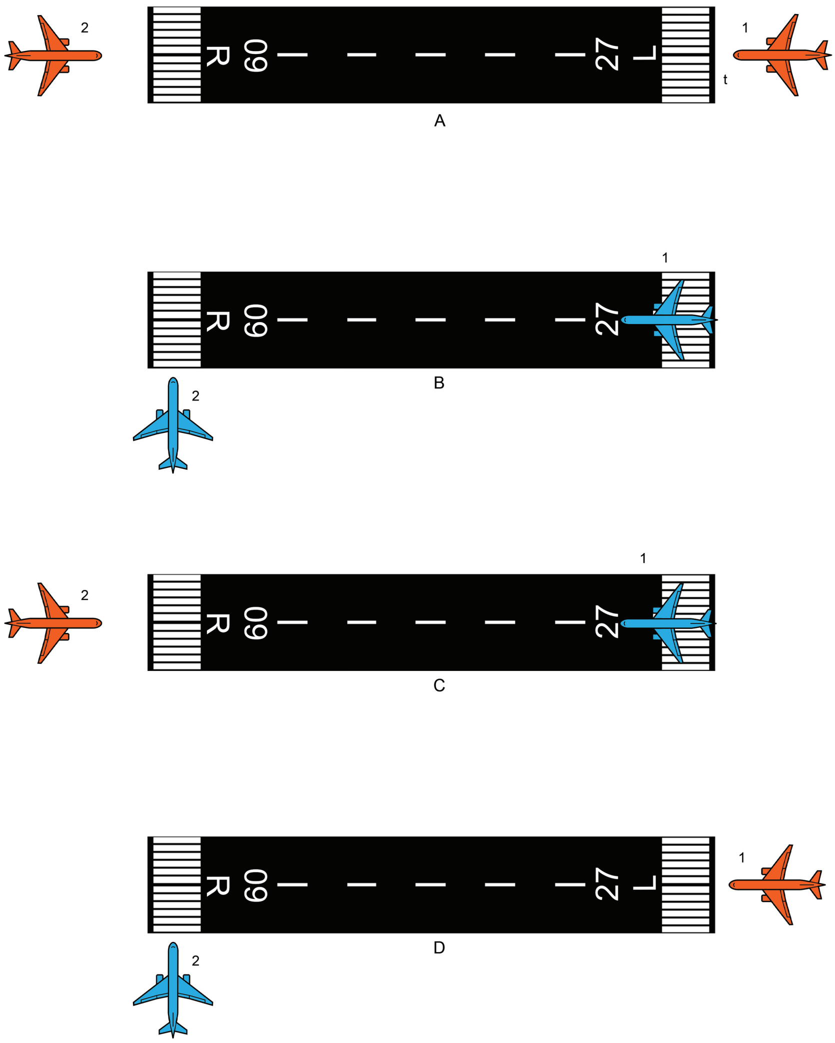

Figure 4.5: Four possible profiles for operations in opposite direction (blue = departure; red = arrival).

4.4. Modeling Process

The availability of a runway at a certain time is a major factor in the runway allocation process. An operational runway becomes unavailable once an aircraft is about to operate from or to that runway, is operating from or to that runway or has just operated from or to that runway. Within such a time frame an aircraft occupies the runway, making it unavailable to other aircraft. The occupation time is defined in the runway occupation dependency matrix (DM). This time frame depends on the type of operation, type of aircraft, and, in some cases the type of aircraft that is following the aircraft taken into account. Moreover, a DM should be defined for each unique aircraft type, each operation type and each possible aircraft pair. These aircraft pairs are described in Table 4.1.

In the case of London Heathrow, the DM takes form of:

- four rows, defining all four runways 09L, 27R, 09R and 27L, respectively.
- 14 columns, defining the time frame (in time steps of 20 seconds) in which a runway can be occupied.
- 25 matrices, describing all possible aircraft pairs (SH, UH, LH, UM and LM) that can occur at Heathrow.

The occupancy of a certain runway at a specific time is identified by a binary state value of 1. In case a runway is available at a certain time, the binary state equals 0.

Figure 4.6: Sequence

The runway allocation model evaluates each aircraft within the defined time frame. Each aircraft is considered as a possible leading aircraft i in a certain consecutive aircraft pair. This is done by considering all following aircraft j within the range of i - 10 and i + 30 as shown in Figure 4.6. Doing so, enables the model to consider each consecutive aircraft pair that can occur during the optimization of the operation sequence. For each consecutive pair a DM is defined for both Single Direction Operations (SDO) and ODO. This DM is later used to identify runway occupancy conflicts with other flights. In cases such conflicts arise, the specific runway occupancy time is written as a constraint which is then be used in the linear programming definition as described in Chapter 7. An overview of the RECAT-EU separation algorithm can be found in Table 4.3.

Table 4.3: Algorithm of pairwise RECAT-EU separation preprocessor.

Algorithm RECAT-EU Separation Preprocessor
Input: A set of operations types (Arrival/Departure), operation modes (SDO/ODO), ODO safety factors and RECAT-EU aircraft categories. **Output:** A runway occupancy conflict constraint denoting the runway ocupancy conflicts for all possible RECAT-EU aircraft category pairs, operation types and operations modes.
1. *Initialize* DM= [**0**] and RECAT-EU separation minima from Eurocontrol [46]. 2. **For** all leader flights ∈ F, all runways ∈ R and all delay steps ∈ D **do** 3. **For** all follower flights ∈ F, all runways ∈ R and all delay steps ∈ D **do** 4. **If** leader flight is arrival and follower flight is arrival **do** 5. Define DM according to RECAT-EU TBS minima (based on Table 2.3) for SDO. 6. Define DM according to RECAT-EU TBS minima (based on Table 2.3) for ODO. 7. **If** leader flight is departure and follower flight is departure **do** 8. Define DM according to IDT minima (Table 4.1) for SDO. 9. Define DM according to IDT minima (Table 4.1) for ODO. 10. **If** leader flight is arrival and follower flight is departure **do** 11. Define DM according to AROT (Table 4.2) for SDO. 12. Define DM according to AROT (Table 4.2) for ODO. 13. **If** leader flight is departure and follower flight is arrival **do** 14. Define DM according to maximum DROT (Table 4.2) and 2nm final TBS for SDO. 15. Define DM according to maximum DROT (Table 4.2) and 2nm final TBS for ODO. 16. Evaluate pairwise runway occupancy conflicts with other aircraft. 17. Return runway occupancy conflict by means of a LP constraint.

5
Noise Modeling

Noise, in the case of airport operations and pretty much every outdoor event, is a subject of high importance to airport operators, governments as well as people that live near airports. For residents, the observation of noise is part of their daily life and can cause certain health-related issues as well [26]. Therefore, the noise exposure seems hardwired into the collective line of thought of the government and the airport operator. To regulate the amount of emitted noise, airport specific regulations have emerged. That is, Noise Preferred Routes (NPR) and multiple other concepts are realized in order to minimize noise annoyance on the ground surface.

Noise annoyance is one of the two key indicators of this research. Above all, each stakeholder in the airport operations process aims to minimize the observation of noise on the ground. As described in Section 2.3, the line of development, with respect to noise mitigation techniques, that has been drawn in recent years shows a drastic decrease in noise emissions by modern aircraft. However, these mitigation techniques are limited to some extent. Recent mitigation techniques reflect more operational and regulatory constraints, and therefore have their impact on flight operations from the airline's perspective. However, certain noise mitigation techniques have created a paradox in which aircraft are made less noisy, but, as a consequence, results in more aircraft that are being allowed to operate within a certain time frame.

The importance of noise annoyance in the airport operations process shows the essence of modeling and regulating noise events caused by aircraft. Many residents in the vicinity of Heathrow complain about the amount of noise that is observed throughout the day. These complaints are a clear result of the fact that Heathrow is surrounded by large communities, especially on the eastern side of the airport. With this in mind, at an airport like Heathrow the likelihood of noise disturbance is serious when analyzing the fully utilized airport capacity as is being operated at this moment.

In order to model noise emission and its related noise annoyance, the airport, including its surrounding area, should be analyzed in terms of flight procedures and population density. The methodology to do so differs to large extent compared to the initial model created by Delsen [11]. The major difference with this model is the fact that Standard Flex concerns a reference aircraft and add penalties to this aircraft in cases larger aircraft are considered. Improved Flex aims to create a model that fits to reality even more, and therefore analyzes each flight in specific. That is, each aircraft type is being modeled on its own in order to analyze a more accurate noise profile.

This chapter is set-up to provide an insight in the steps that are taken in order to model the noise profile of each single flight on its own. Section 5.1 elaborates on the grid definition of the case study on London Heathrow. Moreover, the London area is analyzed with respect to the impact of arrival and departure trajectories to communities. Subsequently, the impact at certain locations on the grid is reinforced by the estimation of population density in those areas. Additionally, the actual produced noise by specific flights is computed by use of the Integrated Noise Model (INM). Section 5.2 describes the methodology behind this computation and the impact of specific aircraft types on the observed noise on the ground. Furthermore, Section 5.3 elaborates on the process of accumulating single noise events in order to establish an average sound level, taking into account the impact of a single noise event with respect to the time of the day. Lastly, Section 5.4 gives a visualization of the sequence of functions that take place in the noise modeling process as part of the flexible runway allocation model.

5.1. Population & Household Estimation

Starting in the center of London Heathrow Airport, one of the major aviation gateways to the European continent, the area to be modeled must be defined. There are numerous districts in the London area making it a largely spread region. Greater London, defined as the area comprising all 32 boroughs, spans around the City of London. With Heathrow located in the westmost point of Greater London, the majority of boroughs that may be affected by noise annoyance will be those located east of the airport's boundaries. To the west of the airport, less populated areas are situated, with the exception of towns like Slough in the northwest.

In order to take into account the areas that may be affected the most as a result of Heathrow's flight operations, a grid must be defined. This grid is evenly spread around Heathrow taking into account the inclusion of certain towns which are located on the boundaries of the grid. The boundaries of this area are defined by using the knowledge of the vertical position of aircraft on approach or departure tracks at a certain location. The numerical boundaries of the grid have been defined as in Table 5.1.

Table 5.1: Boundary coordinates of defined population grid.

	Borough/Town			
Coordinates	*Medmenham*	*East Barnet*	*Wokingham*	*Beckenham*
Latitude [DMS]	51°33'30.00"N	51°33'30.00"N	51°23'30.00"N	51°23'30.00"N
Longitude [DMS]	00°51'00.00"W	00°03'00.00"W	00°51'00.00"W	00°03'00.00"W

With over eight million inhabitants, expanding industrial sites and urban centers, Greater London is one of the most crowded areas in Europe. The spreading of this enormous population is illustrated in Figure 5.1. This plot is generated by data obtained from the Global Rural-Urban Mapping Project (GRUMP) database [5] [10]. This database is a commonly used resource in scientific research and describes the patterns and trends of human settlement around the globe.

According to GRUMP [5] [10], roughly 3.3% of the Greater London population is estimated to live in the area inside the defined grid. By applying an average number of persons per house of 2.4, this counts an estimated total of over 1.6 million residents divided over 686,451 households within the defined grid. This estimation is based on a resolution of 30 arc-seconds.

5.2. The Integrated Noise Model

The Integrated Noise Model [17] as designed by the Federal Aviation Authority (FAA) was intensionally designed to model and evaluate the impacts of aircraft noise on surrounding areas near airports. The model uses airport-, aircraft- and area-related data to provide a detailed insight on the noise emissions as a consequence of operating the flights that has been used as input to the model. This data comprises aircraft types, approach speeds, runway configurations, flight tracks, grid areas and population data of the airport to be analyzed. The latter two of the dataset used as input have been described in the last two paragraphs. The remainder of data will be further explained in Chapter 6.

The outcome of the model takes form of a population grid as predefined in the model input parameters. The population grid, identifies all grid locations within the predefined grid together with its related value of the selected noise metric. This metric, as described in Section 5.3, reflects the Sound Exposure Level.

In contradiction to the procedure as described by Delsen [11], this research is based on an increased level of detail to model aircraft noise emission. Generally speaking, this research uses a generated noise contour for each unique aircraft type, unique departure or arrival track and each unique runway, rather than the generalized noise profile used by Delsen [11]. In his research, Delsen applied a penalty factor to certain flights to describe the level of impact with respect to the reference aircraft noise profile included in the runway allocation model. By improving the level of detail, this research aims to reflect reality to a larger extent.

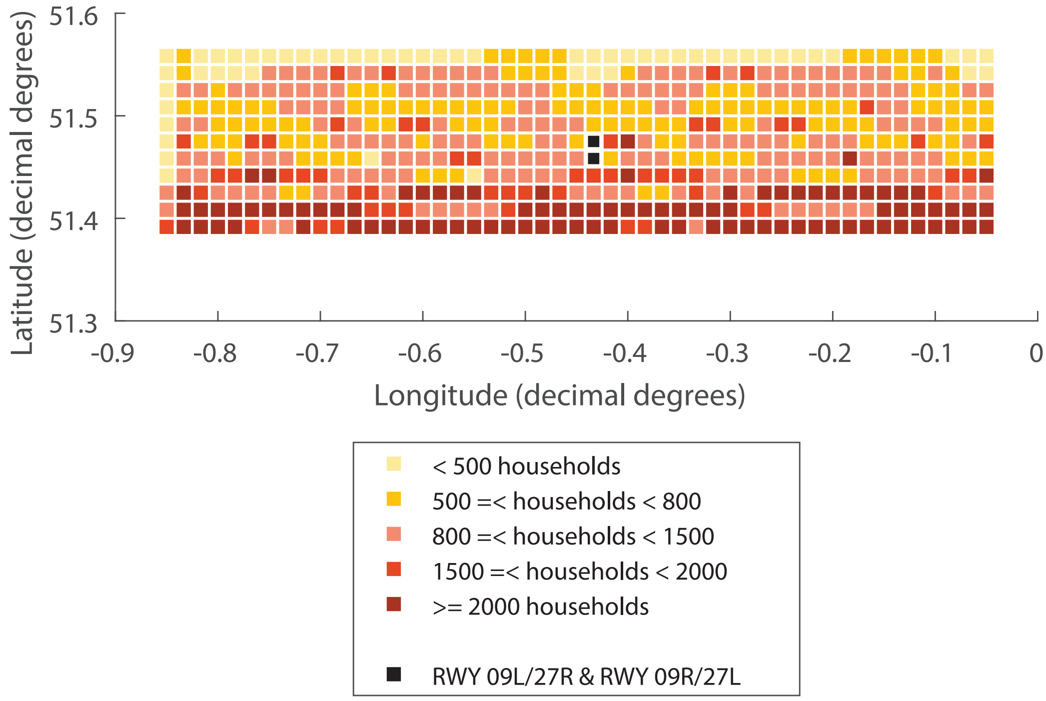

Figure 5.1: Population London Heathrow area [5] [10].

5.3. Cumulative Noise Calculation

As described in Section 2.3.2, the human perception of sound is defined by the Sound Pressure Level (SPL). Besides the SPL (Equation 2.3), the observation of noise is dependent on multiple other factors. These factors include duration, frequency, regularity and time of the day [47]. Since noise can have different frequencies, its observed loudness differs per frequency spectrum. SPL does not quantify this loudness. To correct sound pressure levels according to their frequency, use is made of frequency weighting filters. These filters have been standardized into four weighting filters A, B, C and D. The most often used filter is the A-weighting filter. According to Ruijgrok [47], this filter is found to work well for loudness comparisons at all levels. Equation 5.1 defines the the A-weighting corrected band level, L_A, that is used to reflect the human response to loudness. The correction, ΔL_A, is negative for center frequencies which are found to be less annoying for the human ear.

$$L_A(i) = SPL(i) + \Delta L_A(i) \tag{5.1}$$

Using Equation 5.1, the overall A-weighting sound level can be computed by a summation over 1/3-octave band frequencies, as defined in Equation 5.2.

$$L_A = 10 \log \sum_i 10^{\frac{L_A(i)}{10}} \tag{5.2}$$

In order to investigate the effect of duration of several noise events, it is essential to know the distribution of all individual noise events over time. Having this defined, the level of annoyance can be related to such events. The metric used to analyze the effects of duration is the Sound Exposure Level (SEL). The SEL, as expressed in Equation 5.3, is defined as the steady sound pressure level integrated over a measuring period (T_0) of one second.

$$\mathrm{SEL} = 10 \log \left[\frac{1}{T_0} \int_0^T 10^{\frac{L_A(t)}{10}} \, dt \right] \tag{5.3}$$

To relate the effects of specific noise events at different times of the day to noise annoyance among residents, use can be made of the Day-Evening-Night Average Level (DENL). This noise exposure metric enables differentiation in the weights or penalties applied to noise events in the evening or night. Equation 5.4 defines the DENL by distinguishing the influence of noise events during day, evening and night. The time span that is analyzed in terms of DENL is specified by T_{ref}. This variable often reflects a day (24 × 3,600 seconds) or a year. As said, this metric specifies three types of weights. These weights, as defined in Table 5.2, add cost to a certain noise event. These weights, w_i, are in decibel. Therefore, an increment of three decibels represents a doubling in observed noise. Equation 5.4 defines the day-evening-night average level for all noise events, F, that take place in a specified time frame. These noise events reflect time-varying fluctuations, as aircraft flyovers are concerned.

$$L_{DEN} = 10 \log \left[\frac{1}{T_{ref}} \sum_{i=1}^{F} 10^{\frac{(SEL_i + w_i)}{10}} \right] \tag{5.4}$$

Table 5.2: Definitions of day, evening and night in Day-Evening-Night Average Level noise metric [47].

	Day	**Evening**	**Night**
Time Period (hrs)	07:00 - 19:00	19:00 - 22:00	22:00 - 07:00
Penalty (dB)	0	$\sqrt{10}$	10

Since DENL is a logarithmic approach to a cumulative exposure metric, it is not directly suitable for linear optimization. To enable the model to use the estimated noise data, this data should be translated by use of a linear function. The Acoustic Energy Level (AEL) function, as defined in Equation 5.5 does so. Therefore, the data that is obtained as an output of the INM is preprocessed by applying Equation 5.5 making the data applicable for linear optimization.

$$\text{AEL} = \frac{E_i}{E_0} = 10^{\frac{SEL_i}{10}} \tag{5.5}$$

Combining Equations 5.4 & 5.5 yields Equation 5.6 which is now a linear function to be used in the optimization process. This function is used to check whether a specified L_{DEN} limit is overshot at certain gridpoints. This noise related constraint is further discussed in Section 7.3.

$$L_{DEN} = 10 \log \left[\sum_{i=1}^{F} w_i \frac{E_i}{E_0} \right] - 10 \log \left[\frac{T_{ref}}{T_0} \right] \tag{5.6}$$

5.4. Modeling Process

To summarize, Table 5.3 describes the process of noise modeling in terms of an algorithm. The flight-specific noise emission model uses a set of flights, trajectories and a noise emission database as input. The data obtained from the INM comprise modeled single event noise contours for each specific flight. These noise contours represent the take-off or arrival path of each flight. For departures this comprises the ground run, first segment climb, second segment climb, third segment climb and the continued climb phase. For arrivals this yields the initial approach, final approach, flare maneuver and the ground run. After applying the algorithm, a noise matrix is defined providing all noise emission AEL per flight and per runway. It should be noted that within the noise modeling process it is assumed that noise emission is independent of any assigned delay step in the optimization process.

Table 5.3: Algorithm of flight-specific noise emission preprocessor.

Algorithm Flight-specific Noise Emission Preprocessor
Input: A set of flights, a set of SIDs and approach trajectories and a database containing aircraft-specific SEL values per gridpoint. **Output:** A noise matrix N denoting the noise emission at each gridpoint in terms of AEL per flight and per runway.
1. *Initialize* N= [**0**] and noise emission data from INM [17]. 2. **For** all flights $\in F$, all runways $\in R$ and all gridpoints $\in G$ **do** 3. **If** flight is arrival **do** 4. Select noise emission profile for approach trajectory based on IAF. 5. Set noise emission profile to N. 6. **If** flight is departure **do** 7. Select noise emission profile for SID based on departure fix. 8. Set noise emission profile to N. 9. **For** each member in N **do** 10. **If** SEL ≤ 40 dB **do** 11. SEL = 0 12. **For** each member in N **do** 13. AEL = $10^{\left(\frac{SEL}{10}\right)}$ 14. N = AEL 15. Return N.

6
Fuel Burn Modeling

As Section 2.4 describes, fuel consumption plays an important role in the airline's fuel economics. Fuel cost covers a large part of the direct operating cost of a flight. An increment or reduction in fuel consumption will therefore have a direct impact on these costs. In order to implement fuel consumption as an objective in the flexible runway allocation model, aircraft specific fuel burn profiles have to be modeled. This chapter describes the modeling of fuel burn during the arrival, taxi and departure phase of a certain aircraft. This modeling technique is then applied to each specific aircraft type that is operated at London Heathrow. The associated computations contain navigational and aircraft specific parameters that define the fuel consumption of an aircraft during a certain flight phase. These parameters are based on flight trajectory lengths as well as aircraft characteristics such as speed and fuel flow. The following sections describe the navigational and aircraft specific parameters related to fuel burn. Furthermore, Section 6.3 describes the relation of these parameters regarding fuel burn and elaborates on the methodology to apply a certain delay in terms of fuel consumption.

6.1. Navigational Parameters

London Heathrow has a limited amount of runways resulting in an extensively utilized runway occupation throughout most of the day. Like many airports, Heathrow applies strict navigational procedures for outbound as well as inbound traffic. These procedures are designed to manage high amounts of traffic through the TMA. As the London TMA comprises multiple airports in the vicinity of London, such as Gatwick, Stansted, Luton and London City, some additional approach and departure procedures have been designed. The UK Aeronautical Information Service (NATS) is responsible for publishing these procedures. This is done through the publication of the Integrated Aeronautical Information Package (IAIP). Paragraph EGLL AD 2.22 describes regulations and procedures regarding flight operations. These flight procedures, among others, comprise approach procedures with radar control and departure procedures. Some practical procedures, which are strongly related to the navigational parameters in the fuel burn computation, comprise regulations concerning speed restrictions and the common approach routes through the TMA. Procedures of these types are further described in the following two paragraphs.

6.1.1. Speed Restrictions

A dense airspace is a matter of concern for the ANSP providing ATC service within the London TMA. High amounts of traffic together with multiple approach and departure fixes mean not only an increased safety risk but also lead to complex separation strategies. Despite the fact that aircraft would like to operate at a certain optimized speed, specific trajectory-related speed restrictions have been designed to obtain sufficient separation distances between aircraft inside the TMA. These speed restrictions are defined as follows:

- Departure speed restriction of 250 kt IAS below FL100 is applicable until removed by ATC.
- Approach speed restriction of 220 kt IAS from the holding facility during the initial approach phase.
- Approach speed restriction of 180 kt IAS on base leg/closing heading to final approach.
- Approach speed restriction between 180 kt and 160 kt IAS when established on final approach.

- Approach speed restriction of 160 kt IAS to 4 DME.

6.1.2. Flight Segment Distance

A variety of approach and departure trajectories pass through the London TMA in order to organize inbound and outbound traffic of the London airports in a safe and efficient manner. These trajectories are often connected to the lower and upper ATS route system of the Flight Information Region (FIR). On the other side, these trajectories are connected to an active departure or arrival runway. The beginning and end of a flight comprises multiple flight segments in which aircraft are instructed to operate according to specified regulations. For departures, the first segments of the flight consist of taxi, take-off and the departure trajectory. For arrivals, this includes the approach trajectory, common approach path and taxi. In order to model the fuel burn characteristics of aircraft along these trajectories, the length of these trajectories have to be defined. The following paragraphs provide a definition of the lengths of these trajectories per runway.

Standard Instrument Departure

Many urban communities surround Heathrow making the airport located in a critical area. Critical in terms of safety as well as noise sensitivity. The efforts of the airport in cooperation with the ANSP of minimizing noise annoyance have led to the design of NPR. These routes are designed with regards to noise emissions. London Heathrow defined nine exit points for flights on departure. These exit points are defined in terms of the following SID indicators: BPK (Brookmans Park), BUZAD, WOBUN, CPT (Compton), DET (Detling), GASGU, GOGSI, MAY (Mayfield) and MID (Midhurst) and are illustrated in Figure 6.1. These indicators have been distributed over multiple directions in the FIR. The assignment of a certain SID to a flight depends on the routing of the flight as well as the capacity along the route and TMA. Each SID consists of a specific trajectory which aims to circumnavigate densely populated areas and often comes with speed and altitude restrictions as well. These restrictions regulate noise exposure and often relate to departure and arrival conflict management. Table 6.1 indicates the length of each departure trajectory, specified per departure runway and SID indicator. As can be obtained from the table, a SID can differ in length for different departure runways. As a result, this difference can lead to more or less preferable runways in terms of trajectory length and therefore fuel burn. Section 6.3 provides a more in depth analysis on the correlation between trajectory length and fuel consumption.

Table 6.1: Standard Instrument Departures at London Heathrow with track mileage in nautical miles.

	Track (nm)			
SID	*09L*	*09R*	*27L*	*27R*
BPK	23	23	32	32
BUZAD	38	38	-	-
WOBUN	-	-	37	37
CPT	22	21	15	15
DET	41	41	49	50
GASGU	33	33	-	-
GOGSI	-	-	24	24
MAY	38	37	39	40
MID	29	29	30	31

Approach Trajectory

Besides the defined departure trajectories, London's congested TMA has multiple arrival trajectories to separate outbound from inbound traffic. These trajectories consist of three major phases. These phases are defined as the Standard Terminal Arrival Route (STAR), initial approach phase and final approach phase. The initial approach phase comprises the segment between the Initial Approach Fix (IAF) and the Final Approach Fix (FAF). The STAR is not taken into account in this research. Usually ATC separates and sequences traffic in all three segments by applying speed, altitude and heading instructions. As a result, the trajectory length of the initial approach segment can be different for each aircraft in the approach sequence. In order to enable accurate modeling of the approach trajectory length use has been made of the published initial approach procedures without radar control for each specific runway and IAF. Heathrow has six IAFs of which four are a VHF Omni Directional Radio Range (VOR) beacon and two are a Non-Directional Beacon (NDB). The latter two are located in the close vicinity of a VOR which is also used as an IAF. Therefore, in this simulation

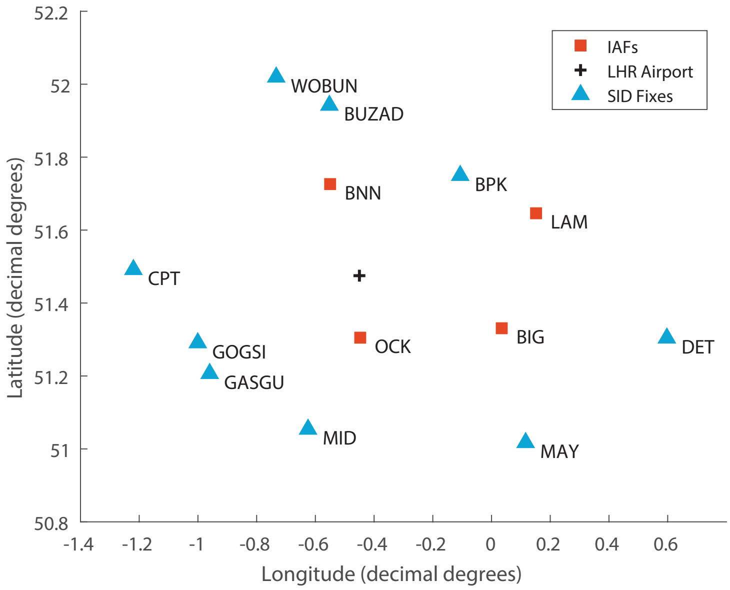

Figure 6.1: SID fixes and IAFs locations.

four IAFs will be used to assign arrival aircraft to. These IAFs are defined as BIG (Biggin), BNN (Bovingdon), LAM (Lambourne) and OCK (Ockham) and are illustrated in Figure 6.1. Table 6.2 indicates the length of each approach trajectory, specified per arrival runway and IAF indicator. The same yields as is described for the departure trajectories. A certain runway can be preferable for a specific approach trajectory in terms of trajectory length and therefore fuel burn.

Table 6.2: Approach Trajectories at London Heathrow with track mileage in nautical miles.

	Track (nm)			
IAF	*09L*	*09R*	*27L*	*27R*
BIG	49	48	35	36
BNN	35	36	36	35
LAM	55	56	36	35
OCK	31	30	30	31

The approach trajectories, as shown in Figures 6.2 and 6.3, provide a clear visualization of the noise annoyance problem at Heathrow. Usually, the airport operates in either a west configuration or an east configuration. Throughout the day, the airport applies a runway alternation schedule to provide a predictable and fair distribution of the noise annoyance regarding the northern and southern runway operations. As can be clearly denoted from the figures, the population density (indicated in grey) on the eastern side of the airport differs dramatically in extent compared to the western side. That is, the majority of London's boroughs are located east of the airport. As aircraft are to emit noise the most during departure, the so-called west configuration is preferable over the east configuration. However, weather conditions might affect the selection of configuration at the airport on a certain day.

Common Approach Path

The final part of the arrival trajectory contains the common approach path. This segment is defined as the trajectory from the FAF until the touch-down point of the arrival runway. At Heathrow, all four runways have the same common approach path length. This length is defined to be 7.5 nautical miles. The common approach path is split into two parts. The first part, defined as the segment between 7.5 DME (D7.5) and 4.0 DME (D4), relates to the fifth speed restriction as described in Section 6.1.1. The second part is defined as the segment between 4.0 DME (D4) and the touchdown zone. These two parts have a trajectory length of 3.5 nm and 4.0 nm, respectively.

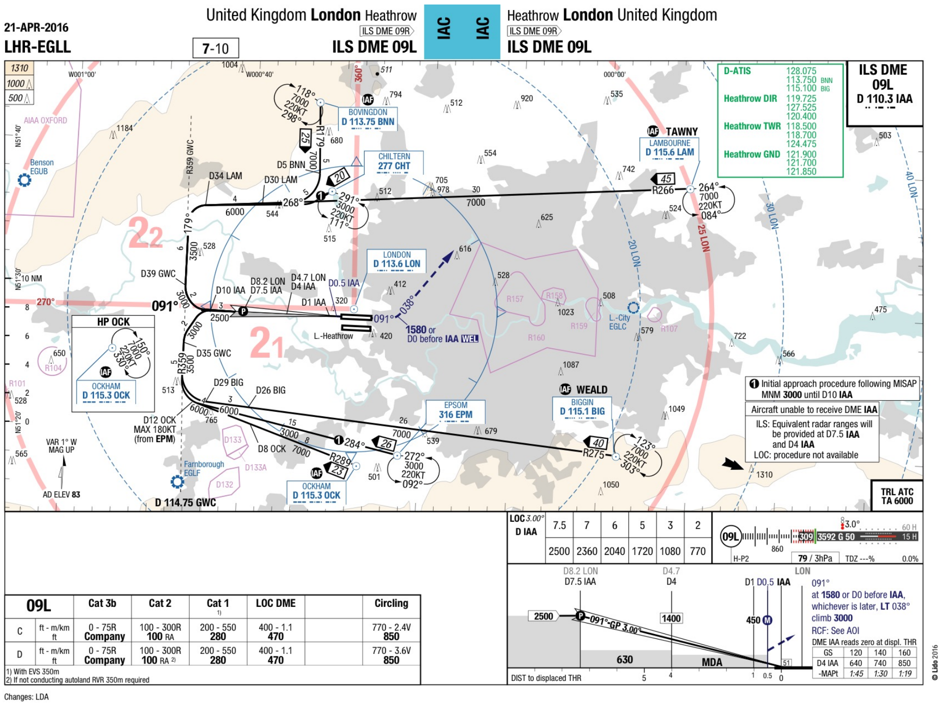

Figure 6.2: Approach trajectory for runway 09L per IAF.

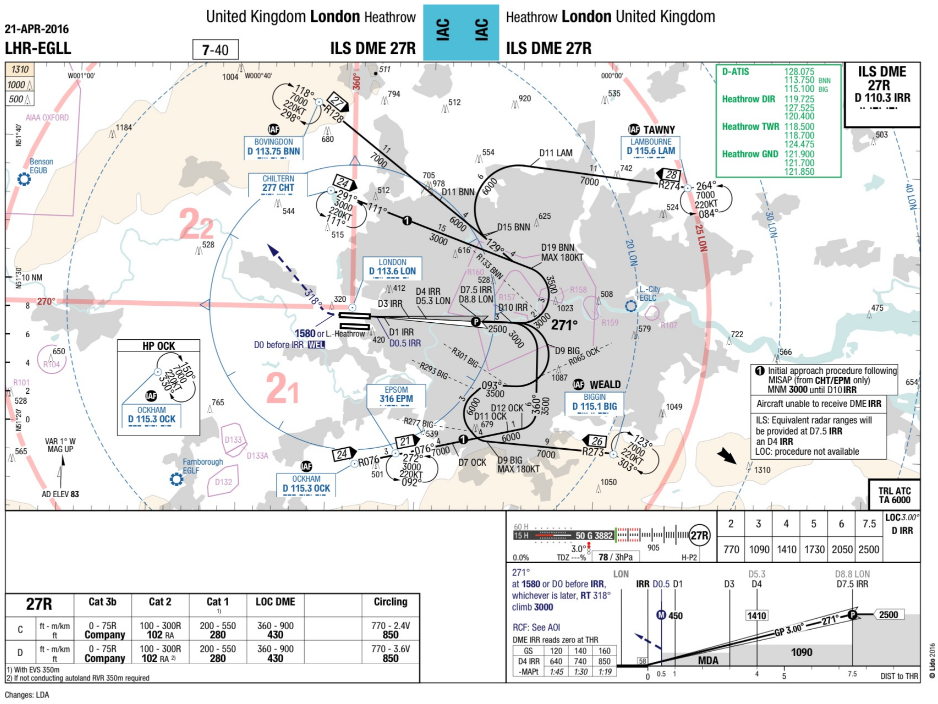

Figure 6.3: Approach trajectory for runway 27R per IAF.

Taxi Time

At Heathrow taxi procedures play an important role. As the airport is limited in space and utilized to the maximum capacity, ground operations need to be well managed in order to reduce delay on the ground. Terminals 1, 2 and 3 are located in the vicinity of each other in the middle of the airport's terrain. Terminal 5 is located in the western part of the airport as shown in the Airport Ground Chart (AGC) in Figure 3.1. With respect to taxi time, in contrast to terminals T1-T3, operations from and to T5 have a preference for RWY 09L/R or 27L/R, for

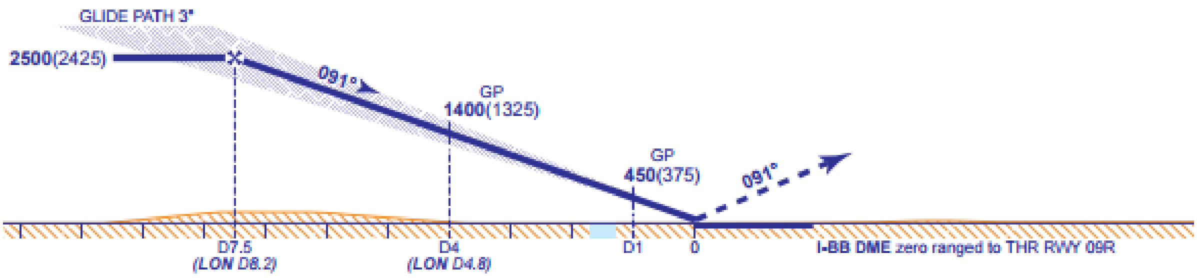

Figure 6.4: Common approach path for Heathrow's RWY 09R.

departures and arrivals, respectively. Terminal 4, however, has a limitation in ground operations. Aircraft are limited to operate from RWY 09R/27L only. In cases RWY 09L/27R is operational, physical runway crossings would lead to a reduction in runway capacity on the southern runway. This is further explained in Section 3.7.

As shown, multiple factors influence the ground operations at Heathrow. In order to model the taxi time per flight in an accurate manner, a taxi-in and taxi-out time have been estimated per airline. That is, each airline is assumed from a specific terminal at Heathrow as specified in the operational schedule. Appendix B elaborates on the assumptions that have been made to estimate the taxi times for each terminal. The results of this estimation can be found in Table 6.3.

Table 6.3: Taxi-in time (left) and taxi-out time (right) per runway per terminal in minutes.

	Terminal				
Runway	*T1*	*T2*	*T3*	*T4*	*T5*
09L	2	6	9	11	11
09R	8	2	9	2	10
27L	10	7	5	6	5
27R	7	10	4	11	5

	Terminal				
Runway	*T1*	*T2*	*T3*	*T4*	*T5*
09L	12	14	8	15	5
09R	17	11	8	10	4
27L	7	4	11	4	12
27R	4	7	11	10	12

6.2. Aircraft Performance Parameters

Apart from the routing parameters, aircraft characteristics play an important role in the fuel burn process. Among these are the fuel flow rate of the engines as well as the approach speed of the aircraft. These type of parameters can be obtained from the Base of Aircraft Data (BADA), comprising aircraft data of nearly the entire European fleet mix. The importance of modeling these parameters accurately comes with the direct relation to the total fuel used parameter as is defined in Section 6.3.

6.2.1. Base of Aircraft Data

Many approaches have been designed to model aircraft performance. One of these approaches is the kinetic approach. This approach is based on aircraft forces. The Base of Aircraft Data (BADA) uses the kinetic approach in its Aircraft Performance Model (APM). The aircraft performance parameters modeled by BADA can be used in trajectory simulation and prediction. Regarding the flexible runway allocation model, fuel modeling makes use of two important aircraft performance parameters. These parameters, fuel flow and approach speed, are therefore obtained from BADA for each specific aircraft in the flight schedule. BADA can be defined as a model consisting of five submodels. These submodels are further discussed in Appendix G.

6.2.2. Fuel Flow

Fuel flow defines the rate of fuel that is being used by an aircraft during operation. For the airline's economics, this means that this parameter plays a major role in defining the direct operating cost of a certain flight. In order to model fuel usage accurately, it is of high importance to use the correct fuel flow values. Fuel consumption differs per aircraft type. Factors that affect the fuel consumption of an aircraft include the number, the size, the thrust production as well as the age of the engines. Usually, the efficiency of engines degrades over time. A degradation in efficiency leads to an increase in fuel consumption which will have its influence on the operation costs of a certain flight. This is neglected in this model. Besides the efficiency of the engines, other aspects such as meteorological conditions affect the fuel consumption of an aircraft as well. However, this impact can also be translated to the fuel flow of the engines. As there are multiple factors that influence the behaviour of the aircraft in terms of fuel consumption, it is wise to model fuel consumption per aircraft type, with aircraft specific fuel parameters instead of using a reference model and apply penalties for differentiation in aircraft types. This is done by means of Equation 6.1 specifying the fuel flow of an aircraft's engine, based on the thrust specific fuel consumption, $TSFC$, and thrust, T.

$$\dot{m}_f = \frac{TSFC}{T} \tag{6.1}$$

6.2.3. Final Approach Speed

Another important aspect is the final approach speed of the aircraft. This speed parameter defines the speed of the aircraft in the very last segment of flight, being the common approah path between 4.0 DME (D4) and shortly before the touchdown zone. Inside this segment the aircraft is expected to reduce its airspeed to the final approach speed before it starts its flare maneuver. This speed is unique per aircraft type and often is unique per flight as well. Namely, the stall speed (V_{stall}), per aerodynamic definition, is dependent of the aircraft's weight (W), wing area (S) and maximum lift coefficient ($C_{L_{\max}}$) as shown in Equation 6.2. The latter is of high importance during the landing phase. The maximum lift coefficient can be increased by extending the slats and flaps, also known as high-lift devices, on the aircraft's wings. By doing this, the lift coefficient is increased as a result of an increase in the camber of the airfoil as the flaps are deflected downward. A regular aircraft has multiple flap deflection stages which can be selected by the pilot regarding certain wind conditions as well as noise and fuel burn regulations.

$$V_{\text{stall}} = \sqrt{\frac{2W}{\rho_\infty S C_{L_{\max}}}} \tag{6.2}$$

To implement some sort of safety factor, the stall speed of an aircraft is multiplied with a factor of 1.3. The obtained operational speed that arises as a result of this multiplication is referred to as the reference landing speed (V_{REF}) as defined in Equation 6.3.

$$V_{\text{REF}} = 1.3 \times V_{\text{stall}} \tag{6.3}$$

In the end, the reference landing speed is corrected for operational factors such as strong wind conditions, wind shear and icing. Besides corrections can be applied in case an aircraft lands with a reduced flap setting. The final approach speed (V_{APP}) that includes the speed corrections (ΔV_{cor}) as defined in Equation 6.4, enables the aircraft to land in an optimal configuration with respect to its stall margin, controllability and maneuverability.

$$V_{\text{APP}} = V_{\text{REF}} + \Delta V_{\text{cor}} \tag{6.4}$$

6.3. Modeling Process

Comprising the navigational and aircraft specific parameters, the total fuel burn metric defines the fuel consumption of an aircraft over a certain trajectory. This metric consists of an addition of multiple fuel burn values specified per phase of flight. For departures these phases comprise taxi time to the runway and the departure phase, defined as the period between take-off and arrival at the first navigational fix in the flight plan. Moreover, the latter comprises the SID. For arrivals these phases comprise the approach segment between the IAF and the FAF, the common approach path of a certain runway and the taxi time to the gate. As the ADS-B data used in this research is limited, some assumptions regarding the direction of flight have been made. One of these assumptions relate to the first and last navigational fix in the flight plan of a flight. As these fixes define the expected SID or IAF, the trajectory can be selected based on this information. To get a good estimation of the SID and IAF trajectories of flights, a methodology is used based on the ICAO airport identifiers of each flight. Appendix C elaborates on this methodolgy.

The total amount of consumed fuel (TFU) that is related to the assignment of a specific flight to a certain arrival or departure runway can be computed by Equations 6.5 and 6.6. As this equation defines, the total amount of fuel burn is a summation of the fuel burn related to each segment of the flight phase, s, regarding a departure or arrival flight. The total fuel burn parameter is dependent on three parameters which are extensively described in the above paragraphs. These parameters comprise trajectory distance (D), fuel flow ($\dot{m}_f$) and true airspeed (V_{TAS}).

$$TFU = \sum_{s \in S} TFB_s \tag{6.5}$$

$$TFB_s = \left[\frac{D \cdot \dot{m}_f}{V_{\text{TAS}}} \right]_s \tag{6.6}$$

Using the equations formulated above, the total fuel burn preprocessor computes the total fuel consumption for each flight, each runway and each possible assigned delay. This data is used as the cost value reflecting the fuel burn objective cost for all decision variables in the problem. Table 6.4 visualizes the algorithm that is used in this preprocessor.

Table 6.4: Algorithm of total fuel burn preprocessor.

Algorithm Total Fuel Burn Preprocessor
Input: A set of flights, a matrix with estimated taxi, departure and arrival trajectory lengths and a database containing aircraft-specific fuel flow parameters. **Output:** A matrix TFB denoting the total fuel burn per flight, per runway and per possible delay step.
1. *Initialize* TFB= [**0**] and fuel flow parameters from BADA [16] 2. **For** all flights ∈ F, all runways ∈ R and all delay steps ∈ D **do** 3. **If** flight is arrival **do** 4. $TFU_{taxi} = \frac{D_{RWY\|GATE} \cdot ff_{taxi}}{V_{taxi}}$ 5. $TFU_{APP} = \frac{D_{IAF\|FAF} \cdot ff_{IAF\|FAF}}{V_{IAF\|FAF}} + \frac{D_{FAF\|RWY} \cdot ff_{FAF\|RWY}}{V_{FAF\|RWY}}$ 6. $TFB = TFU_{taxi} + TFU_{APP}$ 7. **Else** 8. $TFU_{taxi} = \frac{D_{GATE\|RWY} \cdot ff_{taxi}}{V_{taxi}}$ 9. $TFU_{SID} = \frac{D_{RWY\|FIX} \cdot ff_{RWY\|FIX}}{V_{RWY\|FIX}}$ 10. $TFB = TFU_{taxi} + TFU_{SID}$ 11. Return TFB

6.3.1. Implementation of Delay

In this simulation, in order to find the optimal solution to the flexible runway assignment problem, the model is allowed to assign a certain delay to a flight. This delay can be assigned in 20 seconds interval steps up to a predefined maximum. This delay should, in the end, lead to an improved runway assignment based on the multi-objective function regarding noise annoyance and fuel burn. However, the delay should be specified in terms of one of these parameters in order to implement the dependency of the delay factor in the optimization problem. To do so, the delay factor is defined in terms of an extension of the approach path, in the case of an arrival flight, and, an increased holding time on the ground, in the case of a departure flight. Figure 6.5 provides a visualization of the delay assignment during flight upon arrival. Both scenarios will have their impact on the fuel burn of their specific flight segment and will therefore affect the objective function as needed.

For the delay on departure the total fuel burn function is defined as in Equation 6.7. A delay on arrival will be assigned in the first segment of the approach phase, being the segment between the IAF and FAF. An arrival delay can therefore be incorporated in the total fuel burn function as defined by Equation 6.8.

$$TFB_{\text{taxi}} = (t + \Delta t) \cdot \dot{m}_f \tag{6.7}$$

$$TFB_{\text{IAF}\,|\,\text{FAF}} = \frac{(D + \Delta D) \cdot \dot{m}_f}{V_{TAS}} \tag{6.8}$$

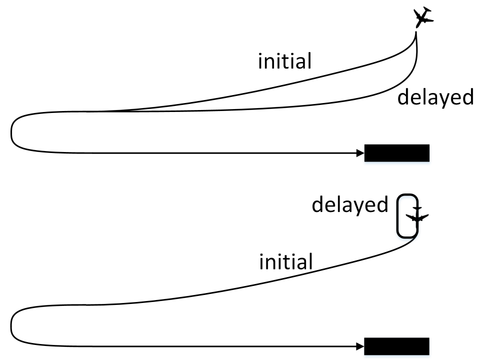

Figure 6.5: In-air delay assignment options upon arrival.

6.3.2. Differentiation per Runway

As the previous paragraphs argued, the assignment of a certain runway has a large impact on the fuel consumption of the first or last segment of flight for departures and arrivals, respectively. However, the assignment of a certain runway can result in an extended approach path, but will lead to a reduced taxi time to the gate, resulting in an overall fuel burn saving. The example given below gives a clear indication on the effects of runway selection in the runway allocation process with respect to fuel consumption.

Table 6.5: Operation time (s) of flights departing from each terminal per SID per runway.

	SID						
T1	*BPK*	*CPT*	*DET*	*MAY*	*MID*	*WOBUN*	*GASGU*
09L	1,292	1,574	1,746	1,668	1,433	1,715	1,214
27R	1,069	975	1,539	1,273	1,054	1,210	631
09R	1,638	1,935	2,092	1,998	1,779	2,060	1,560
27L	1,209	1,115	1,648	1,397	1,162	1,350	771
T2	*BPK*	*CPT*	*DET*	*MAY*	*MID*	*WOBUN*	*GASGU*
09L	1,463	1,745	1,917	1,839	1,604	1,886	1,385
27R	1,213	1,119	1,682	1,416	1,197	1,354	775
09R	1,265	1,562	1,719	1,625	1,406	1,687	1,187
27L	1,041	947	1,479	1,228	994	1,181	602
T3	*BPK*	*CPT*	*DET*	*MAY*	*MID*	*WOBUN*	*GASGU*
09L	1,099	1,381	1,553	1,475	1,240	1,522	1,021
27R	1,445	1,352	1,915	1,649	1,430	1,586	1,007
09R	1,104	1,401	1,558	1,464	1,245	1,527	1,026
27L	1,450	1,356	1,888	1,638	1,403	1,591	1,012
T4	*BPK*	*CPT*	*DET*	*MAY*	*MID*	*WOBUN*	*GASGU*
09L	1,456	1,738	1,910	1,832	1,597	1,879	1,378
27R	1,330	1,236	1,799	1,533	1,314	1,470	891
09R	1,200	1,497	1,653	1,560	1,340	1,622	1,121
27L	1,061	967	1,500	1,249	1,014	1,202	623
T5	*BPK*	*CPT*	*DET*	*MAY*	*MID*	*WOBUN*	*GASGU*
09L	891	1,173	1,345	1,267	1,032	1,314	813
27R	1,543	1,450	2,013	1,747	1,528	1,684	1,105
09R	840	1,137	1,293	1,200	980	1,262	761
27L	1,516	1,422	1,954	1,704	1,469	1,657	1,078

Table 6.6: Operation time (s) of flights arriving at each terminal per SID per runway exluding the aircraft specific last 4 nm glidepath.

	IAF			
T1	*BIG*	*BNN*	*LAM*	*DET*
09L	884	664	978	602
27R	981	966	966	903
09R	1,227	1,039	1,352	945
27L	1,130	1,146	1,146	1,052

	IAF			
T2	*BIG*	*BNN*	*LAM*	*DET*
09L	1,127	908	1,221	845
27R	1,151	1,136	1,136	1,073
09R	880	693	1,006	599
27L	978	993	993	900

T3	*BIG*	*BNN*	*LAM*	*DET*
09L	1,300	1,081	1,394	1,018
27R	799	784	784	721
09R	1,273	1,085	1,398	991
27L	827	843	843	749

T4	*BIG*	*BNN*	*LAM*	*DET*
09L	1,351	1,132	1,445	1,070
27R	1,142	1,127	1,127	1,064
09R	886	699	1,012	605
27L	884	900	900	806

T5	*BIG*	*BNN*	*LAM*	*DET*
09L	1,410	1,191	1,504	1,128
27R	841	826	826	763
09R	1,354	1,166	1,479	1,072
27L	835	851	851	757

Example
In this example a single aircraft operation is concerned. The aircraft in this analysis is of type Boeing 777-200 and is operated by British Airways with flight number BA124. This flight origins from Bahrain and is about to arrive at Heathrow. As defined in Appendix B, British Airways operates at Heathrow's Terminal 5. This terminal is located on the western part of the airport as illustrated in Figure 3.1.

In case fuel burn would only concern taxi fuel, it is obvious the preferred runway for this flight would be either RWY 27L or 27R as the taxi distance to Terminal 5 would be far less compared to the opposite runways. However, fuel consumption in the approach trajectory can be predominant and might result in the preference of RWY 09L or 09R over the other two runway ends. However, besides the preference from the airline's perspective, the allocation of a runway is based on many other factors such as runway occupancy, airspace density and weather conditions.

As the flight that origins from Bahrain enters the London TMA at IAF BIG, the length of the approach trajectories can be translated into a fuel burn parameter indicating the total amount of fuel burned over the entire approach and taxi trajectory. This is shown in Table 6.7.

Table 6.7: Operation time profile for a British Airways Boeing 777-200 on arrival via IAF BIG, parking at T5.

	Operation time (s)			
IAF	*IAF | FAF*	*FAF | RWY*	*Taxi*	*Total*
09L	691.7	162.8	643.0	1497.5
09R	675.0	162.8	603.0	1440.8
27L	458.3	162.8	288.0	909.1
27R	475.0	162.8	278.0	915.8

The table shows clear evidence of what is recently discussed. Indeed, RWY 27L and 27R show a clear preference over the other two runway ends. This is what the optimization algorithm does for the overall fuel consumption within the specified time frame. However, besides fuel consumption, the optimization model must also concern the reduction of noise annoyance which can decrease the improvements made with respect to fuel consumption to some extent.

7
Linear Programming Model

The linear programming model as part of this research consists of multiple parts. These parts are related to objectives that have an important role in the runway allocation process. To define a linear programming problem, all factors that affect the optimization process in some sense need to be categorized. In general, an optimization problem consists of resources and activities. Reflecting these definitions to the runway allocation problem yields the following categorization. The operational runways at the airport to be analyzed, in this case Heathrow, are defined as the resources to which activities should be assigned. Consequently, the activities in this problem are defined as the flight operations, i.e. the departures and arrivals in a certain time frame. Within this research, linear programming is applied in such a way that the optimization process allocates a certain runway to a specific flight. This allocation is to be performed within the collection of all feasible solutions, also referred to as the feasible region of the optimization problem. As a consequence, the optimal solution will comprise the most favorable value of the objective function as will be defined in Section 7.2.

7.1. Integer Linear Programming

Linear programming is known as a mathematical technique. This technique concerns optimization problems in which it is tried to minimize or maximize a linear objective function. This objective function is often referred to as the cost function of the optimization problem. Such optimization problem is to be solved given a set of requirements in the form of constraints which the solution has to comply to. These requirements can be inequality as well as equality constraints as is elaborated on in Section 7.3. In general, a linear programming problem is defined as is shown in Equation 7.1.

$$\begin{aligned} \text{minimize} \quad & c^T x \\ \text{subject to} \quad & Ax \geq b \\ & x \geq 0 \end{aligned} \tag{7.1}$$

In this standard form, the objective function is preceeded by the term minimize or maximize, indicating the purpose of the optimization problem. Here c is defined as the cost vector of the problem, whereas x specifies the decision variables. The objective function for this research is introduced in Section 7.2. Once a set of decision variables satisfies all the linear constraints in the problem, this set is called a feasible solution. With this in mind, a optimal solution is defined as a feasible solution if the solution minimizes or maximizes the objective function for all feasible solutions.

There are multiple types of linear programming. All of them have their characteristics to efficiently solve certain problems. In this research, use has been made of Binary Integer Linear Programming (BILP). Somehow restricted in terms of possible states of each decision variable, this technique reflects the airside operations problem the most. Moreover, in BILP the decision variables are limited in their state. That is, they all need to be positive, integer and binary. Consequently, they can only have an active state, 1, or an inactive state, 0.

7.1.1. Weighted Sum Method

There might be cases in which Binary Integer Linear Programming problems concern multiple objectives. These types of optimization problems are named Multi Integer Linear Programming (MILP) problems. In these problems multiple objectives are concerned which all have their influence on the overall cost function. This research has multiple objectives as it concerns fuel burn and noise annoyance. However, when having multiple objectives, these objectives should be defined in terms of importance with respect to each other. To do so, use is made of a popular method to add weights to certain objectives in the optimization problem. This methodlogy is called the Weighted Sum Method. It enables the decision maker to set a certain weight, $w_i \in [0,1]$, to each objective. All assigned weights in the objective function should be such that $\sum_{i=1}^{s} w_i = 1$. Doing so, results in a single objective function which can be solved on its own. The outcome will provide an optimal solution based on the given importance of the sub-objectives. By changing the weights, a pareto front can be generated which is further described in Section 8.1.

$$\text{minimize } f(x) = \sum_{i}^{s} w_i \cdot f_i \tag{7.2}$$

7.1.2. CPLEX Search Strategies

The optimization software used in this research, CPLEX [27], enables two types of search strategies when concerning mixed integer programming. The first strategy is named Branch & Cut, utilizing cuts when solving subproblems defined in the feasible solution set. Besides the robust Branch & Cut strategy, Dynamic Search has been introduced as a Branch & Cut-based strategy with improved characteristics. That is, some extra features enable this strategy to solve certain problems faster [23]. In order to let the software choose the most suitable search strategy, the related CPLEX parameter has been set such, that the model selects the best strategy to solve the runway allocation problems defined in this research.

7.2. Objective Function

The allocation process involves the selection of levels of activities which achieve the most value of the overall measure of performance. The overall measure of performance, Z, is also referred to as the objective function of the linear programming model and is defined in Equation 7.3. The objective function in the runway allocation process is described by two objectives, making this optimization problem a multi-objective optimization. The two objectives in this problem are defined as noise annoyance and fuel burn. The first objective relates to the annoyance caused by departing and arriving flights in the vicinity of the airport. The latter relates to the fuel burn as a consequence of noise preferred departure and arrival routes from the airline's perspective. These objectives will be further described in Sections 7.2.2 and 7.2.1, respectively.

$$\text{minimize} \quad Z = \alpha \cdot n_f \sum_{f\in F} \sum_{r\in R} \sum_{d\in D} C^F_{f,r,d} \cdot x_{f,r,d} + \beta \cdot n_n \sum_{xy\in P} C^G_{xy} \cdot g_{xy} \tag{7.3}$$

7.2.1. Fuel Burn

The objective regarding fuel burn from the airline's perspective is highlighted by Equation 7.4. This part of the total objective function, Z, is composed out of a set of decision variables and a set of corresponding cost coefficients as well. The weight factor, α, defines the importance of fuel burn with respect to the noise annoyance objective.

$$Z_{\text{fuel}} = \alpha \cdot n_f \sum_{f\in F} \sum_{r\in R} \sum_{d\in D} C^F_{f,r,d} \cdot x_{f,r,d} \tag{7.4}$$

Decision Variables

The decision variable concerning the fuel burn objective is of binary form. That is, the decision variable, as defined in Equation 7.5, can only have two states, being either 0 or 1. The fuel burn decision variable comprises three types of information. These types of information are stored within the variable as follows:

(A) Flight number.

(B) Allocated runway.

(C) Operation time including possible delay (in time steps).

With, X(A, B, C).

$$x_{f,r,d} = \begin{cases} 1 & \text{if yes} \\ 0 & \text{if no} \end{cases} \tag{7.5}$$

Cost Coefficients
Regarding the cost coefficient of a certain decision varible as defined in Equation 7.5, a detailed fuel burn analysis has been performed as described in Chapter 6. The cost coefficient of each flight operating to or from a specific runway at a certain operation time is defined as the related total fuel burn value as defined in Equation 7.6. Moreover, just like the fuel burn decision variable, the fuel burn cost coefficient is dependent on flight, runway and operation time (including delay).

$$C_{f,r,d} = TFU_{f,r,d} \tag{7.6}$$

7.2.2. Noise Annoyance

The objective function as stated in Equation 7.3 defines the optimization process to generate an optimal solution regarding two objectives. Obviously, such optimal solution needs to be selected by deciding about the levels of the flights that are allocated to a certain runway. The decision on the levels of the activities in the optimization problem are described by the decision variables. These decision variables are paired with their corresponding cost coefficient. Equation 7.7 highlights the objective related to noise annoyance. This objective consists of a set of decision variables, g_{xy}, and the corresponding set of cost coefficients, C^G_{xy}. The weight factor, β, defines the importance of the noise annoyance with respect to the fuel burn objective.

$$Z_{\text{noise}} = \beta \cdot n_n \sum_{xy \in G} C^G_{xy} \cdot g_{xy} \tag{7.7}$$

Decision Variables
Regarding the noise annoyance objective, the decision variables are defined as the indicators defining the excess of the noise limit at certain geographic locations within the vicinity of the airport. Moreover, each decision variable will have a binary form as described by Equation 7.8. The geographic location is defined by means of a latitude and longitude coordinate based on a 1 km^2 resolution.

$$g_{xy} = \begin{cases} 1 & \text{if yes} \\ 0 & \text{if no} \end{cases} \tag{7.8}$$

Cost Coefficients
The noise cost coefficients define the weight of the impact of selecting a certain solution. These weights are defined in terms of population. Each noise cost coefficient reflects the population count for a certain geographic locations defined by latitude and longitude. Data regarding the population count have been gathered as described in Section 5.1.

$$C_{xy} = \text{POP}_{xy} \tag{7.9}$$

7.3. Constraints

The formulated linear programming problem, as defined by the objective function in Equation 7.3, comes with certain boundary conditions. These boundary conditions are defined by means of constraints. The constraints used in this research are of type: i) equality constraints, ii) inequality constraints, and, iii) non-negativity constraints. The following paragraphs introduce the variety of constraints that together form the boundaries for this optimization problem.

7.3.1. Flight Assignment

In order to ensure all flights in a certain time frame are to be taken into account, a constraints related to flight operations needs to be defined. The flight assignment constraint concerns the allocation of each flight in the defined time frame only once. Moreover, it ensures that every flight will be allocated only to one runway at one time by means of an equality constraint. The theoretical definition of this constraint can be found in Equation 7.10. Furthermore Equation 7.11 illustrates a practical example of the flight assignment constraint.

$$\sum_{r \in R} \sum_{d \in D} x_{f,\,r,\,d} = 1 \quad \forall f \in F \tag{7.10}$$

Example

$$\begin{aligned} &X(120, 09L, 1250) + X(120, 09L, 1251) + X(120, 09L, 1252) + X(120, 09L, 1253) \\ &+ X(120, 27R, 1250) + X(120, 27R, 1251) + X(120, 27R, 1252) + X(120, 27R, 1253) \\ &+ X(120, 09R, 1250) + X(120, 09R, 1251) + X(120, 09R, 1252) + X(120, 09R, 1253) \\ &+ X(120, 27L, 1250) + X(120, 27L, 1251) + X(120, 27L, 1252) + X(120, 27L, 1253) = 1 \end{aligned} \tag{7.11}$$

7.3.2. Runway Availability

To enable the possibility to have maintenance on a certain runway, a second constraint has been built in to identify closed runway ends. Besides, this constraint can also be used to simulate "standard" operations instead of flexible operations, by closing both runway ends in a certain direction (e.g. 27L/R or 09L/R). The runway availability constraint, as defined in Equation 7.12, is an equality constraint and concerns the allocation of every flight on a runway that is available within the simulated time frame. Moreover, Equation 7.13 gives a practical example of the runway availability constraint in case runway 27L is closed for the time frame in which flight 120 operates.

$$\sum_{f \in F} \sum_{d \in D} x_{f,\,r,\,d} = 0 \quad \forall r \in R_{\text{closed}} \tag{7.12}$$

Example

$$X(120, 27L, 1250) + X(120, 27L, 1251) + X(120, 27L, 1252) + X(120, 27L, 1253) = 0 \tag{7.13}$$

This constraint can be further utilized to specify operational restrictions of a specific runway for either departure or arrival operations. For example, the model identifies all departure flights. Subsequently, it writes constraints for these flights to not operate from a certain runway.

7.3.3. Runway Occupation

The third constraint in the runway allocation optimization process concerns the runway occupancy and related pairwise flight separation constraint. This constraint plays a major role in the available capacity on a certain runway regarding the aircraft mixture within a certain time frame. By means of analyzing the pairwise flight dependencies the minimum time separation between two flight operations can be defined. This is done by applying the dependency matrices as defined in Chapter 4.

Table 7.1 provides a summary of the equations used to establish the dependency matrices. As shown, two types of directional operations are defined, being Single Direction Operations (SDO) and Opposite Direction Operations (ODO). As Heathrow's parallel runway set is separated such, that both runways can be seen as single runways, the dependency of operations is limited to SDO and ODO. Moreover, the parallel runway dependency can be neglected in this case.

Table 7.1: Equations defining the pairwise flight dependencies for single and opposite direction operations.

		Flight Pair			
		AA	**AD**	**DA**	**DD**
Operations	**Single Direction**	$\max(\text{TBS}_{ij}, \text{AROT}_i)$	AROT_i	$\max(\text{TBS}_{2\text{nm}}, \text{DROT}_i)$	$\max(\text{TBS}_{ij}, \text{DROT}_i)$
	Opposite Direction	$\frac{\text{MVA}}{\text{ROD}} + c$	AROT_i	$\frac{\text{MVA}}{\text{ROD}} + \text{DROT}_i + \frac{\text{MVA}}{\text{ROC}}$	DROT_i

The runway occupation constraint itself defines the availability of a runway for a specific flight at a certain time based on the equation in the table above. Moreover, the constraint concerns two aircraft at a time, being the leading aircraft and the following aircraft respectively. Furthermore, each constraint is defined per runway and per time slot. That is, per aircraft pair, a maximum of 32 constraints can be defined (four runways and eight time slots). A practical example of such a constraint can be found in Equation 7.15 describing the runway occupancy constraint for Flight 120 (leader) with respect to Flight 121 (follower) on RWY 27L at time 1250.

$$\sum_{f \in F} \sum_{d \in D} n_{f,r,d}^{DM} \cdot x_{f,r,d} \leq 1 \quad \forall r \in R_{\text{conflict}} \ \forall t \in T \tag{7.14}$$

Example

$$\begin{aligned} &X(120, 27\text{L}, 1250) + X(121, 27\text{L}, 1253) + X(121, 27\text{L}, 1254) + X(121, 27\text{L}, 1255) \\ &X(121, 09\text{R}, 1253) + X(121, 09\text{R}, 1254) + X(121, 09\text{R}, 1255) + X(121, 09\text{R}, 1256) \\ &X(121, 09\text{R}, 1257) + X(121, 09\text{R}, 1258) + X(121, 09\text{R}, 1259) \leq 1 \end{aligned} \tag{7.15}$$

7.3.4. Noise Limit Switching

This constraint concerns the identification of grid points at which a certain noise limit is exceeded. The noise limit, defined in decibel L_{DEN}, is selected as one of the imput parameters upon initiating the model. The L_{DEN} parameter concerns a day-evening-night average level as described in Section 5.3.

The mathematical definition of this constraint can be seen in Equation 7.16. The constraint simply adds all the SEL-values corresponding to each flight at each grid point and checks whether the noise limit is exceeded at each grid point. If so, this grid point is activated, meaning it will have a value 1 instead of 0, and will be taken into account as decision variable in the objective function. This switch is initiated by means of the Big M method. This method concerns the decision variables related to noise annoyance. The M represents a large positive number creating an overwhelming penalty in cases the related decision variable becomes active [23].

$$\sum_{f \in F} \sum_{r \in R} \sum_{d \in D} C_{xy(f,r,d)}^{G} \cdot x(f, r, d) - M \cdot g_{xy} \leq L_{limit} \ \forall xy \in G \tag{7.16}$$

Despite the fact that this type of constraint seems straightforward, it comes with certain difficulties in terms of model performance. As the value for M in this model is quite large, it increases the numerical complexity of the model, decreasing its computational performance. To avoid this, the Big M constraint has been changed into an indicator constraint. An indicator constraint, as shown in Equation 7.17 consists of two constraints describing the relation in case the binary value is inactive, whereas the second describes the relation when the binary value is active.

$$\begin{aligned} g_{xy} = 1 &\rightarrow \sum_{f \in F} \sum_{r \in R} \sum_{d \in D} C_{xy(f,r,d)}^{G} \cdot x(f, r, d) \leq L_{limit} + M \\ g_{xy} = 0 &\rightarrow \sum_{f \in F} \sum_{r \in R} \sum_{d \in D} C_{xy(f,r,d)}^{G} \cdot x(f, r, d) \leq L_{limit} \end{aligned} \tag{7.17}$$

7.4. Assumptions

Regarding the design of the linear programming model some assumptions need to be made in order to establish a well founded optimization model. These assumptions deal with uncertainties and reflect them such that they can be applied in a clear manner. With respect to the runway allocation model, two types of assumptions are defined. The first, being the mathematical modeling assumptions which help define information on the activities and parameters used in the linear programming model. The latter helps in clarifying the uncertainties from the operational perspective.

7.4.1. Mathematical Modeling

Concerning the mathematical model constraints which come with the application of linear programming, three assumptions should be made in order to ensure a satisfactory representation of the problem to be analyzed. These assumptions reflect i) proportionality, ii) additivity, and, iii) certainty.

Additivity Assumption (M1)
Every function in the linear programming model is the sum of the individual contributions of the respective flights and/or gridpoints.

Certainty Assumption (M2)
The value assigned to each parameter of the linear programming model is assumed to be a known constant. This constant is obtained from a third-party model or a computational method based on literature.

7.4.2. Operational Modeling

Other than mathematical constraints, several operational modeling constraints are applied to the model to clarify certain decisions that have been made in order to get the model optimize in a correct sense.

Taxi Assumption (O1)
In order to define average taxi times during ground operations at Heathrow estimations are made based on estimated taxi trajectory lengths from Google Earth [20]. The estimation of taxi times is elaborated on in Appendix B. For departure operations it is assumed that the taxiway capacity at Heathrow does not influence the taxi maneuver of the aircraft. That is, the aircraft is assumed to taxi to the assigned runway without disruption. The same yields for arriving aircraft for which it is assumed that upon arriving, the assigned parking stand or gate is available such that no additional delay is added during the taxi in maneuver.

Departure Delay Assumption (O2)
Delay on departure is assigned during taxi by ground or tower control. This delay can be an intermediate hold position clearance during taxi or at a remote holding stand, an extended taxi routing or an extended holding time at the holding point upon departure. In all cases a departure delay is assigned when all engines of a certain aircraft are operating.

Arrival Delay Assumption (O3)
Delay on arrival is assigned in terms of an extended approach trajectory by means of a holding pattern or a delaying vector to extend the initial approach phase as illustrated in Figure 6.5.

Departure Speed Assumption (O4)
Aircraft on the SID are assumed to fly at a constant speed of 230 kt IAS reflecting the average speed over the entire SID trajectory for common aircraft.

Arrival Speed Assumption (O5)
Aircraft on arrival are assumed to fly at a constant restricted speed which is defined in the AIP [41] per approach segment as described in Section 6.1.1.

Aircraft Performance Modeling Restriction (O6)
The aircraft performance parameters used for the calculation of the TFU are based on the Total Energy Model as described by Eurocontrol [16].

Aircraft Sound Exposure Level Contour Modeling Restriction (O7)
The aircraft specific sound exposure level contours are based on the noise computations as being part of the Integrated Noise Model [17].

Best Pareto Optimal Solution Definition (O8)
The Pareto optimal solution that results in the best improvements with respect to the reduction of noise annoyance and fuel consumption compared to a specific reference case is assumed to be the best Pareto optimal solution in a scenario.

7.5. Optimization Process

With the above described objective function and corresponding constraints, the optimization algorithm can be formulated as in Table 7.2. The algorithm provides a clear insight in the input and methodology that is needed to obtained the requested results. The initiation of the LP problem as identified in the first step is a crucial part of the runway allocation process. This step defines the requirements that must be taken into account when finding a optimal solution as in done in the steps after. Once the optimal solution has been found, the optimal vector of decision variables is translated into recognizable matrices as have been used in the preprocessor of the model. Once these matrices have been identified, steps three to five can be initiated to compute the corresponding costs for each selected decision variable. These costs can be summed in order to obtain a general overview of the impact of the optimal solution that has been found.

By knowing the states of the decision variables in the optimal solution vector, a noise exposure grid can be generated. This grid comprises the area defined in Section 5.1 and initially shows green markers at the grid points that are exposed to a L_{DEN} value that is smaller than the predefined exposure boundary. The boundary in this research is set to 55 dB L_{DEN} as research has shown that this number results in a significant amount of awakening during night and will have its impact on human well-being as well [26]. This significance is also illustrated in Figure 2.7. The households at grid points that suffer an overshoot of the predefined L_{DEN} boundary are indicated in red.

Another important feature that comes with the optimal solution vector is the allocation of flights in a certain time domain. The activated decision variables, being the ones with value 1, provide information on the assigned delay and the allocated runway. By having this information, a runway allocation and occupancy scheme is generated showing the runway occupancy of each single runway at the airport. By generating such an allocation and occupancy scheme, an insight can be gained in the utilization of all available runways in the specified time frame. Furthermore, the impact of each flight operation on the other runways can be identified in terms of visualized runway occupancy.

Table 7.2: Algorithm of flexible runway allocation optimization process.

Algorithm Optimization Process
Input: A set of objective costs, decision variables and linear constraints $Ax \diamondsuit b$ with $\diamondsuit = \{\leq, \geq, =\}$. **Output:** An optimal runway allocation solution with visualization of runway occupancy and noise exposure over the time frame to be analyzed. Additionally, the total number of houses exposed to 55 dB L_{DEN} and the total amount of fuel burn and delay should be provided.
1. *Initialize* Set up LP file as in Sections 6.3, 5.4 & 4.4. 2. Solve LP obtaining $\bar{x}_{f,r,d}$, $\forall f \in F$, $\forall r \in R$, $\forall d \in D$ and $\bar{g}_{xy}$, $\forall xy \in G$ 3. Translate optimal solution vector into readable matrices 4. Compute total amount of households exposed to 55 dB L_{DEN} in analyzed time frame. 5. Compute total fuel consumption in analyzed time frame. 6. Compute total assigned delay in analyzed time frame. 7. Return # exposed households, total fuel consumption and total assigned delay. 8. Return grid with visualization of the exposed households. 9. Return runway allocation and occupation scheme visualizing the runway allocation per flight.

8

Flexible Runway Allocation at Heathrow

Now the model's structure and computational methodology has been discussed thoroughly, it is time to apply the added features in Improved Flex to a real life case. As introduced in the previous chapters, London Heathrow is centerpiece in the case study that is being concerned in this research. Nevertheless, the model as it is developed in Improved Flex can be applied to different airports as well. A guideline on the application of Improved Flex to other airports can be found in Appendix E.

Throughout almost the entire day, Heathrow faces a peak period in terms of flight operations. This peak period can be subdivided into peak hours that roughly span from 07:00 a.m. until 10:00 p.m. To analyse the effects of Improved Flex compared to the regular runway alternation strategy that is being used nowadays, Improved Flex is applied to a single peak hour. This peak hour is analyzed in terms of a Pareto front. Section 8.1 introduces this type of analysis. The next step is to create the Pareto front. This is discussed in Section 8.2. After all, Section 8.3 elaborates on the effects in the long run of changing to the Improved Flex strategy in the current ATM system.

8.1. Pareto Optimality

As there are several stakeholders to be concerned in the runway allocation process, it might be impossible to comply to everyone's visions on the ideal strategy of operations. The importance of individual stakeholders can be somehow related to the weight factors α and β which are applied to the respective objectives in the runway allocation optimization problem.

As multiple weight factors can be chosen, the set of optimal solutions for a certain time frame is not limited to only one solution. Moreover, flexible runway allocation can take place based on the relative importance of fuel burn and noise annoyance, respectively. The set of possible solutions to such a scenario can be visualized in a pareto front, showing the impact of the selection of a certain weight factor combination with respect to the sub-objective costs of such a decision. The coming paragraphs introduce the concept of pareto optimality and visualize the pareto front for the time frame to be analyzed.

8.1.1. Pareto Definition

When analyzing the set of possible solutions to a certain problem, one can make some statements regarding the several outcomes to that problem. Moreover, sometimes, one outcome A is at least as good as outcome B for all agents in the problem. However, for some specific agents outcome A is highly preferred over outcome B. It can therefore be stated that outcome A Pareto-dominates outcome B. Having stated that, an outcome X is Pareto optimal if there is no other outcome that Pareto-dominates it [44].

To put this in the perspective of this research an optimal runway allocation solution can be defined Pareto optimal if the optimal runway allocation scheme results in an objective cost for fuel burn and noise annoyance which is not Pareto-dominated by another optimal solution in the same region.

8.1.2. Pareto Front

Having defined the definition of a Pareto optimal solution, a Pareto front is created for a fpeak hour of operations on August 3, 2016. An entire day of operations at Heathrow comprises around 1,300 operations in summer periods compared to 1,200 operations during winter. For this purpose, the coming sections focuss on specific time frames of one hour. By this way the analysis reflects real operations the most as during real operations the actual time of departure or arrival cannot be assured a couple of hours before the actual operation.

The Pareto front has been set-up by applying different weight factors to both objectives in the optimization problem. This is done by using Equation 8.1. With this in mind, 21 scenarios have been set-up in order to obtain a adequate dataset to create a Pareto front. These scenarios are defined with decrement and increment steps of 0.05 for alpha and beta, respectively. The following section discusses Pareto optimality and variations on the optimal solution for the time frame between 10:00 a.m. and 11:00 a.m.

$$\alpha = 1 - \beta \tag{8.1}$$

8.2. Pareto Optimal Peak Hour Operations

To further analyze the impact of certain decisions regarding the importance of the optimization objectives, a peak period of one hour has been selected. This peak period is defined as the time frame between 10:00 a.m. and 11:00 a.m. Within this time frame 73 flights are being operated as can be found in Table 3.1 and Appendix A. The type of operation within this time frame is equally devided, being 36 departures and 37 arrival flights. Since the model enables flights to be delayed slightly in order to generate an optimal sequence and select the optimal runway for operation, some extra flights at the beginning and at the end of the time frame are taken into account which might cause a conflict with the flights within the specified time frame.

8.2.1. Results

With this in mind, the model is initiated to create 21 scenarios in which α and β take different weights. This is done according to Equation 8.1 as described in Section 8.1. Optimization of each scenario leads to a set of objective values for fuel burn and noise annoyance. The outcome of the optimization of all scenarios is shown in Table 8.1.

Table 8.1: Objective values for the Pareto optimal solution set for operations between 10:00 a.m. and 11:00 a.m.

	Scenario					
	1	**3**	**4**	**5**	**9**	**21**
Objective Weight α	1.00	0.90	0.85	0.80	0.60	0.00
Objective Weight β	0.00	0.10	0.15	0.20	0.40	1.00
Fuel Burn (kg x100,000)	1.355	1.362	1.363	1.374	1.379	1.524
Exposed Households (x 1,000)	119.79	53.99	50.64	45.14	39.67	37.93
Total Assigned Delay (min:sec)	78:20	91:00	89:40	93:00	122:20	208:20

As Table 8.1 shows, six Pareto optimal solutions have been found in the set of 21 optimal solutions. These six Pareto optimal solution together form the Pareto front indicating the Pareto dominant solutions in the solution set. The solution set, together with the Pareto front is illustrated in Figure 8.1. This figure provides an overview of the related objective values of each scenario that has been optimized according to a certain set of input parameters. For all scenarios the noise exposure boundary has been set to 55 dB L_{DEN}.

Having defined the Pareto Front as shown in Figure 8.1, enables decision makers to identify the most suitable set of objective weights in which certain requirements are met. To select the best set of objective weights, the Pareto optimal solutions should be compared to a certain reference scenario. This reference scenario is defined as the runway alternation scenario as Heathrow operates nowadays. The runway configuration scheme that belongs to this operation strategy is further explained in Section 3.2. In this strategy four typical runway configurations can occur. For the reference scenario the following configuration is used:

- Departures: RWY 27R

- Arrivals: RWY 27L

This scenario is initiated using Improved Flex with a set of additional constraints. These additional constraints regard the operational availability of certain runways. Moreover, the runway allocation options are being restricted as only one out of the four runway ends is available for departure operations, whereas only one other runway end is available for arrival operations. As a consequence, these additional constraints reduce the number of runway allocation possibilities. In the end, this approach leads to a good representation of the runway allocation as it takes place at Heathrow nowadays.

The outcome of the optimization regarding the runway alternation configuration defines boundary conditions which can be used to identify the most suitable Pareto optimal solution regarding flexible runway allocation. These boundary conditions have been illustrated in Figure 8.1. The boundaries, illustrated in purple and green, show the number of households exposed to 55 dB L_{DEN} and total fuel burn for the defined runway alternation configuration, respectively. This yields to a total of 45,443 exposed households and 155,070 kilograms of burned fuel.

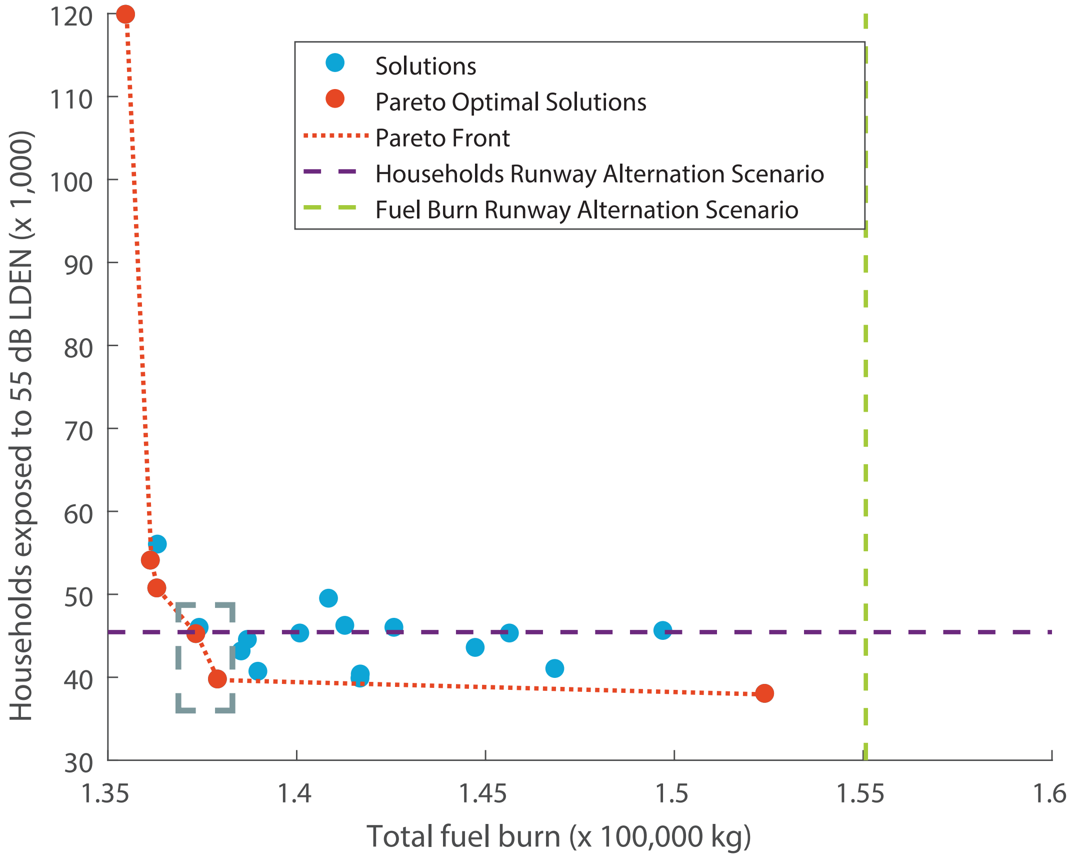

Figure 8.1: Pareto Front for operations between 10:00 a.m. and 11:00 a.m. based on a 55 DENL noise exposure boundary.

With the boundaries defined the most suitable Pareto optimal solution can be found which should be benificial for all stakeholders in the case to be analyzed. Comparing the objective values related to the Pareto optimal solutions in Table 8.1 with the boundaries that have been obtained from the reference scenario, identifies a solution which is benificial with respect to both objectives. The proposed Pareto optimal solution belonging to scenario five provides a 0.7% reduction in exposed households in the specified time frame. A greater contribution has been made with respect to fuel consumption. This is obvious as flexible runway allocation, and thereby releasing more available runways to operate from or to, will have a positive effect on the overall fuel burn in a certain scenario. As a result, the total fuel consumption within the specified time frame is reduced by 11.4%.

As Figure 8.1 indicates, greater contribution can be made with respect to the number of exposed households. However, this has a negative effect on the overall fuel burn. It can be stated that there are two Pareto optimal solutions which can be proposed as final solution in this scenario. These solutions are highlighted by the grey box in Figure 8.1. Nevertheless, for each possible solution, the overall fuel consumption is lower compared to the reference scenario. As a result, each Pareto optimal solution that comes after the one related to scenario five, results in a positive effect with respect to noise annoyance and overall fuel burn in the specified time frame.

Runway Occupation

The allocation of flights to a runway comes with an occupation period in which no other flight operations can be allowed on that specific runway. In order to prevent conflicts during the operation, the optimization model takes care that the number of flights operating at a runway at a specific time is not more than one. As Heathrow contains a independent runway set, assigning a flight to a runway leads to a direct unavailability of the opposite runway end of that same runway. That is, the other parallel runway, for example 09L/27R, will not be affected by a flight operation on RWY 09R/27L. To get a clear insight in this purpose, a runway allocation scheme has been designed. This scheme visualizes the flight operations that take place within the specified time frame. Blue and red colors distinguish departure and arrival flights, respectively. The occupancy of a runway is identified with the yellow color.

Runway occupancy in this case can have two forms. Either a flight operations has just taken place or is about to take place on that specific runway. Or, a flight operation is taking place or about to take place on the opposite runway end and therefore makes the respective runway end unavailable. The runway allocation scheme belonging to the Pareto optimal solution as selected in the above paragraph can be found in Figure 8.2. As the figure shows the number of flights is somewhat equally divided over the 4 runway ends, ensuring the noise emissions resulting from the flight operations are divided over the area around the airport. Doing so, leads to a spreading of the noise events, ensuring a minimization of activated gridpoints that overshoot the noise exposure limit. Another interesting feature that can be obtained from the figure is the fact that the model uses the inter-arrival separation of consecutive arrival aircraft to allow a departure in between. In this way, the available runway capacity is utilized to its maximum, allowing more flights to operate in a certain time frame. Furthermore, the scheme identifies operation banks in east and west directions. That is, the runway configuration switches within the hour a couple of times. This feature can be benificial in terms of fuel burn when multiple aircraft approach or depart from/to the same direction. However, switching direction is only efficient when multiple aircraft are in such a departure or arrival bank. Switching direction based on a single flight operations would lead to an increased runway occupancy as go-around and missed approach procedures must be taken into account. Therefore, a switch in direction for a single flight is rarely seen, unless demand and capacity permit.

Noise Exposure

Having seen the allocation of the flights in the concerned time frame, it is interesting to see the effects with respect to community noise exposure. This is what is done in Figure 8.3. The figure visualizes the analyzed grid as defined in Section 5.1. The green colors identify the gridpoints at which the noise exposure boundary is not exceeded. On the contrary, the gridpoint indicated in red identify the locations at which the noise exposure boundary is overshot. This means that at the households located within these areas will be exposed to a L_{DEN} noise level higher or equal to 55 dB.

The locations being exposed to a noise level that exceeds the predescribed limit show a clear relation with the conventional flight trajectories of a flight. As operations from Heathrow spread over the entire globe, not all aircraft come from or go to the same direction. Their routing is defined by means of a flight plan which is used to assign a certain arrival or departure route to the flight. Nevertheless, the first part of the departure trajectory as well as the last part of the arrival trajectory is the same for each aircraft when concerning a particular runway end. This is explained in Section 6.1. As a result, each aircraft assigned to that runway end, overflies the same area. This supports the fact that all activated gridpoints are roughly located in the extension of the the parallel runway set. Evidently, in combination with the flexibility in runway allocation that is added, the spreading of arrival and departure routes for the flights in the specified time frame is such that noise exposure is limited to the areas located in the extension of the runway centerlines.

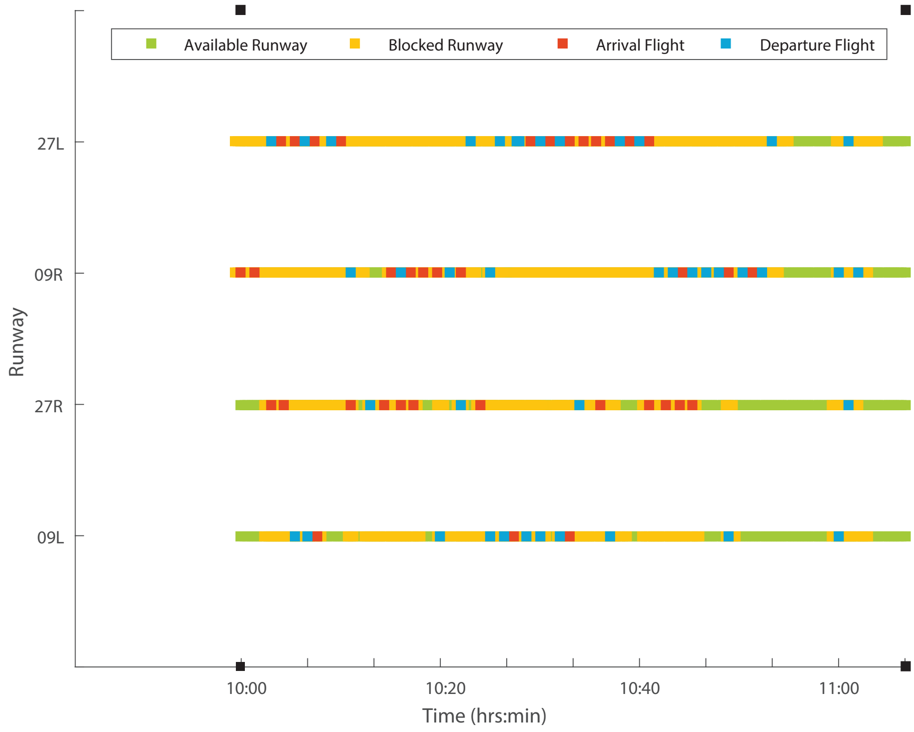

Figure 8.2: Runway allocation and occupancy scheme for flights between 10:00 a.m. and 11:00 a.m. for selected Pareto optimal solution.

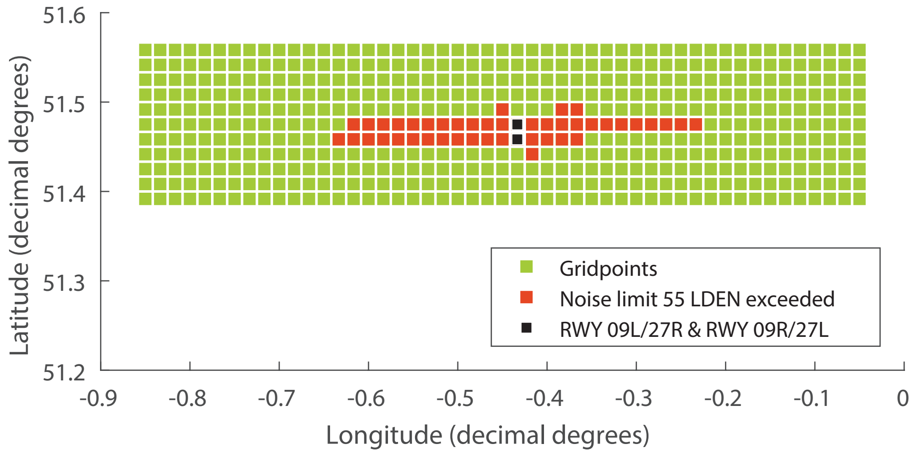

Figure 8.3: Noise exposure grid for flights between 10:00 a.m. and 11:00 a.m. for selected Pareto optimal solution based on a L_{DEN} boundary of 55 dB.

Delay Distribution

The Pareto optimal solution as obtained from scenario five, is subject to a total assigned delay to come to this optimal allocation solution. The optimization model in this scenario has the ability to assign delays in steps of 20 seconds. The maximum delay that can be assigned to a particular flight in this scenario equals 300 seconds. To analyze the assignment of certain delays to flights, Figure 8.4 illustrates the delay distribution of the respective scenario. As the figure shows, two-third of the total number of assigned delays is within one minute. This is because delay is related to fuel burn as described in Section 6.3. The model therefore aims to keep the total assigned delay to a minimum, while by definition it does not minimize for delay right away.

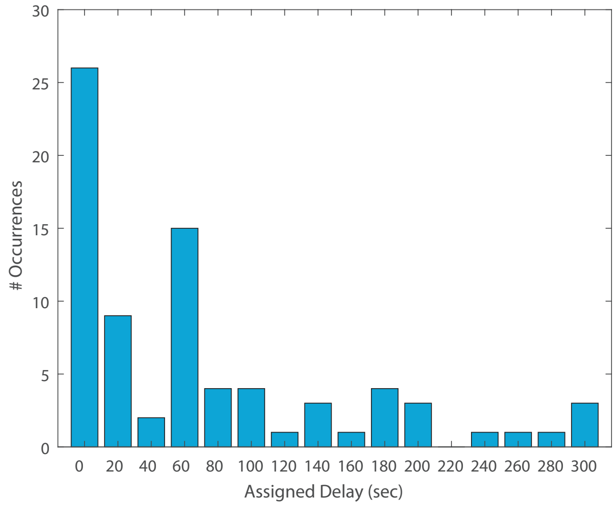

Figure 8.4: Assigned delay distribution of flights between 10:00 a.m. and 11:00 a.m. for selected Pareto optimal solution.

Terminal 4 Operations

Operations from and to Terminal 4 are different from the other terminals. As Terminal 4 is located south of RWY 09R/27L, aircraft need to cross the runway in case they have to operate to or from RWY 09L/27R. As a result, additional separation needs to be implemented in the operations on RWY 09R/27L in order to allow such a runway crossing. Of course, this affects the runway throughput. These types of runway crossing should therefore be avoided. As the model concerns taxi fuel as part of the fuel consumption of the aircraft, it somehow accounts for this effect. Obviously, taxi trajectories to and from RWY 09L/27R are larger compared to those to and from RWY 09R/27L. As a result, less fuel would be consumed in cases aircraft operate from the southern runway. Generally speaking, the model outcome proves this theory in the runway allocation of flights operating to and from Terminal 4. The model scarcely assigns Terminal 4 flights to and from the northern runway. It only does so, in cases runway capacity limits the amount of available options at a certain time.

Environmental Impact

The contributions made with respect to fuel consumption also have their influence on the environmental impact of Heathrow's flight operations. In the last decades, humanity has become more and more aware of the impact it has on the environment. As a result, this environmental awareness has found its way into the aviation industry as well. A major contributor in aviation that affects the degradation of the global climate is the aircraft's engine. Besides the heat and noise it emits, it also emits engine exhaust gasses. The environmental impact that comes with these exhaust gasses can be described by the interaction of these particles and gasses with themselves and the atmosphere which affects the environment to some extent.

As this research does not aim to investigate the effects of decisions on the future climate, the impact analysis on the environment is limited to a quantification of the change in gas emissions that are related to radiative forcing from aviation effects. The most important elements from aviation emissions are defined as [33]:

- HC - Hydrocarbons
- CO - Carbon Monoxide
- NOx - Nitrogen Oxides
- SN - Smoke Number

To analyze the effects of operating according Improved Flex compared to the regular runway alternation strategy, these four engine exhaust gasses are computed for each segment of segment of flight. This done by using engine emission indices as defined by ICAO's Aircraft Engine Emissions Databank [33]. For each unique aircraft type the emission indices are defined and used to compute the related emission quantity. Figure 8.5

visualizes the benifits that have been made with respect to the regular runway alternation strategy. As the figure shows Improved Flex results in a reduction of the emission of all four exhaust gasses. The emissions of these exhaust gasses are reduced by: HC (20.2%), CO (28.7%), NOx (10.7%) and SN (11.4%). The reason behind the difference in these percentages is related to the fact that the emission of exhaust gasses differs per engine type. Most aircraft in Heathrow's demand mixture have different engine types. Even within one aircraft type, multiple engine types are available. For this quantification, it is assumed that all aircraft of the same type, have the same type of engine that provides the aircraft's propulsion.

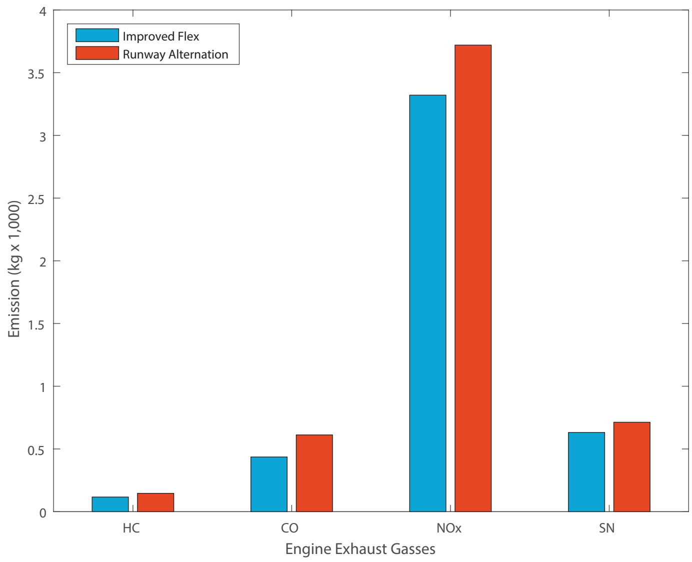

Figure 8.5: Total engine exhaust emissions for flights between 10:00 a.m. and 11:00 a.m. for selected Pareto optimal solution.

8.2.2. Differentiation in Noise Exposure Limit

There are a couple of parameters that influence the model's decision making process regarding finding the optimal solution to a certain runway allocation problem. All of them, obviously, are somehow related to one or both objectives. A typical parameter that has a large influence on the optimization process is the noise exposure boundary. This parameter is defined by a certain L_{DEN} value which is used as a limit in the switch parameter. The purpose of this switch parameter is to activate a certain gridpoint once the predefined limit is overshot within a certain time frame. Once a gridpoint is activated, the related decision variable is taken into account in the optimization with its respective cost value. As a result, the activation of a gridpoint as described in Section 7.3, and thus an overshot in noise exposure at a certain location, will lead to a higher objective cost which must be minimized by the optimization process. Moreover, the activation of gridpoints should be minimized in order to minimize noise annoyance.

Obviously, a lower noise exposure boundary concerns a larger populated area. That is, as aircraft operate in the vicinity of the airport, their level of noise emission is largest near the airport. As aircraft are further away from the airport, their altitude helps to reduce the observed noise on the ground. This, among others, has to deal with engine thrust settings. It can therefore be said that aircraft upon departure will cause a relatively high level of noise emission close to the airport. For arrivals, the exposed region often has a larger span as the glide slope gradient is smaller compared to the climb gradient during departure. As a result, aircraft on departure will reach a higher altitude more fast compared to the descent of an arrival flight. Nevertheless, the noise emission during departure is more extreme compared to an arriving aircraft. The level of noise emission is visualized in aircraft specific noise contours, indicating the areas that are being exposed to a certain noise level. The areas with the highest noise levels are the smallest and are concentrated around the airport. The lower noise level contours are more widely spread around the airport and follow the departure or arrival trajectory to some sense.

To see the impact of changing the noise exposure boundary, the Pareto optimal solution, as obtained from scenario five, is optimized for a set of different noise exposure limits. These limits range from 45 dB until

75 dB L_{DEN}, in steps of five decibels. The impact of changing this major parameter in the optimization process is illustrated in Figure 8.6. The figure consists out of two graphs showing the objective cost values and the total assigned delay, respectively. As the figure shows, the number of exposed households reduces as the noise exposure limit is increased. This can be supported by what is said in the previous paragraph regarding aircraft noise contours. In the 75 dB L_{DEN} noise exposure boundary case, the number of exposed households approaches zero. In this case only a small population is taken into account as the noise contour area is small for this case.

It seems an obvious relation that when a smaller area is taken into account, less people will be exposed to a specific level of noise. As a result, it is apparent that less aircraft are needed to be circumnavigated around densely populated areas, which leads to a reduction in total fuel burn. But this is not the only factor that influences the total fuel consumption. Another important factor that influences the fuel consumption of aircraft is the assigned delay as described in Section 6.3. This factor supports the fact that the total fuel consumption regarding the case in which the noise exposure boundary is set to 60 dB L_{DEN} is slightly higher compared to the 55 dB L_{DEN} case. Namely, the total assigned delay in this case is slightly higher which results in an increase in fuel burn. The reason of this choice lays in the fact that within the transition from 55 dB to 60 dB, the focus on the critical noise-sensitive areas in the extensions of the runway centerlines increases. As a result, aircraft are being directed to a runway which causes less noise annoyance. In this scenario this could lead to a slight increase in fuel consumption as the majority of aircraft has a preferred runway in the opposite direction of which it is being allocated to. The reason of this is the fact that the Pareto optimal weight for β is nonzero.

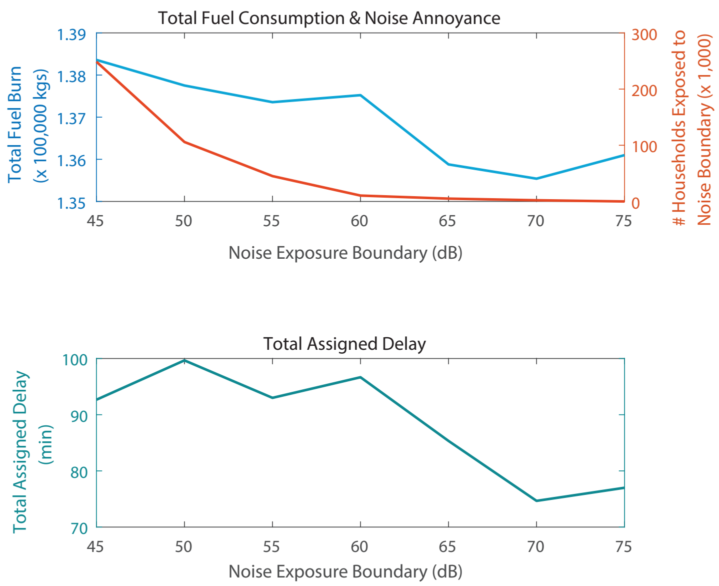

Figure 8.6: Change in total fuel consumption, exposed households and total assigned delay for different noise exposure boundaries.

8.2.3. West Flow Operations

Having a look at Heathrow's annual weather statistics as provided in Appendix F, it is shown that west wind conditions apply throughout almost half of the year. As a result, together with the population distribution as discussed in Section 5.1, it becomes clear that Heathrow currently tries to operate in west configuration whenever possible. In cases wind speeds stay below the specified minimum for tailwind operations, the airport is allowed to operate this preferred runway configuration setting. However, when wind speeds exceed the limit, the airport is forced to operate a configuration which enables headwind operations during the specified time frame.

The analysis in this section provides an insight in Heathrow's operations in case a strong wind condition is active which forces the airport to operate a west configuration. This condition limits the abilities of the flexible runway allocation model in the sense that ODO can not be used. However, the model still tries to optimize for reduced noise annoyance and fuel consumption by concerning all allocation possibilities on the runways 27L and 27R.

Figure 8.7 shows the runway allocation and occupation scheme for all flights between 10:00 a.m. and 11:00 a.m. As the figure illustrates, the flights in this time frame are divided over both runways, making both runways operate in mixed mode. This supports the expected outcome, as in mixed mode operations, the available runway capacity can be used more efficiently. This is done by using the inter-arrival separation time between two consecutive aircraft to let a departure flight take-off on the same runway. This corresponds clearly with what is shown in Figure 8.7.

Concerning the spreading of noise, a clear division with respect to activated gridpoints between the eastern and western side of the airport can be identified. This is because this configuration enables aircraft to depart in western direction only, whereas aircraft land in western direction as well. As a result, arrival aircraft will follow the same common approach path upon arrival, whereas departure aircraft have the ability to fly different departure trajectories. The result of this scenario with respect to the spreading of noise is illustrated in Figure 8.8.

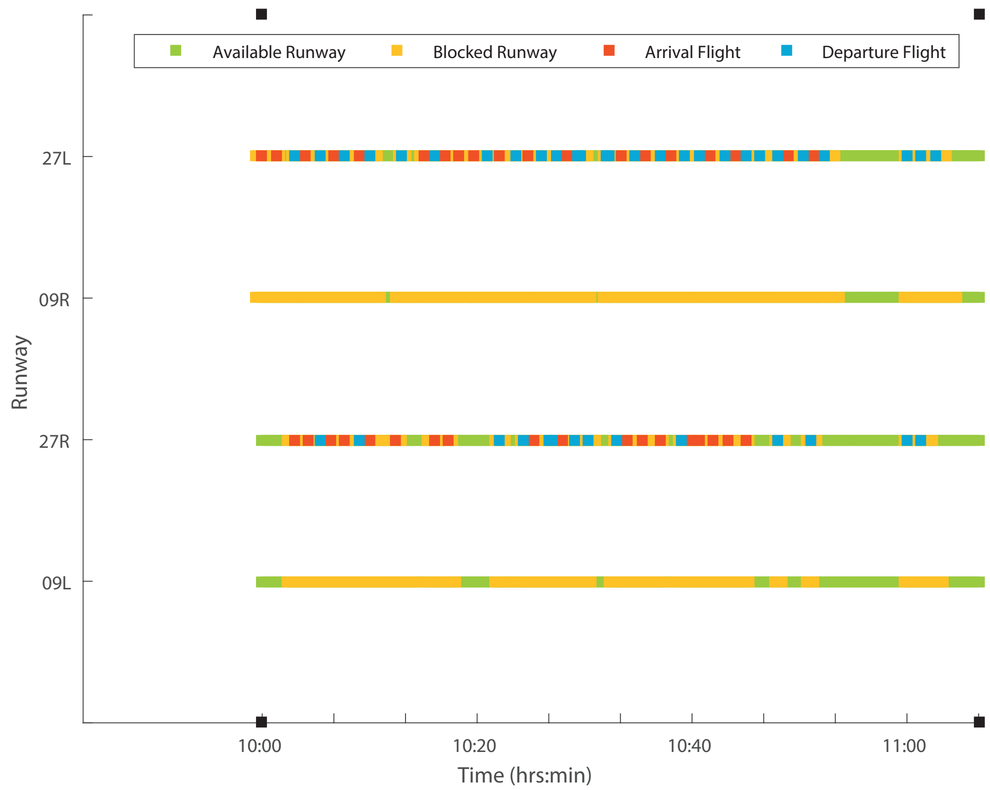

Figure 8.7: Runway allocation and occupation scheme for flexible runway allocation in west configuration between 10:00 a.m. and 11:00 a.m.

An overview of this scenario can be created by analyzing the overall key performance indicators of the model. The implementation of west configuration operation strategy between 10:00 a.m. and 11:00 a.m. results in a total of 150,670 kilograms of consumed fuel together with a total of 39,874 households to be exposed to a minimum of 55 dB L_{DEN} noise dose within this hour. To get to this optimal solution, a total of 100 minutes and 40 seconds of delay is to be assigned. This yields to an average delay slightly above one minute per flight.

The obtained results in this scenario can be compared with the Pareto optimal solution as obtained from Section 8.2.1, in which no restrictions with respect to the availability of runways exists. This comparison shows that being forced to operate in west configuration leads to an increase of 9.7% in total fuel consumption over the hour, whereas the number of exposed households is lower (-11.7%) with respect to the flexible runway allocation scenario without restrictions. However, in case the next available Pareto optimal solution is selected, an increased number of exposed households is found in this comparison.

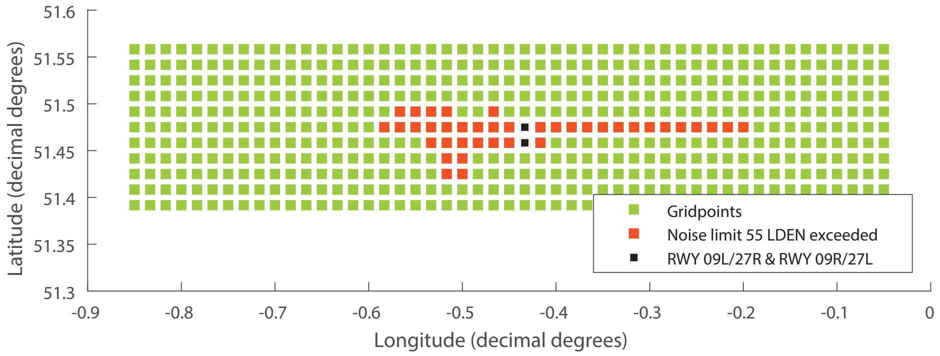

Figure 8.8: Noise exposure grid for flexible runway allocation in west configuration between 10:00 a.m. and 11:00 a.m.

8.2.4. The Cranford Agreement

Looking further into the different runway alternation schemes that apply throughout the year, it is without doubt certain configurations are preferred over others. Several decades ago, an agreement was set up in order to prevent the residents that were living close to the eastern part of the northern runway from extreme noise exposure. This agreement, named after the village of Cranford, prevents departure operations from RWY 09L in East configuration.

Based on the weather analysis as discussed in Appendix F, Heathrow's east configuration is active rougly 20% of the year. This configuration is less preferred as additional regulations regarding noise exposure apply. Ceasing departure operations from RWY 09L would indeed lead to less noise exposure over the village of Cranford. However, as multiple communities have been stating the last years, the Cranford Agreement has negative effects on other populated areas in the vicinity of Heathrow. That is, these areas will be exposed to noise for a longer time as no runway alternation can be applied because of the agreement.

To see the effects of applying flexible runway allocation with respect to the limited runway alternation strategy as is being used now, two scenarios have been set up. The first scenario relates to flexible runway allocation enabling aircraft to operate from or to runways 09L and 09R in either single or mixed mode. The second scenario limits the number options in terms of available runways for departure and arrival operations. That is, only arrival operations are allowed on RWY 09L, whereas RWY 09R can be used for both departures and arrivals.

Figure 8.9 illustrates the runway allocation and occupation scheme according to the first scenario. As the figure clearly shows both runways are operated in mixed mode in order to efficiently use the available capacity on the runways. This scenario would lead to a total fuel consumption of 149,510 kilograms and 46,794 households being exposed to a minimum of 55 dB L_{DEN} noise dose between 10:00 a.m. and 11:00 a.m. In this scenario a total of 98 minutes and 20 seconds of delay has been assigned to the flights in this time frame. This leads to an average delay of less than 1.5 minutes per flight, which is far less than the regular delay at the airport nowadays. However, current delays at Heathrow are result of a multitude of other factors such as taxiway as well as airspace capacity which are not taken into account in this research.

To illustrate the spreading of noise exposure over the entire grid, Figure 8.10 indicates the gridpoints at which the noise limit of 55 dB L_{DEN} is exceeded. The figure shows a clear relation to the SDO strategy that is being applied in this scenario. The activated gridpoints on the western side of the airport are centrated around the centerlines of runways 09L and 09R, whereas the activated gridpoints east of the airport are more spread. This is because after departure aircraft are to follow different departure trajectories, whereas on arrival they follow the same common approach path in the final approach phase. As a result noise emissions will be more spread on the eastern side of the airport.

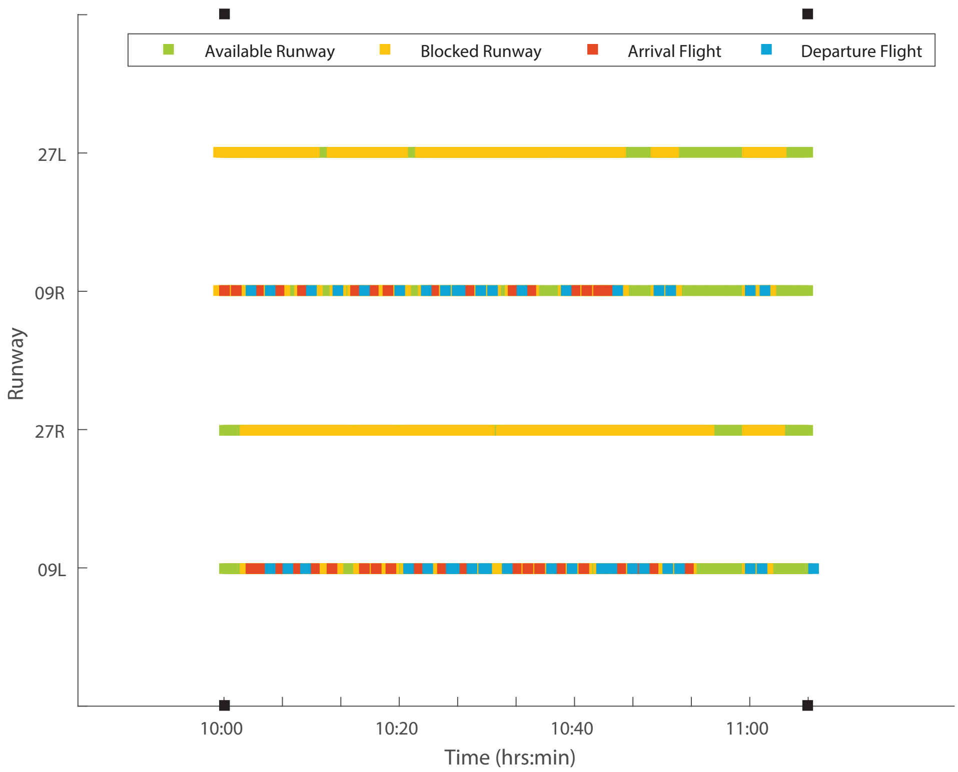

Figure 8.9: Runway allocation and occupation scheme for flexible runway allocation in east configuration between 10:00 a.m. and 11:00 a.m.

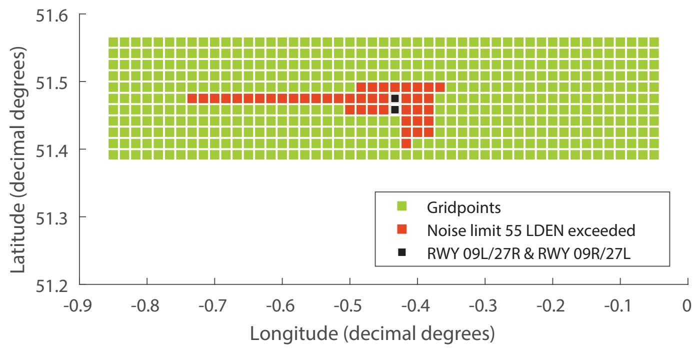

Figure 8.10: Noise exposure grid for flexible runway allocation in east configuration between 10:00 a.m. and 11:00 a.m.

The obtained results in this scenario can be compared with the Pareto optimal solution as obtained from Section 8.2.1, in which no restrictions with respect to the availability of runways exists. This comparison shows that being forced to operate in east configuration leads to an increase of 8.8% in total fuel consumption over the hour, whereas the number of exposed households is increased by 3.7% with respect to the flexible runway allocation scenario without restrictions.

Putting the focus on the second scenario adds an additional constraint with respect to the previous one. As this scenario concerns the residents of Cranford, it restricts the airport from operating departures on RWY 09L. As a result, all departure operations during east configuration will have to depart from RWY 09R. It seems likely that because of this, the level of efficiency in departure and arrival operations is limited. This is what is reflected in the key performance indicators of this research as well. The scenario based on the runway alternation strategy regarding the Cranford Agreement results in the following outcomes with respect to the model's objectives. In the first place, the total amount of fuel burn is calculated to be 150,300 kilograms. This is 9.4% higher compared to the first scenario. Concerning noise annoyance, an increase of 7,343 exposed households results in a total of 52,483 (+16.3%) households to be exposed to a minimum of 55 dB L_{DEN} noise dose between 10 a.m. and 11 a.m. The major cause of this increase lies within the centration of departure flights out of RWY 09R. As these departures are now centrated on one runway only, the likelihood of an increased noise exposure due to this fact is much higher than the effects that take place on the arrival side. This is because departure operations are found to generate much more noise emission with respect to arriving aircraft. To summarize, the runway allocation and occupation scheme together with the spreading of noise exposure in the grid to be analyzed are shown in Figures 8.11 and 8.12, respectively.

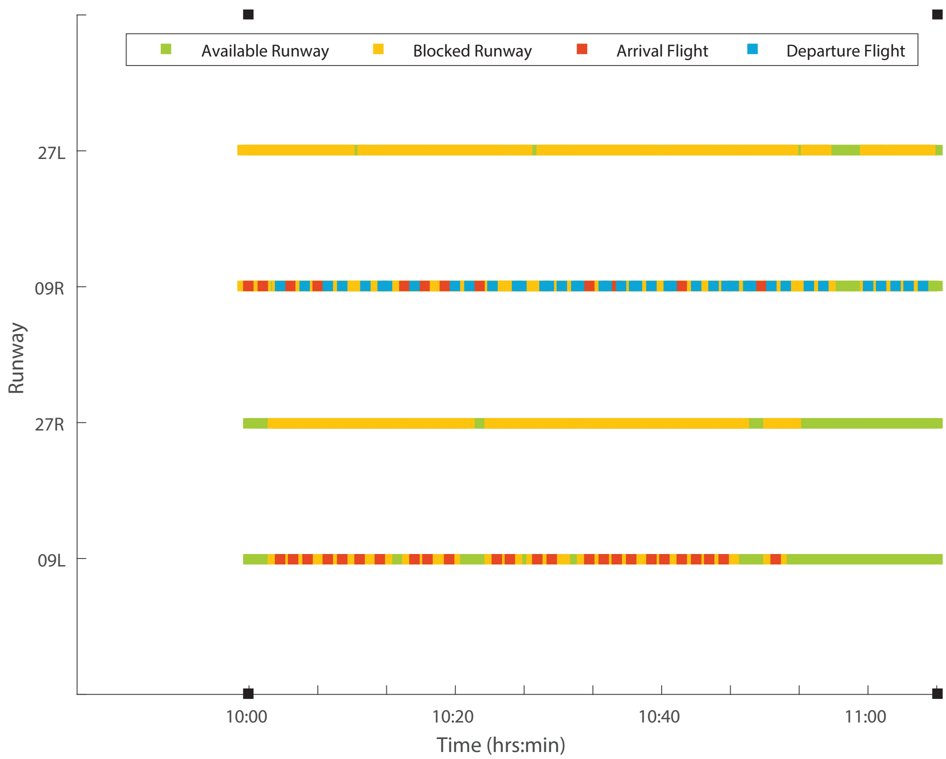

Figure 8.11: Runway allocation and occupation scheme for flexible runway allocation in east configuration between 10:00 a.m. and 11:00 a.m., including the Cranford Agreement operational restriction.

8.3. Expected Annual Savings

Based on the results obtained in Section 8.2, an expected annual savings projection can be made. To do this in a proper way, some additional scenarios need to be taken into account. As the previous section has discussed the effects of Improved Flex on flight operations during one of Heathrow's multitude of peak hours on a regular day, also evening and night operations must be taken into account. This should be done because for these periods in time, an adapted noise metric is used in order to quantify the impact of late night operations on the noise exposure in the region. This quantification is elaborated on in Section 5.3.

In the same way as performed in the previous section, two flexible runway allocation scenarios have been set up to analyze the effects in terms of fuel consumption and reduced noise annoyance for the time frames between 07:00 p.m. - 08:00 p.m. and 10:00 p.m. - 11:00 p.m., respectively. This is done by using the Pareto op-

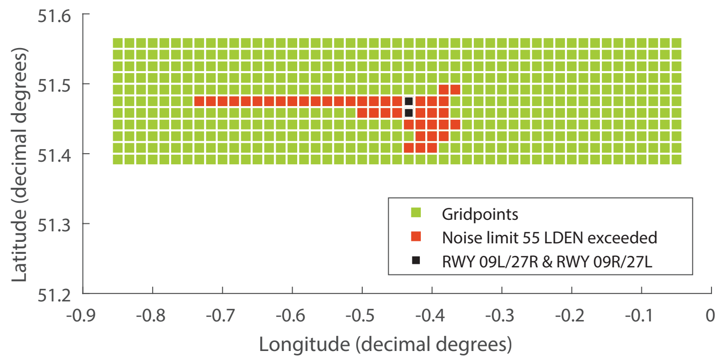

Figure 8.12: Noise exposure grid for flexible runway allocation in east configuration between 10:00 a.m. and 11:00 a.m, including the Cranford Agreement operational restriction.

timal objective weight set that has been obtained in Section 8.2. The results of these scenarios are compared to their respective runway alternation scenario. The improvements made by the application of Improved Flex have been summarized in Table 8.2.

Table 8.2: Summary of savings obtained from Improved Flex compared to a regular runway alternation strategy in calm weather conditions.

	Fuel Consumption Saving (kg | %)		
Time frame	*Full Flex*	*East Flex*	*West Flex*
10:00 a.m. - 11:00 a.m.	17,670 | 11.4	790 | 0.5	4,950 | 3.2
07:00 p.m. - 08:00 p.m	32,580 | 19.2	1,370 | 1.0	4,530 | 2.8
10:00 p.m. - 11:00 p.m.	20,810 | 14.9	1,100 | 0.9	4,680 | 3.4

In order to quantify the estimated savings with respect to fuel consumption, a full day of operations needs to be used as a basis of this estimation. To do so, three different scenarios, as have been previously discussed in Table 8.2, are taken into account. The first scenario represents a regular peak hour during daytime, as the majority of the operation hours at Heathrow do so. Secondly, the scenario defining flights between 07:00 p.m. and 08:00 p.m. represents Heathrow's evening hour operations, which have an increased noise impact on the Day-Evening-Night Average Level. The last scenario represents Heathrow's night operations as take place between 06:00 a.m. - 07:00 a.m. and 10:00 p.m. - 11:00 p.m. on a daily basis. As Figure 3.2 illustrates, Heathrow regularly operates 18 hours throughout a day. Besides these operation hours, the airport is open for emergency operations only. Furthermore, the airport allows a limited number of night arrivals between 05:00 a.m. - 06:00 a.m. Based on the operating hours, the percentages with respect to day (66.7%), evening (16.7%) and night (16.7%) operations can be defined. As comes clear of this division, two-third of the daily operating hours at Heathrow span within daytime operating hours. On the contrary, one-third of the operating hours come with an increased impact on the Day-Evening-Night Average Level.

These noise penalties influence the model's final solution to large extent in cases β is nonzero. This also has its effects on the fuel consumption of flights to be concerned by the model. Therefore the computed percentages for day, evening and night operations are used to create an overall indicator for the reduction of exposed households and fuel consumption on a daily basis. This indicator is then used to project an annual estimated saving with respect to noise annoyance and fuel consumption.

Having defined the overall savings with respect to fuel consumption as is shown in Table 8.2, the annual savings can be predicted as a function of these values. To do so, a detailed weather analysis should be performed in order to establish representative percentages on the occurance of certain weather conditions at Heathrow. A summary of this weather analysis can be found in Appendix F. From this analysis it is found that 36% of the year, Heathrow faces light to moderate wind conditions which result in the ability to operate the runway set in both directions. This situation is referred to as $\Delta_{FullFlex}$ in Equation 8.2. During the majority of days throughout the year (44.8%), Heathrow has to deal with predominant winds from the west, forcing the airport to operate according to its west configuration. The less favorable runway configuration, being the east configuration, is operated 19.2% of the year, during predominant winds from the east. The predominant west and east configurations are referred to as $\Delta_{WestFlex}$ and $\Delta_{EastFlex}$ in Equation 8.2.

$$\text{Fuel Savings} = 365 \cdot \left(44.8\% \cdot \Delta^{fuel}_{WestFlex} + 19.2\% \cdot \Delta^{fuel}_{EastFlex} + 36.0\% \cdot \Delta^{fuel}_{FullFlex}\right) \tag{8.2}$$

Based on Equation 8.2 an estimation on the annual savings with respect to fuel consumption can be made. Taking into account the percentages discussed in this section, the estimation consists of three combined scenarios reflecting the three types of meteorologically dominated runway configuration settings. Using the estimated values, Equation 8.2 defines an expected annual saving of 60,746.4 tonnes of fuel. Using the Jet-A fuel price of 64.5 \$/bbl [45], the expected annual fuel consumption saving would lead to an economic benefit of over 34 million U.S. dollars. The expect annual saving in terms of kilograms burned fuel will also have its benefits to the environmental impact of Heathrow flight operations.

Regarding annual savings in terms of exposed households, such an equation is much more complex to establish. This is because of the fact that a reduction in number of exposed households can be result of active gridpoints that differ from the reference case. Therefore, exposed households throughout the day can not be easily summed up to create an overall picture. Nevertheless, the Pareto optimal objective weights are selected such, that in each scenario the number of exposed households is reduced. It can therefore be said that the implementation of Improved Flex would lead to a reduction in the number of exposed households throughout the day and year.

9
Discussion

Having analyzed the results that come from Improved Flex, the contributions made in this research are discussed in this chapter. These improvements can be divided in two types. The first, concerning the improvements with respect to the research objectives, whereas the second relates to the constraints in the optimization model. Both types of improvements are discussed in Sections 9.1 and 9.2, respectively. After the significant improvements are quantified and the research question is answered, the application of the model is discussed in terms of the possible expansion of London Heathrow in the near future. This topic is one of high interest within the United Kingdom nowadays and is elaborated on in Section 9.3. This chapter concludes with a verification and validation of Improved Flex in Sections 9.4 and 9.5, respectively.

9.1. Optimization Objectives

Besides the effects of the improvements made with respect to the constraints of the optimization model, the refinement regarding the objectives in the model can be quantified as well. This section elaborates on the effects that come as a consequence of improving the computation strategy behind the objectives and their related cost coefficients. That is, the improvements with respect to total fuel burn computation as well as the noise emission computation are being analyzed in the following paragraphs. This section concludes with a short analysis on the environmental impact of decisions made in this research. Doing so, the scope of this research touches upon a subject which has become a major factor in the aviation industry, and, plays an important role in the well-being of humanity and nature on Earth.

Fuel Burn Modeling

The fuel burn computation method as introduced by Delsen [11] in Standard Flex allows to compute fuel consumption over an approach or departure segment for a flight with a specific delay. However, a major downside of this methodology is the generalization of aircraft that are being operated at the airport to be analyzed. The Standard Flex fuel burn methodology focuses on two aircraft in general. These aircraft types, being the Boeing 737-800 and the Boeing 777-200ER, are used as reference aircraft to compute fuel burn profiles based on ICAO WTC categorization. That is, this methodology generalizes all aircraft grouped as Heavy to be equal in terms of fuel consumption. The same yields for Medium and Light. In the long run, this generalization can lead to a major flaw in the estimation of fuel burn within the model.

To improve the methodology used in Standard Flex, Improved Flex enables a computational method for fuel consumption which is unique for each aircraft type that is being operated at the airport to be analyzed. In brief, this leads to an aircraft specific fuel burn profile which matches reality far more compared to the generalized method in Standard Flex. Evidence of this is shown in Figure 9.1 showing the relative difference in fuel consumption on a hourly basis between Improved Flex and Standard Flex given an average assigned delay of two minutes. As this figure indicates, Standard Flex shows an average daily overshoot of 4.24%, 3.78%, 4.24% and 3.80% for runways 09L, 27R, 09R and 27L, respectively. This shows the importance of the modification that is being made as part of this research.

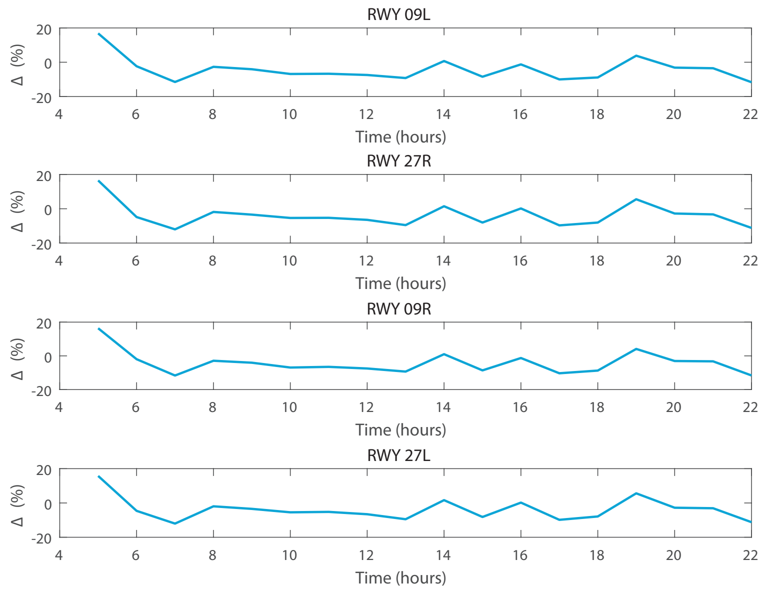

Figure 9.1: Relative difference in fuel consumption estimation between Improved Flex and Standard Flex based on a daily schedule comprising 1,300 operations.

With this in mind, the deviations as identified in Figure 9.1 can be quantified. By taking the average overshoot over all runways, the impact in terms of fuel weight counts up to 135 tonnes on a daily basis. Despite the fact that this leads to an average overshoot of just over $60 per flight, the difference in overall fuel consumption on a yearly basis reflects a number that is more significant. Therefore, flight specific fuel burn modeling is a worthwhile contribution that is made to the model. Besides the economic impact, there is also an effect on environmental impact as this depends on fuel consumption.

As Standard Flex only concerns two aircraft types, it will have its consequences in the estimation of engine exhaust emissions. An overview of the differences between both models has been illustrated in Figure 9.2. For nitrogen oxides the estimated emittance is higher in Improved Flex. This is a result of the enhancements made to the emission index database used in both researches. In Improved Flex this database contains emission indices for all unique aircraft and thereby improves the level of accuracy of the estimated emittance values per flight. As the emission indices of nitrogen oxides are relatively low for the reference aircraft used in Standard Flex, the estimated values in Improved Flex are remarkably higher. As a result, when concerning an increased amount of aircraft types, it is obvious this would lead to an increase in the overall indicator of the engine exhaust type.

Noise Annoyance Modeling

Considering the estimation of noise emission values in Standard Flex shows an equal approach compared to the estimation of fuel consumption. The totality of operations is analyzed by the use of a single reference aircraft. This reference aircraft is the Boeing 737-800. The noise profile of this aircraft is given an additional penalty when a certain aircraft is categorized as Heavy according to ICAO WTC [29]. However, this generalization has its impact in terms of accuracy. As noise emission is of high importance in this model, it is important to model this objective as detailed as possible in order to obtain representable results.

When comparing Standard Flex and Improved Flex in terms of noise emission modeling, some interesting facts arise. As the majority of aircraft in the wide body category as well as in the narrow body category differ to large extent with respect to design age, their impact on noise exposure can differ extensively. Because of this, a generalization of aircraft as in done in Standard Flex can have a large impact on noise exposure. As this manner can influence the estimation of noise emission profoundly, this could lead to improper activation or inactivation of gridpoints in the optimization process. This could lead to a misleading interpretation of the actual case. Besides, an improper estimation of noise contours could lead to a deceptive number of awaken-

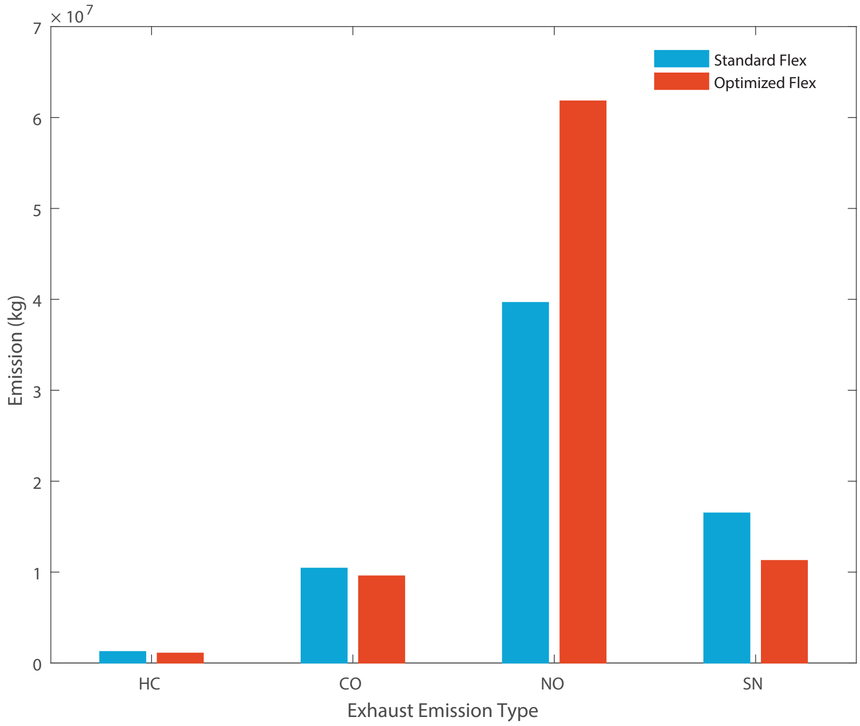

Figure 9.2: Relative difference in engine exhaust emissions estimation between Improved Flex and Standard Flex based on a daily schedule comprising 1,300 operations.

ings during evening and night operations.

Examples of the differentiation in terms of single event noise levels for the Boeing 777-300ER and the Airbus A380 are illustrated in Figures 9.3 and 9.4, respectively. These two aircraft are considered the same in Standard Flex, while both figures show a clear variance in noise profiles for both departure and arrival operations. Moreover, both figures identify gridpoints at which noise emission is neglected where it should not, or vice versa. This has to deal with the fact that the SEL noise contour of a Boeing 737-800, despite the fact of the penalty factor that is applied, has a different shape compared to that of a Boeing 777-300ER or Airbus A380. As a result, certain gridpoints are not taken into account in the optimization of a specific flight, while it actually should. This difference is related to the design generation of the aircraft as well as its size. As Figure 9.4 shows, there are even some gridpoints which reflect positive SEL values in Standard Flex, whereas in Improved Flex it appears that these gridpoints are not exposed to noise at all. These gridpoints, indicated with crosses in the figure, are not exposed to noise for this specific flight, thanks to the noise mitigation techniques that have been applied in the design of the Airbus A380.

Besides the significant impact of a single B777-300ER or Airbus A380 operation in terms of noise modeling, this impact only becomes larger for increasing amounts of such operations on a daily basis. As the flight schedule, as discussed in Section 3.3, shows, the number of A380 and B77W operations is significant throughout the entire day. Together with the identified difference in noise emission of these aircraft, this could have a major influence in the activation of gridpoints in the optimization process as well as on the number of awakenings and amount of annoyed residents according to Figure 2.7. This example, therefore shows the importance of aircraft specific noise modeling to be implemented as it is in Improved Flex. Besides this example, multiple other aircraft can be analyzed such, resulting in a large divergence of reality when considering the relatively old Boeing 747-400 and the next generation Airbus A350 XWB and Boeing 787 Dreamliner.

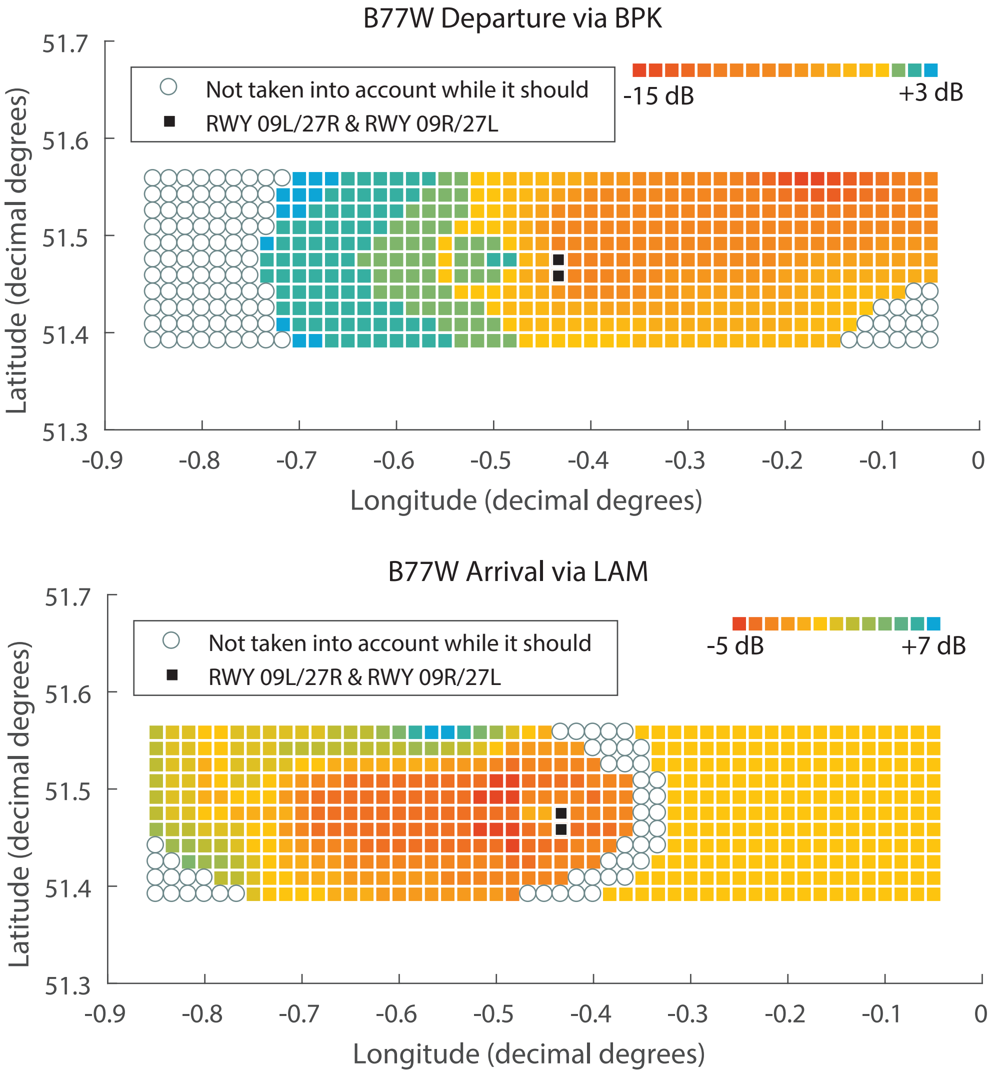

Figure 9.3: Relative difference in SEL between Improved Flex and Standard Flex for B77W.

9.2. Optimization Constraints

Heathrow's daily operations, as it is being performed nowadays, is restricted to the runway alternation scheme that has been set-up in cooperation with surrounding residents and the UK Government. This alternation scheme defines a strict way of operation concerning the configuration of the airport during normal weather conditions. The scheme simply divides the day in two halves, starting at 07:00 a.m. to 03:00 p.m. and the second halve being from 03:00 p.m. until the last departure of the day. At 03:00 p.m., the airport switches operations between the northern runway and the southern in order to equally divide noise emission over the populated area in the vicinity of the airport. However, this strict operational strategy limits operations from being fuel and noise efficient. It might even be considered that this strategy is not the most suitable for all stakeholders in this case.

For the most part of the day the most efficient way of operation would be to utilize both runways into one direction only. However, as the airport contains an independent runway set, both runways can be utilized in different directions with respect to each other. This is what is clearly shown in the results discussed in Section 8.2. To further emphasize on the differences between flexible runway allocation as performed in Standard Flex and Improved Flex, the approach in computing separation minima must be discussed.

RECAT-EU versus ICAO WTC Separation Minima

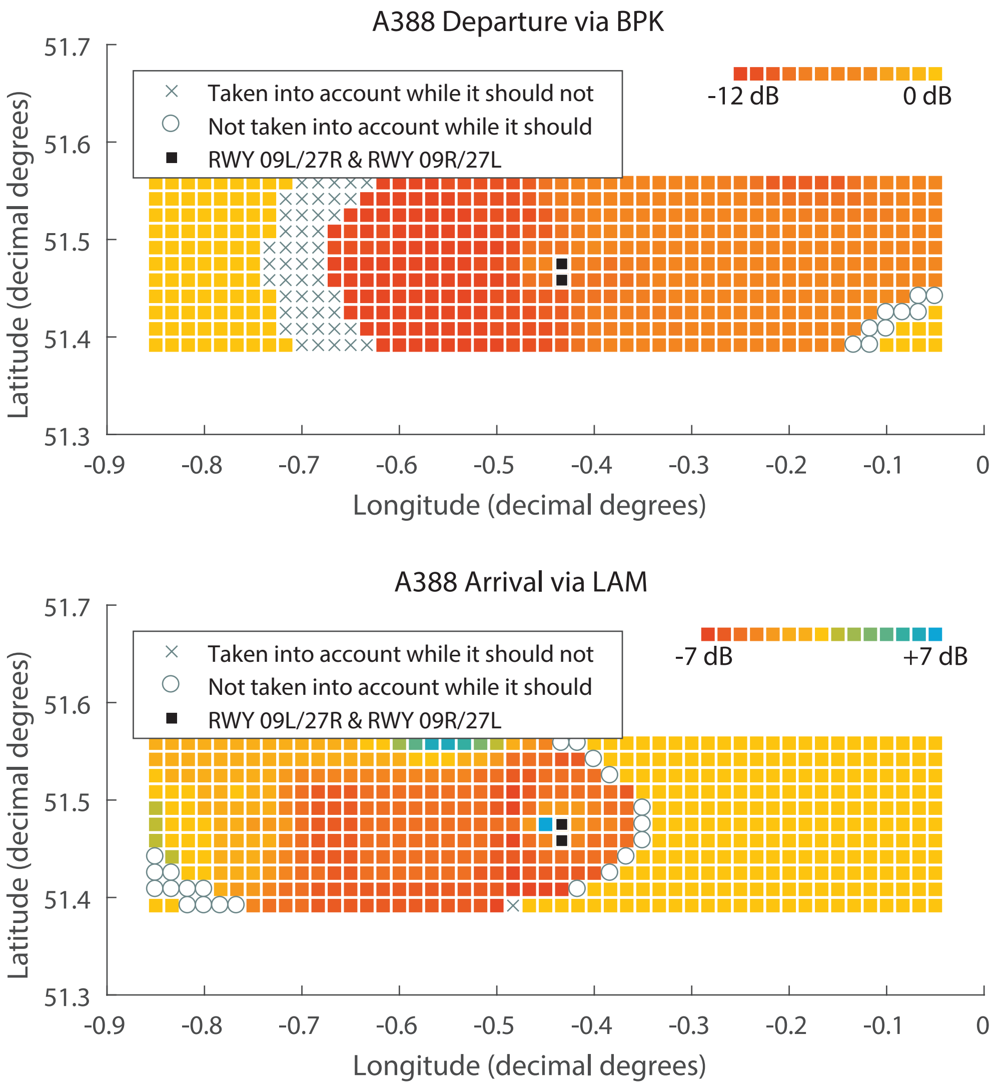

Figure 9.4: Relative difference in SEL between Improved Flex and Standard Flex for A388.

Introduced by Eurocontrol [46], a new strategy to define pairwise separation minima between consecutive aircraft has been designed. This strategy, known as RECAT-EU, is the successor of ICAO WTC which has been used for several years. The major difference between these two methodologies is the amount of available categories and the indicators that define these categories. In the first place, ICAO WTC bases its categorization on the MTOW of an aircraft only, whereas RECAT-EU also concerns wingspan as an important factor to contribute to wake turbulence generation. Appendix D provides a clear insight in the different categorization methods of both strategies.

As becomes clear of this research, the differentiation in aircraft characteristics enables a new way of categorizing aircraft, and, probably will lead to beneficial situations with respect to runway capacity. A comparitive analysis as is performed in this paragraph assesses the essential qualities of both methods.

In the first place, an interesting aspect to analyze is the difference in separation time between two consecutive aircraft. This feature, will have a leading role in the selection of the most preferable method to use. As aircraft, in the RECAT-EU method, are categorized based on multiple characteristics, it can be stated that the categorization of aircraft by this method is more precise. As a result, aircraft that match with respect to one characteristic can still be categorized differently based on the second characteristic. The ICAO WTC method categorizes aircraft based on one characteristic only, nonetheless this characteristic is also used in the RECAT-

EU method.

In order to visualize the differences in terms of separation distance and time between two consecutive aircraft, six types of aircraft are being analyzed. These aircraft are of type Dassault Falcon 10 (FA10), Embraer 190 (E190), Boeing 737-800 (B738), Boeing 757-200 (B752), Airbus A350-900 (A359) and Airbus A380-800 (A388). These aircraft are being categorized as Light, Lower Medium, Upper Medium, Lower Heavy, Upper Heavy and Super Heavy, according to RECAT-EU categorization, respectively. Based on the traditional ICAO WTC categorization, these aircraft are categorized as Light, Medium, Medium, Medium, Heavy and Super, repectively.

Tables 9.1 and 9.2 provide an insight in the differences in distance-based and time-based separation between the two methodologies. As the tables show, the RECAT-EU values, with respect to distance- and time-based separation, are in most cases equal or smaller than the corresponding values for the ICAO WTC method. This means that by providing a more detailed categorization structure, aircraft can be more accurately categorized, resulting in a more suitable time-based separation between consecutive aircraft, which can improve the capacity of a runway.

Table 9.1: Differences in distance-based arrival separation (nm) between RECAT-EU and ICAO WTC methods.

	Follower					
Leader	*Super Heavy*	*Upper Heavy*	*Lower Heavy*	*Upper Medium*	*Lower Medium*	*Light*
Super Heavy	+0.5	-2	-1	-2	-1	0
Upper Heavy	0	-1	0	-1	0	+1
Lower Heavy	0	-1	-1	-2	-1	0
Upper Medium	0	0	0	0	0	0
Lower Medium	0	0	0	0	0	-1
Light	0	0	0	0	0	+0.5

Table 9.2: Differences in time-based departure separation (s) between RECAT-EU and ICAO WTC methods.

	Follower					
Leader	*Super Heavy*	*Upper Heavy*	*Lower Heavy*	*Upper Medium*	*Lower Medium*	*Light*
Super Heavy	0	-20	0	-40	-20	0
Upper Heavy	0	0	0	-20	0	+20
Lower Heavy	0	0	0	-40	-20	0
Upper Medium	0	0	0	0	0	0
Lower Medium	0	0	0	0	0	-20
Light	0	0	0	0	0	+20

To further analyze the theoretical impact of both methods, a simple case study can be applied. This case study comprises out of a set of 25 arrival aircraft. The categorization of these aircraft is based on a uniform distribution. By applying a distribution that has a constant probability, the chance of occurance of each category is equal. As a result a set of 25 consecutive arrival aircraft is being categorized according to both RECAT-EU and the related ICAO WTC. To quantify the impact of the categorization method, the total operation time, being the sum of all time-based separation values between all consecutive aircraft, is summed. The results of this case study, comprising out of 25 runs, is shown in Figure 9.5. As obtained from this figure, the average difference between RECAT-EU and ICAO WTC methods equals +8.8%. According to Eurocontrol [46], and supported by the outcome of this case study, the difference typically lies between +5 to +10%, respectively.

9.3. Heathrow's Additional Runway

During 2016, the possible expansion of Heathrow has been centerpiece of nationwide discussions concerning noise-related issues. The essence of these discussions is based on the fact that the construction of an additional third runway at Heathrow would lead to a drastic increase in noise exposure. The answer to this question is obvious. However, from the Government point of view, a third runway at Heathrow would lead to an improved position of the airport in the global aviation sector.

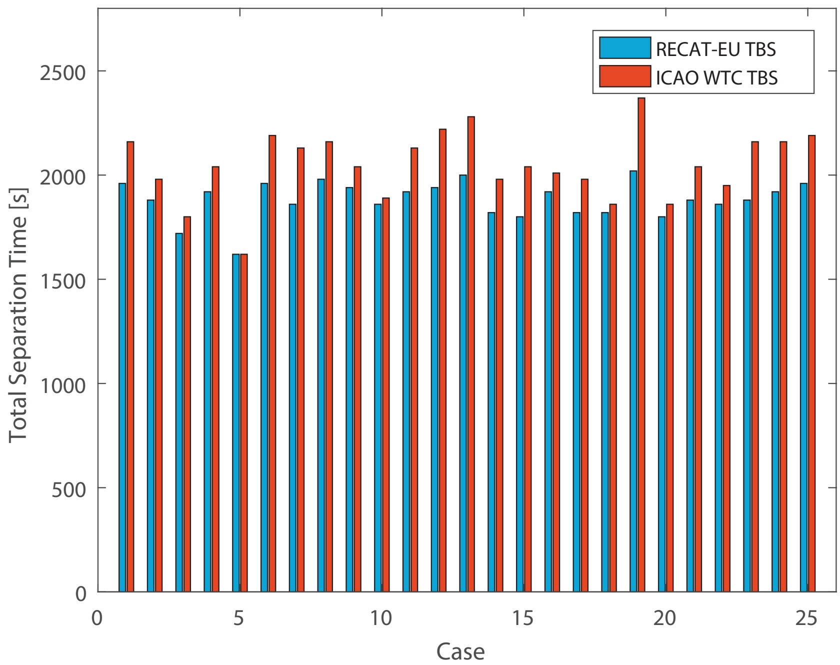

Figure 9.5: Results of a case study concerning the total separation time between a set of consecutive aircraft for RECAT-EU (blue) and ICAO WTC (red) methodologies.

Despite the fact that an increase in capacity would result in an increase in flight operations which can generate revenue for the airport as well as the country by itself, it could harm the health of London's citizens drastically. According to Figure 2.7, besides the increase in pollutions, increased operations would also result in a rise in number of awakenings during evening and night, as well as increased annoyance throughout the entire day.

The addition of the new runway therefore has a multitude of downsides and advantages. The final decision that must be made will be one of ethical and political level. However, as the results from this research have shown, the addition of a new runway at Heathrow would enable several options related to noise reduction when allowing flexible runway allocation to be part of the operational ATM system. In this way, the impact of additional flights at Heathrow can be minimized with respect to the model's objectives.

9.4. Verification

The verification of Improved Flex comprises the analysis on the behaviour of the model. This behaviour is tested against the expected outcome that should represent a result that is both reasonable as well as feasible. In the first place, the verification of Standard Flex is based on the research as performed by Delsen [11]. All modifications as well as additions to this model are verified separately in order to ensure reasonable results. In the end, the outcome of each optimization scenario is checked on feasibility and adherence to a multitude of constraints. Section 8.2 provides an insight in the model's behaviour with reference to several operational constraints that are simulated.

The separation minima between consecutive aircraft in the approach or departure sequence are tested by means of analysis of the optimization model's outcome. An extract of this can be found in Table 9.3 concerning the pairwise separation minima of three consecutive aircraft pairs. These pairs are chosen to illustrate the differences in RECAT-EU categorization and operation type on the related separation minima. As the table shows, all separation minima are met, which proves the model's verification in terms of separation minima.

Table 9.3: Verification of applied wake vortex separation distance between consecutive flights (α = 1.0, delay max= 3 minutes and L_{DEN} threshold= 55 dB).

	Flight Pairs		
	BA737 - AA142	*BA465 - CX254*	*CX254 - BA873*
Leader (Type/RECAT-EU/Ops/RWY)	A320 / UM / A / 27R	A319 / UM / A / 27R	B77W / UH / D / 09L
Follower (Type/RECAT-EU/Ops/RWY)	B772 / UH / A / 27R	B77W / UH / D / 09L	A320 / UM / A /09L
Minimum Separation (s)	60	60	60
Actual Assigned Separation (s)	80	60	120

9.5. Validation

The validation of this model is performed in two stages. The first stage concerns the validity of the orginal model (Standard Flex) as developed by Delsen [11]. Standard Flex is used as a basis of the model which comes out of this research, to be named Improved Flex. As Standard Flex has been validated by the use of official measurement locations in the vicinity of Amsterdam Airport Schiphol, the model was tested to have a reasonable level of validity [11]. Using this statement, the fundaments of Improved Flex are assumed to have the same level of validity.

As Improved Flex has some additional features with respect to the original model, these new features have to be tested for validity as well. To do so, early morning operations at Heathrow are analyzed. As the data in this research is limited in terms of actual measurement data, the model is tested for the time frame specifying early morning operations between 05:00 a.m. and 06:00 a.m. As this time frame is during the night, aircraft noise events are weighted more extreme compared to day operations as described in Section 5.3. Therefore, the limited number of arrival operations in the specified time frame is expected to land in east direction, assuming the weather conditions allow this. This expected scenario is what is obtained from the actual ADS-B data from Flightradar24 [19] on a regular day of operations.

Table 9.4 indicates the runway allocation of all 13 arrival flights that are scheduled between 05:00 a.m. and 06:00 a.m for the actual case as well as the simulated case. The parameter settings in the simulated case are set such that full importance is given to the noise annoyance objective (β = 1.0) as this scenario concerns early morning operations in which reduction of noise exposure plays an important role. As the table shows the model reflects reality in 12 out of 13 operations in this time frame. As a result, in 7.7% of the operations the model does not coincide with Heathrow's special night operation configuration. This small difference can be explained by the fact that this singular A380 operation being allocated to RWY 27L as shown in Figure 9.7, would not lead to a noise limit overshoot for the specified time frame on the eastern side of the airport. In contrast with that, on the western part of the airport it would lead to an extra gridpoint activation, resulting in an increased amount of exposed households within the time frame. It can therefore be said that this difference is result of the flexibility that has been built in with respect to opposite direction operations at times their is sufficient capacity available. Moreover, enabling opposite direction operations in this case leads to the allocation of flight BA56 to RWY 27L without any addional cost in the objective function.

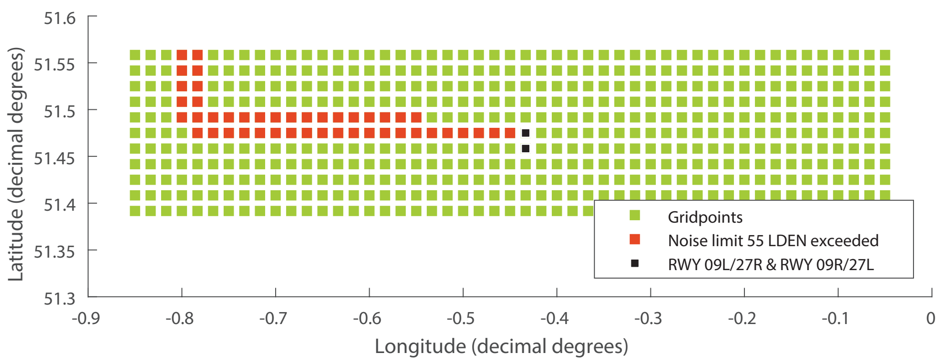

Figure 9.6: Noise exposure grid for flexible runway allocation between 05:00 a.m. and 06:00 a.m. with α = 0.0.

Table 9.4: Validation of Improved Flex by comparing with actual ADS-B data from Flightradar24 [19].

Flight #	Aircraft Type	Origin (ICAO/IATA)	Actual Arrival RWY	Simulated Arrival RWY
BA32	A388	VHHH/HKG	09L	09L
BA16	B77W	WSSS/SIN	09L	09L
BA74	B772	DNMM/LOS	09L	09L
BA34	B789	WMKK/KUL	09L	09L
VS207	B789	VHHH/HKG	09L	09L
BA56	A388	FAOR/JNB	09L	27L
BA262	B772	OERK/RUH	09L	09L
BA28	B77W	VHHH/HKG	09L	09L
CX251	B77W	VHHH/HKG	09L	09L
BA12	A388	WSSS/SIN	09L	09L
UA958	B763	KORD/ORD	09L	09L
SQ322	A388	WSSS/SIN	09L	09L
MH2	A388	WMKK/KUL	09L	09L

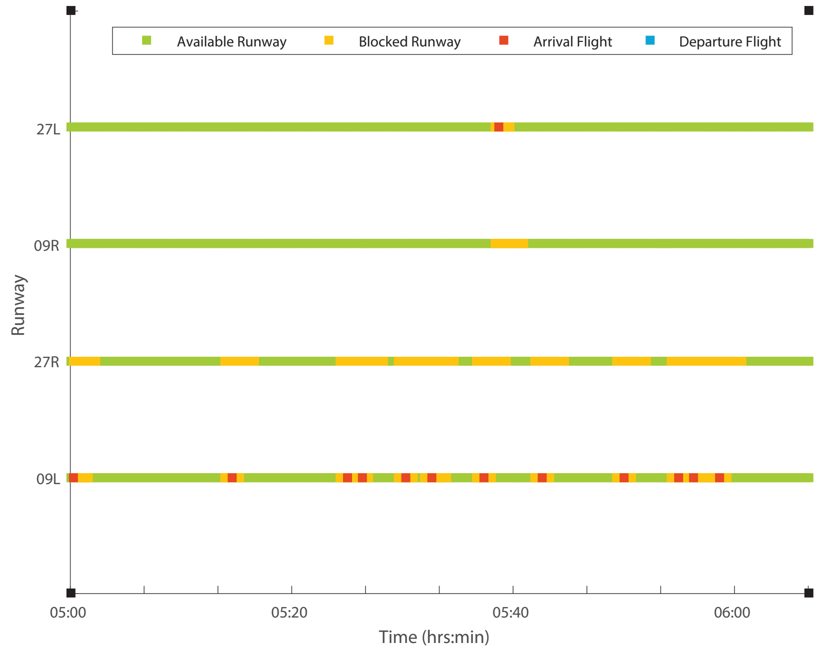

Figure 9.7: Runway allocation and occupation scheme for flexible runway allocation between 05:00 a.m. and 06:00 a.m. with $\alpha = 0.0$.

Furthermore, the aircraft specific fuel flows and engine exhaust emissions are validated by means of two sources of data [16] [33]. Doing so, validates the methodologies used to come to this data set concerning fuel burn characteristics that is used during this research. The dataset concerning aircraft specific noise emission is obtained from the Integrated Noise Model [17] as developed by the FAA. It is assumed that this dataset represents actual data to a level of validity that meets the requirements for this research. The same can be said for the dataset obtained from GRUMP [5] [10].

10 Conclusion

Concluding this research, this chapter gives an overview of the conclusions that can be drawn from the development of Improved Flex. The model shows clear benefits in the light of fuel burn optimization and noise reduction. First, the conclusions of this research are drawn in Section 10.1. Section 10.2 sums up and discusses the limitations that have come with the further development of the Flexible Runway Allocation Model. In Section 10.3 several recommendations are stated which are found to make a worthwhile contribution to the further development of this model.

10.1. Conclusions

Global intensification of passenger and cargo traffic within the aviation industry has led to multiple operational as well as situational difficulties. Besides the positive economical effects that come with an increase in revenue traffic, a multitude of factors show a negative trend. These factors are related to an increased level of noise exposure around airports as well as increased fuel consumption from the airline's perspective as a consequence of lack in runway capacity.

As the airport is constructed such that its two parallel runways are independently spaced, the airport is able to utilize both runways to its maximum. However, the two available runways at Heathrow limit the amount operations the airport would like to have in the coming years. This limitation relates to the fact that the throughput capacity of the runways has reached its maximum. It is found that pairwise flight separation minima are a major contributor to the throughput capacity of a runway.

The current ATM system at Londen Heathrow provides a safe airspace structure in which flight operations can efficiently take place. This system has to comply to several operational as well as regulatory restrictions. These restrictions mostly relate to the noise exposure within the noise-sensitive areas around the aiport. To reduce the level of noise exposure in the vicinity of the airport, Heathrow has designed a runway alternation strategy. This strategy enables the airport to equally spread the noise that is being caused by flight operations over the entire region.

Consequently, the point of focus has moved away from other important elements that affect the airport's daily operations. One of these important elements is fuel consumption. The efficiency of arrival and departure sequences, with respect to air traffic control, is limited to the operational runways as prescribed by the active runway alternation configuration. As a result, aircraft are forced to land or depart from a specific runway. This often comes with an increased fuel burn as aircraft have to circumnavigate around the airport in order to be lined up with the active runway.

Reduction of noise annoyance together with a cutback in fuel consumption forms the topic of this research. By means of a multi-objective optimization model, this research provides a way to differentiate from the current operation strategy and thereby contribute to the global environmental impact as well. The research question that has been posed in this thesis relates to development of the initial model, to be referred to as Standard Flex, that has been created prior to this research with respect to both objectives. This research questions is defined as follows:

Can the performance of Standard Flex be further optimized by applying pairwise flight dependencies, while ensuring and contributing to a valid trade-off between runway capacity, noise emission, fuel burn and safety based on a specific demand of flights?

The outcome of this research has led to a new version of the Flexible Runway Allocation Model, to be referred to as Improved Flex. Improved Flex reflects modifications from both the modeling as well as the computational perspectives in this research. These modifications have resulted in a positive answer to the main research question posed in this research. That is, large improvements have been made with respect to the flight specific modeling of multiple aircraft characteristics.

In contradiction to the single aircraft based separation modeling in Standard Flex, Improved Flex reflects separation modeling based on the pairwise analysis of consecutive flight operations. That is, the model now concerns both the leading aircraft as well as the following aircraft in the operational sequence in order to define the impact on the predecessor's level of safe operations. Moreover, this research applies the RECAT-EU methodology to define pairwise separation minima. This comes with a contribution to the runway's throughput by 5-10% as RECAT-EU allows a reduced separation time between the majority of aircraft pairs that occur at an airport as Heathrow compared to the wake turbulence categories as defined by ICAO. This answers subquestions RQ1, RQ2 and RQ3 which are posed to identify the elements that affect runway capacity as well as how they can be used to model flight operations in a pairwise approach.

Subquestion RQ4, however, is answered by the improved way of modeling aircraft noise in the Flexible Runway Allocation Model. Improved Flex uses aircraft specific noise emission profiles to model the impact of noise exposure on the communities on the ground, whereas Standard Flex uses a reference aircraft only. Modeling aircraft noise contours per aircraft specifically, has proven to result in a significant contribution to this model. The results obtained from the initial model have shown a remarkable difference in sound exposure level at different gridpoints which ranges between -12 dB and +7 dB in the extreme cases. As a result, the simulated noise exposure values at these gridpoints do not reflect reality on an accurate level. In other words, this can lead to improper activation of gridpoints in the optimization process which leads to an incomplete simulation and outcome. In essence, this leads to an imperfect estimation of exposed households. As the estimation of disturbed households is defective, this flaw continues in the estimation of (highly) annoyed residents as well as the amount of awakenings during evening and night.

This can be continued with the answer to subquestion RQ5, which is posed to identify the improvements that can be made with respect to fuel burn modeling. From the fuel consumption point of view, the improvements comprise aircraft specific fuel burn profiles, approach and departure speed profiles as well as aircraft specific airline based ground operations. These improvements have contributed to an increased level of accuracy (+4.0%) with respect to the generalized case in which Standard Flex based its computations on a reference aircraft after which it applies a certain penalty factor. As a result, this improved approach to model fuel consumption leads to a better representation of reality. Thereby, it provides a feasibile way for airlines to reduce variable direct operating costs in terms of fuel consumption. Another contribution that comes from the improved modeling approach in fuel burn relates to the fact that reduced fuel burn leads to reduced engine exhaust emissions. Essentially, this contribution is of large importance from an environmental perspective as well as from the perspectives of airlines and airports.

Only subquestion RQ7 requires to look at Heathrow in specific. The introduction of an addition to the current ATM system enables all four runways at Heathrow to be operational during calm weather conditions. This new type of operations, being referred to as opposite direction operations, has proven to reduce the number of households exposed to a Day-Evening-Night Average Level of at least 55 dB by 2.1% on a daily basis. In addition, creating an increased availability of the runway system has shown to reduce the overall annual fuel consumption of flights operating to and from Heathrow by over 60,000 tonnes. This means that the overall noise emission is more spread over the region such that less people would suffer from extreme noise exposure. From the airline's perspective, this next generation allocation strategy leads to a cutback of fuel consumption which contributes to the airline's profit and loss statement.

The flexible runway allocation strategy as concerned in this research comes with a parameter that allows the model to allocate a slight delay to a flight in order to have it operated on its preferred runway. This preference is based on a combination of Pareto optimal objective weights which are result of the Pareto front that is obtained from the optimization results. This model proves that despite the fact of slightly delaying a flight on the one hand, the fuel consumption as well as noise exposure impact can be reduced. However, it should be noted that the Pareto optimal solution that has been selected in this research remains a rather subjective statement. That is, as the obtained Pareto front shows, there are multiple Pareto optimal solutions to a runway allocation assignment. These Pareto optimal solutions, per definition all provide an optimal solution to the assignment. However, the solutions differ in terms of relative importance of both objectives to be taken into account in the optimization process. This relative importance, obviously, differs per stakeholder. As a result, from the community's perspective, a different Pareto optimal solution might be preferred compared to the perspective of the airline or airport.

Nevertheless, the picture created by this research shows major contributions that can be made with respect to the reduction of noise annoyance and fuel consumption. However, these contributions come with the fact that new technologies and principles are introduced. The assumptions made on these technologies and principles are assumed to be sufficient in terms of safety and feasibility. These assumptions are adequate for this stage in the development of flexible runway allocation, and, thereby answer RQ9. However, these assumptions definitely need more research in later stages. Nevertheless, this research proves that the computational approach of Standard Flex has been improved by the introduction of Improved Flex. Results show that for operations at Heathrow, the deployment of Improved Flex would lead to major contributions with respect to the reduction of noise annoyance (2.1%), fuel consumption ($75 per flight) as well as environmental impact.

The aircraft dependent parameters and variables, that have been identified by the answering of subquestion RQ6, help to understand and quantify the significance to which the model has been improved. Besides the computational improvements, the visualization of the model outcome has been improved by means of an updated runway allocation and occupation scheme. The scheme provides a clear insight in the availability of each runway end at each period in time. This improvement is related to the answer of subquestion RQ8.
The answer to subquestion RQ10 spans over multiple subjects that have been discussed in the above stated conclusion of this research. All in all, the answer to the set of subquestions that have been answered by this research give a complete overview to answer the main research question. The answer to this question is as follows:

Yes, the performance of Standard Flex has been significantly improved by the implementation of multiple aspect to the existing model. The improved model, Improved Flex, now considers pairwise flight dependency analyses which allow the model to define separation minima based on consecutive flight pairs. Furthermore, significant refinements have been made with respect to the modeling of both objectives in the optimization process.

10.2. Limitations

The outcome of this model aims to encourage further development of the feature flexible runway allocation. Compared to regular operations, flexible operations enable the airport to utilize its runways even more. Despite the fact that safety, in this stadium of development, is still a matter of concern, this could be reduced when allocating resources on further development of this concept.

It is important to identify the limitations in order to cast a critical eye on the developed model. This section concerns the limations observed during this research.

- Besides the multiple benificial aspects this model has come with, the model faces some drawbacks in the form of computational performance. Of course, some of these drawbacks can be taken away by improving resources in terms computer performance characteristics. However, some of these limitations concern the model itself. As Improved Flex contributes to a major step in the accuracy of aircraft separation modeling in the flexible runway allocation process, it adds a high level of complexity to the base of the model. As a result, the added complexity leads to an extensive increase in computation time. That is, writing the linear programming file now takes significant more time as the model now concerns each consecutive aircraft pair within a specified time frame, whereas in Standard Flex the model does not concern consecutive aircraft pairs. Because of the increased linear programming file, it obviously takes longer to find the optimal solution to the problem. In most cases, when concerning both objectives to be non-zero, it can take extremely long to find the optimal solution which meets the initiated parameter settings of the optimization. To contribute to the feasibility of this research, the initial optimization parameter settings are set such that a sufficiently good feasible solution can be found within a feasible amount of time. Despite of this, the complexity that arised when developing Improved Flex has caused a major limitation to the model as it is now.

- The model by itself concerns all flights that take place within the time frame specified by the user. Despite the fact that the model concerns possible conflicting flights that take place shortly before or after this time frame, the model does not use the optimal solution of the previous time frame when considering a full day of operations. For the overall picture, this can be a limitation. This can resolved by adding a moving window in the optimization process.

- When looking at the noise objective, a limitation is identified in terms of the importance of particular households over others. This importance is included in Improved Flex to some extent only. That is, a L_{DEN} noise limit is to be defined by the user at the start of the simulation. This noise limit reflects the importance of the relative distance of households to the airport to some extent. However, when selecting a relatively high limit, the model only concerns the households that are located very close to the airport. In this way, it puts the focus on these households to minimize noise exposure. Nevertheless, it does not account for the rest of the households in the vicinity of the airport anymore. On the contrary, when selecting a low limit, the model does. However, the importance of the households closely located to the airport is somehow generalized with the rest of the households being taken into account.

- The modeling of aircraft noise emissions, as is done by using data obtained from the INM, reflects arrival and departure tracks based on single direction operations. In case flexible runway allocatin would be applied to an airport, the arrival and departure procedures should be adapted in terms of conflict resolution. Doing so, would lead to adapted approach and departure tracks which will have their influence on the flight specific noise contours as well. Specifying SDO and ODO departure and arrival tracks would contribute to the completeness of the model.

- Because of limited data on actual operations at Heathrow, this model is subject to several assumptions made in the modeling of the model's cost values. These assumptions comprise the estimation of taxi times as well as approach and departure trajectory times. The model's level of accuracy could be improved by having a dataset comprising real life operational data of Heathrow. This would make the model more representative.

10.3. Recommendations

During this research multiple ideas have arised in order to continue the development of Improved Flex. This section elaborates on the recommended steps that can be taken in order to realize this development. The recommendations in this section are based on the limitations that have been identified in Section 10.2 and are lister below.

- To cast a critical eye on the outcome of this research, it can be concluded that the feasibility of this complex concept of operations, at this point in time, has not yet reached a sufficient level. That is, the implementation of ODO would lead to additional safety concerns which must be resolved by new ATM techniques in the first place. It is therefore recommended that in the following stages of the development of flexible runway allocation resources should be directed to studies that concern the regulations and feasibility of opposite direction procedures at complex airports. For Heathrow in specific, the additional resources that should be put on the development of these techniques should not outweigh the advantages which can be gained by the implementation of ODO.

- As Improved Flex contributes to the development of pairwise flight analysis in the flexible runway allocation strategy, the model's computational performance with respect to Standard Flex has been downgraded to some extent. Resources should be directed to the investigation of making Improved Flex more optimal in terms of the computation strategy that is being used to define the optimization constraints.

- To follow up on the previous recommendation, Improved Flex would be more complete if the model would concern the optimal solution of the time frame before the current time frame that is being analyzed. That is, Improved Flex should be further improved by adding a moving horizon technique in order to ensure the connection between optimal solutions over a larger period of time.
- Improved Flex allocates flights to a specific preferred runway by concerning both optimization objectives. The model does so by assigning a delay step to a flight in order to have it operated on the optimal runway. The assignment of a delay can cause a disruption on the ground or within the TMA. For small delay assignments this would not be a big issue. However, If flights are found to be assigned a delay that is larger than one minute, they can cause major disruptions. Therefore, the model could be extended by giving a certain penalty in cases the optimization chooses a large delay step. In this way the congestion on the ground and inside the TMA can be reduced.
- As Terminal 4 is located south of RWY 09R/27L, aircraft operating from or to this terminalare preferred to depart or arrive on RWY 09R/27L, as runway crossings will decrease the capacity of the runway. Therefore, the model should be extended to understand that runway crossings would need an increased arrival or departure separation in order to allow a runway crossing as is needed at an airport like Heathrow. At this moment, the model only takes into account the taxi time to a certain runway, and therefore does not account for the effects of runway crossings. However, as the taxi time to and from the southern runway is significantly less, the model chooses the southern runway for T4 operations as preferred runway in all cases in which capacity allows to do so.

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Appendices

A

Flight Schedule

This appendix provides the flight schedule between 10:00 a.m. and 11:00 a.m. based on Flightradar24 [19].

Time (hrs:min)	Callsign	Airline	Aircraft Type	O/D IATA	Operation Type	SID/IAF
10:00	KU102	Kuwait Airways	A343	JFK	Arrival	BNN
10:01	AI115	Air India	B788	DEL	Arrival	BIG
10:03	UA28	United Airlines	B764	EWR	Departure	CPT
10:03	BA833	British Airways	A319	DUB	Arrival	BNN
10:04	BA391	British Airways	A319	BRU	Arrival	BIG
10:04	BA282	British Airways	A388	LAX	Arrival	BNN
10:05	BA728	British Airways	A319	GVA	Departure	MAY
10:05	BA862	British Airways	A320	PRG	Departure	DET
10:05	BA551	British Airways	A321	FCO	Arrival	BIG
10:05	VS116	Virgin Atlantic	A333	ATL	Arrival	BNN
10:05	DL1	Delta Air Lines	B763	JFK	Departure	CPT
10:05	SN2093	Brussels Airlines	A320	BRU	Arrival	BIG
10:09	AA101	American Airlines	B772	JFK	Departure	CPT
10:09	BA1325	British Airways	A320	NCL	Arrival	BNN
10:10	SK804	SAS	B737	OSL	Departure	BPK
10:10	BA208	British Airways	B744	MIA	Arrival	BNN
10:11	BA499	British Airways	A320	LIS	Arrival	OCK
10:13	BA253	British Airways	B772	NAS	Departure	GASGU
10:15	UA924	United Airlines	B772	IAD	Arrival	BNN
10:16	BA1310	British Airways	A320	ABZ	Departure	WOBUN
10:16	TP354	TAP Portugal	A320	LIS	Arrival	OCK
10:16	BA296	British Airways	B744	ORD	Arrival	BNN
10:17	UA940	United Airlines	B752	EWR	Arrival	BNN
10:17	EI380	Aer Lingus	A320	SNN	Arrival	BNN
10:17	AA78	American Airlines	B77W	DFW	Arrival	BNN
10:19	AC888	Air Canada	B763	YOW	Arrival	BNN
10:20	LO282	LOT Polish Airlines	B734	WAW	Departure	BPK
10:21	BA65	British Airways	B744	NBO	Departure	MAY
10:22	BA185	British Airways	B773	EWR	Departure	CPT
10:23	BA1386	British Airways	A320	MAN	Departure	WOBUN
10:23	BA143	British Airways	B772	DEL	Departure	DET
10:23	AA173	American Airlines	B763	RDU	Departure	CPT
10:24	BA700	British Airways	A320	VIE	Departure	DET
10:24	BA885	British Airways	A321	OTP	Arrival	BIG
10:24	BA384	British Airways	A320	NCE	Departure	MAY
10:25	BA202	British Airways	B744	BOS	Arrival	BNN

Time (hrs:min)	Callsign	Airline	Aircraft Type	O/D IATA	Operation Type	SID/IAF
10:25	AY832	Finnair	A321	HEL	Departure	BPK
10:25	AA104	American Airlines	B772	JFK	Arrival	BNN
10:25	SK526	SAS	B738	ARN	Departure	BPK
10:25	BA834	British Airways	A320	DUB	Departure	CPT
10:26	BA207	British Airways	B744	MIA	Departure	CPT
10:27	BA514	British Airways	A321	MAD	Departure	MAY
10:28	BA154	British Airways	B788	CAI	Arrival	BIG
10:29	UA928	United Airlines	B763	ORD	Departure	CPT
10:32	BA676	British Airways	B763	IST	Departure	DET
10:33	UA924	United Airlines	B772	IAD	Arrival	BNN
10:33	BA1439	British Airways	A320	EDI	Arrival	BNN
10:33	DL195	Delta Air Lines	B752	PHL	Departure	CPT
10:33	BA1341	British Airways	A319	LBA	Arrival	BNN
10:34	VS2	Virgin Atlantic	B789	EWR	Arrival	BNN
10:34	BA292	British Airways	B772	IAD	Arrival	BNN
10:37	BA139	British Airways	B77W	BOM	Departure	DET
10:37	BA162	British Airways	B772	TLV	Arrival	BIG
10:37	KM101	Air Malta	A320	MLA	Departure	MAY
10:38	BA785	British Airways	A320	ARN	Arrival	LAM
10:39	BA308	British Airways	A319	CDG	Departure	MAY
10:40	VS107	Virgin Atlantic	A333	DTW	Departure	CPT
10:40	AF1580	Air France	A320	CDG	Arrival	BIG
10:40	BA429	British Airways	B763	AMS	Arrival	LAM
10:41	BA1423	British Airways	A319	BHD	Arrival	BNN
10:41	LH904	Lufthansa	A320	FRA	Arrival	LAM
10:42	LH2473	Lufthansa	A321	MUC	Departure	BPK
10:43	IB3160	IBERIA	A319	MAD	Arrival	BIG
10:45	LH903	Lufthansa	A319	FRA	Departure	BPK
10:45	DL403	Delta Air Lines	B763	JFK	Arrival	BNN
10:46	BA546	British Airways	A320	FCO	Departure	MAY
10:48	KL1009	KLM	B737	AMS	Arrival	LAM
10:48	BA962	British Airways	A319	HAM	Departure	BPK
10:48	QR10	Qatar Airways	A388	DOH	Departure	DET
10:49	BA962	British Airways	A319	HAM	Departure	BPK
10:51	SK4629	SAS	B736	SVG	Arrival	LAM
10:51	BA904	British Airways	A319	FRA	Departure	BPK
10:52	DL37	Delta Air Lines	B763	SEA	Departure	WOBUN

B

Taxi Time Estimation

This appendix provides an elaboration on the estimation of taxi times at Heathrow. As the airport consists of multiple terminals (T1, T2, T3, T4 and T5) of which most are located in between the parallel runway set, the taxi time to and from these terminals differs. Airlines are being distributed over T2, T3, T4 and T5, T1 is not operational at this time. The distribution of airlines over the terminals can be found in Table B.2. Within the definition taxi time, a differentiation is made between the taxi-in and taxi-out time. The related values can be found in the paragraphs below.

Taxi-In Time

The taxi-in time is based on the distance of the projected taxi route from the location at which the aircraft vacates the runway until it reaches the terminal. To simplify the estimation, aircraft are assumed to vacate the arrival runway at the same high speed runway exit (HSE). These HSEs are assumed to be A6 (09L), N4E/S4E (09R), N6/S6 (27L) and A10E (27R). From this projected routes, the distance has been estimated by the use of Heathrow's Aerodome Ground Chart. Subsequently, an average taxi speed of 10 kt is assumed, after which the taxi-in time is estimated. It is assumed that the assigned parking stand or gate is available once the aircraft has landed, such that no additional delay should be implemented during taxi. The taxi-in distance is specified per runway per terminal in Table B.1.

Taxi-Out Time

The taxi-out time is based on the distance of the projected taxi route from the terminal to the holding point at the departure runway. To simplify the estimation, aircraft are assumed to depart from the holding point that is closest to the beginning of the runway, whereas in real life operations aircraft are assigned intersection holding points in some cases. These holding points are assumed to be AB13 (09L), NB11 (09R), NB1 (27L) and A3 (27R). For the taxi-out time, the same assumptions are used as yield for the taxi-in time. It is assumed that the taxiway capacity at Heathrow does not influence the taxi maneuver of the aircraft. That is, the aircraft is assumed to taxi to the assigned runway without disruption. The taxi-out distance per runway per terminal is shown in Table B.1.

Table B.1: Taxi-in distance (left) and taxi-out distance (right) per runway per terminal in meters [20].

	Terminal				
Runway	*T1*	*T2*	*T3*	*T4*	*T5*
09L	600	1,852	2,741	3,007	3,307
09R	2,447	664	2,682	695	3,098
27L	2,996	2,212	1,437	1,730	1,478
27R	2,150	3,024	1,213	2,978	1,430

	Terminal				
Runway	*T1*	*T2*	*T3*	*T4*	*T5*
09L	3,588	4,469	2,596	4,431	1,526
09R	5,366	3,447	2,620	3,111	1,259
27L	2,034	1,166	3,272	1,273	3,611
27R	1,314	2,052	3,249	2,653	3,753

Table B.2: Terminal specification per airline [36].

Terminal 2

Aegean Airlines	Croatia Airlines	Singapore Airlines
Aer Lingus	Egypt Air	South African Airways
Air Canada	Ethiopian Airlines	Swiss International Airlines
Air China	Eurowings	TAP Portugal
Air New Zealand	EVA Air	Thai Airways
ANA	Germanwings	Turkish Airlines
Asiana Airlines	Icelandair	United Airlines
Austrian	LOT Polish Airlines	
Avianca	Lufthansa	
Brussels Airlines	SAS - Scandinavian Airlines	

Terminal 3

American Airlines	Iran Air	Qantas
Cathay Pacific Airways	Japan Airlines	Royal Jordanian
Delta Air Lines	LATAM Airlines	Sri Lankan Airlines
Emirates	MEA	Virgin Atlantic
Finnair	Pakistan International Airlines	Vueling
Garuda Indonesia		

Terminal 4

Aeroflot	Biman Bangladesh Airlines	Malaysia Airlines
Aeromexico	Bulgaria Air	Oman Air
Air Algerie	China Eastern	Philippine Airlines
Air Astana	China Southern	Qatar Airways
Air France	El Al	Royal Air Maroc
Air India	Etihad Airways	Royal Brunei Airlines
Air Malta	Gulf Air	Saudia
Air Mauritius	Jet Airways	Tarom
Air Serbia	Kenya Airways	Tunisair
Alitalia	KLM - Royal Dutch Airlines	Turkmenistan Airlines
Arik Air	Korean Air	Uzbekistan Airways
Azerbaijan Airlines	Kuwait Airways	Vietnam Airlines

Terminal 5

British Airways	Iberia	Iberia Express

C

SID & IAF Estimation

This appendix elaborates on the methodology behind the estimation of SID and IAF fixes for all flights to be taken into account in this research. The estimation of these navigational fixes is based on the ICAO airport identi- fiers. For each unique destination and/or origin airport the first two letters of the ICAO airport identifier is used to define the expected direction of departure or arrival, respectively.

Departure Trajectory Estimation

Table C.1: Estimated SID allocation for the flight schedule of 3 August 2016.

ICAO	SID	ICAO	SID	ICAO	SID	ICAO	SID
BI	WOBUN	KA	CPT	LL	MAY	RP	BPK
CY	CPT	KB	CPT	LM	MAY	SA	GASGU
DA	MAY	KC	CPT	LO	DET	SB	GASGU
DN	MAY	KD	CPT	LP	MID	SK	GASGU
EB	DET	KE	CPT	LR	MAY	UK	BPK
ED	BPK	KI	CPT	LS	MAY	UT	DET
EF	BPK	KJ	CPT	LT	DET	UU	BPK
EG	WOBUN	KL	WOBUN	LX	MAY	VA	DET
EH	BPK	KM	CPT	LY	MAY	VC	DET
EI	CPT	KO	CPT	MM	GASGU	VG	DET
EK	BPK	KP	CPT	MY	GASGU	VH	DET
EL	DET	KR	CPT	OB	DET	VI	DET
EN	BPK	KS	WOBUN	OE	DET	VO	DET
EP	BPK	LB	MAY	OJ	DET	VT	DET
ES	BPK	LC	MAY	OK	DET	VV	DET
FA	MAY	LD	MAY	OL	DET	WI	DET
FI	MAY	LE	MAY	OM	DET	WM	DET
GC	MAY	LF	MAY	OO	DET	WS	DET
GM	MAY	LG	MAY	OP	DET	ZB	BPK
HA	MAY	LH	DET	OT	DET	ZG	BPK
HE	MAY	LI	MAY	RJ	BPK	ZS	BPK
HK	MAY	LK	DET	RK	BPK		

Arrival Trajectory Estimation

Table C.2: Estimated IAF allocation for the flight schedule of 3 August 2016.

ICAO	IAF	ICAO	IAF	ICAO	IAF	ICAO	IAF
BI	BNN	HK	BIG	LL	BIG	SA	OCK
CY	BNN	KA	BNN	LM	BIG	SB	OCK
DA	BIG	KB	BNN	LO	BIG	SK	OCK
DG	BIG	KC	BNN	LP	OCK	UK	LAM
DN	BIG	KD	BNN	LR	BIG	UL	LAM
EB	BIG	KE	BNN	LS	BIG	UT	BIG
ED	LAM	KI	BNN	LT	BIG	UU	LAM
EF	LAM	KJ	BNN	LX	BIG	VA	BIG
EG	BNN	KL	BNN	LY	BIG	VC	BIG
EH	LAM	KM	BNN	MM	OCK	VG	BIG
EI	BNN	KO	BNN	OB	BIG	VH	LAM
EK	LAM	KP	BNN	OE	BIG	VI	BIG
EL	BIG	KS	BNN	OJ	BIG	VO	BIG
EN	LAM	LB	BIG	OK	BIG	VT	BIG
EP	LAM	LC	BIG	OL	BIG	VV	BIG
ES	LAM	LD	BIG	OM	BIG	WM	LAM
FA	BIG	LE	BIG	OO	BIG	WS	LAM
FI	BIG	LF	BIG	OP	BIG	ZB	LAM
GC	OCK	LG	BIG	OT	BIG	ZG	LAM
GM	OCK	LH	BIG	RJ	LAM	ZS	LAM
HA	BIG	LI	BIG	RK	LAM	ZU	LAM
HE	BIG	LK	BIG	RP	LAM		

D

Aircraft Categorization According to RECAT-EU & ICAO WTC

This appendix provides a visualization of the different categories that belong to the RECAT-EU categorization as well as the ICAO WTC categorization structure. For both methodologies a set of aircraft is used in order to give a clear insight in the differences of categorization.

Table D.1: Example list of aircraft types assigned to RECAT-EU categories [46].

Super Heavy	**Upper Heavy**	**Lower Heavy**	**Upper Medium**	**Lower Medium**	**Light**
A388	A332	A306	A318	AT43	FA10
A124	A333	A30B	A319	AT45	FA20
	A343	A310	A320	AT72	D328
	A345	B703	A321	B712	E120
	A346	B752	AN12	B732	BE40
	A359	B753	B736	B733	BE45
	B744	B762	B737	B734	H25B
	B748	B763	B738	B735	JS32
	B772	B764	B739	CL60	JS41
	B773	C135	C130	CRJ1	LJ35
	B77L	DC10	IL18	CRJ2	LJ60
	B77W	DC85	MD81	CRJ7	SF34
	B77X	IL76	MD82	CRJ9	P180
	B788	MD11	MD83	DH8D	C650
	B789	TU22	MD87	E135	C525
	B78X	TU95	MD88	E145	C180
	IL96		MD90	E170	C152
			T204	E175	
			TU16	E190	
				E195	
				F70	
				F100	
				GLF4	
				RJ85	
				RJ1H	

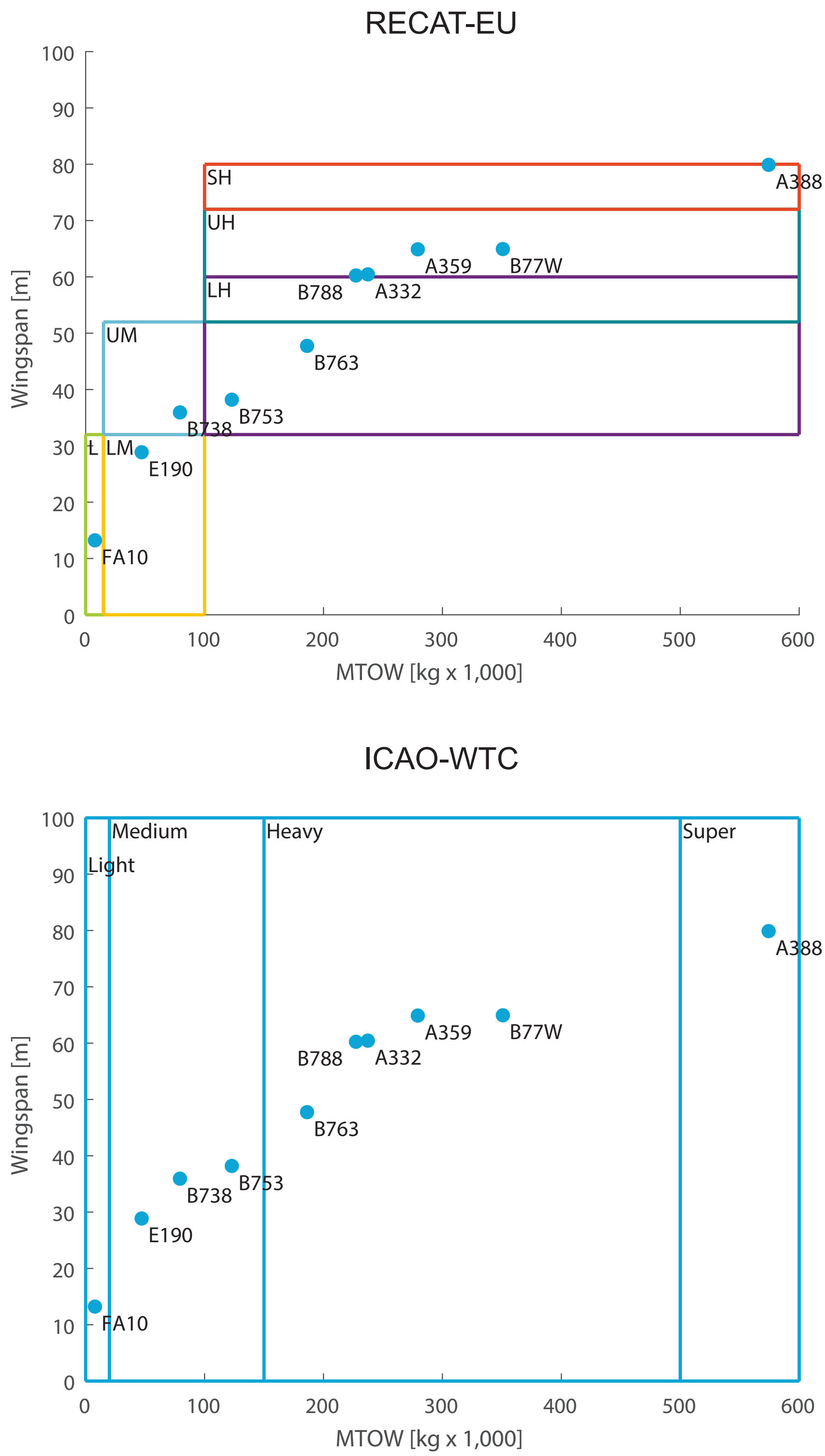

Figure D.1: Relative difference in separation minima between ICAO WTC [29] (Improved Flex) and RECAT-EU [46] (Standard Flex).

E

Guideline Application to Other Airports

This appendix elaborates on the guidelines that should be followed in order to be able to apply the Improved Flexible Runway Allocation Model to complex airports other than London Heathrow. To efficiently use the developed model the following steps must be taken:

1. **Identify the runway lay-out of the airport**
   To create an overall picture of the dependencies of operations at the airport to be concerned, the layout of the airport must be defined. In this way the interdependency of the runways can be determined. This information is usefull to define the pairwise runway dependency matrices later on.
2. **Establish a detailed flight schedule**
   A detailed flight schedule is needed in order to model the flight operations at the airport as accurate as possible. At least, the following flight characteristics must be known: ETA/ETD, origin/destination, aircraft type, terminal/gate/stand number and SID/STAR/IAF.
3. **Define operational regulations**
   Each airport has its own regulations regarding terminal and ground operations. These regulations concern factors related to noise, safety as well as flow management. Therefore, these airport specific regulations which can be obtained from the AIP, should be implemented in the model accordingly.
4. **Estimate population**
   Regarding the noise objective in the optimization model, the population in the vicinity of the airport must be known in order to relate cost to the noise objective decision variables.
5. **Define noise contours**
   The aircraft specific noise contours should be obtained from noise modeling software such as INM or AEDT. In such software types, one can define the departure and arrival tracks and model the noise emission accordingly. The noise emission profiles are then used in the noise limit switching constraint within the linear programming model.
6. **Create fuel burn profiles**
   In order to model the aircraft specific fuel consumption, one should define the fuel burn profiles per unique aircraft type per departure or arrival trajectory. This can be done by using the aircraft specific fuel flow rates that can be obtained from BADA.

F

Weather Analysis

This appendix assesses a weather analysis on London Heathrow Airport (ICAO: EGLL; IATA: LHR).

Wind Statistics

As Figure F.2 indicates the wind speeds at Heathrow vary over the year from 1 m/s to 7 m/s. Assuming a tailwind limit of 5 kts, this results in wind calm conditions during 36% of the year. As a matter of fact, 64% of the year, wind conditions are such that a certain runway configuration must be operated in order to ensure safe operations. For 44.8% of the year the west configuration is expected to be active, whereas 19.2% of the year the east configuration does.

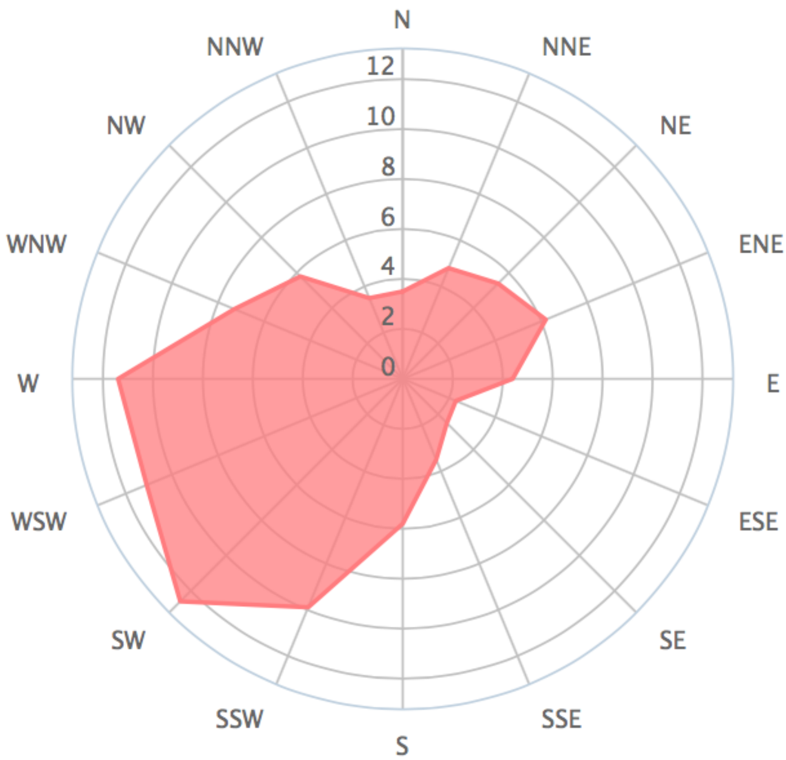

Figure F.1: Windrose of Heathrow based on annual statistics for the year 2016 [52].

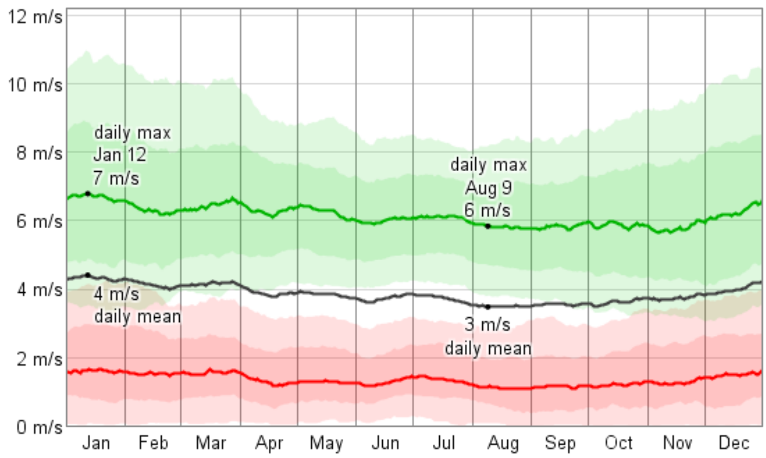

Figure F.2: Wind speed distribution at Heathrow based on annual statistics for the year 2016 [50].

G

Base of Aircraft Data

This appendix elaborates on the computational method that is applied to aircraft data as published in the Base of Aircraft Data (BADA).

- **Forces in Flight**
  This submodel enables the computation of the forces in flight. These forces comprise the four major forces that act on an aircraft being lift (L), drag (D), weight (W) and thrust (T). As mass variates during flight, BADA accounts for a differentiation in mass throughout the modeling period.

- **Aircraft Motion**
  Using the forces computed in the previous submodel, this submodel applies the Total Energy Model (TEM) to relate geometrical, kinematic and kinetic characteristics of the motion of the aircraft. This relation between forces and rate of increase in potential and kinetic energy is described by Equation G.1. This equation can be rewritten into a set of Ordinary Differential Equations (ODE) which is used to compute the aircraft trajectory for a certain flight segment.

$$(T-D)\,v = W\frac{dh}{dt} + mv\frac{dv}{dt} \tag{G.1}$$

- **Flight Operations**
  In addition to the submodel described above, the aircraft flight operations define the type of operation the aircraft operates during a certain flight segment. For example, these operation types can specify speed operations. Different operation types can either be based on flying at a constant Mach number or Calibrated Airspeed (CAS). These factors affect the energy share factor which is part of the ODE. Moreover, this submodel defines the missing part in the mathematical problem that has been established by the first two submodels.

- **Aircraft Limitations**
  This submodel defines the behaviour of an aircraft marked by certain boundaries regarding the limitations of the aircraft's operations. These limitations comprise four categories, being geometrical, kinematic, dynamic and environmental limitations.

- **Aircraft Characteristics**
  The last submodel concerns the aircraft characteristics that are inherent to the aircraft. Among others, these characteristics include wingspan, aerodynamic wing coefficients and center of gravity location.