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Flexible runway use modeling using pairwise RECAT-EU separation minima

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If we would take fuel consumption and noise annoyance into account in the runway allocation process, runway allocation can take place more efficiently, both in terms of fuel cost as well as noise annoyance. In this research, the focus is on the further development of a model in order to make the calculationsmore 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. By means of this research, the flexible runway allocation model 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, based on a specific demand of flights?

I. I. Introduction

D ecreasing 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 impact 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 2015¹, 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 airports². Thanks to the growing industry, airports like Heathrow have reached their maximum capacity. As shown in dynamic and prosperous cities such as Dubai³ and Abu Dhabi⁴, 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 a political perspective.

Heathrow can be considered as one of those airports for which political constraints 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 annoyance⁵, human well-being⁶ and legal regulations form a cycle that affect the airports 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 beneficial from the community perspective.

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Noise-optimized routings often come with an increased flight trajectory length over sparsely populated areas such as seas or countryside. Therefore, the concept of NPR may lead to beneficial contributions with respect to noise annoyance, but can cause an increase in trajectory length. From both an environmental perspective as well as the perspective of an airline, the concept of NPR comes with multiple negative factors, of which the most important is additional fuel burn and delay. The last decade shows a situation in which noise annoyance has obtained an increasing role 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.

This research will be a continuation of earlier research⁷. This research, to be referred to as Standard Flex, focused on the development of a more basic optimization model that is able to allocate runways to arriving and departing traffic operating at a complex airport.

II. Objectives in the Runway Allocation Process

The majority of large international hubs utilize 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. Four major reasons for having a certain runway preference relate to either runway capacity, noise exposure, third-party risk or weather conditions.

Three objectives that form the basis of the multi-objective optimization model concerning runway allocation at complex airports; airport runway capacity & delay, noise annoyance around airports and airline fuel economics.

A. 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 cancellations⁸.

De Neufville and Odoni⁸ 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 airport⁸. These aircraft movements comprise departures and arrivals.

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. 4444⁹. This document describes the separation categories as defined by the International Civil Aviation Organization (ICAO).

One of the major hazards in flight operations is the occurrence 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 counterrotating 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 1.

Identifier	WTC	MTOW[kgx1,000]	Example Aircraft
J	SUPER	MTOW≥560	AN-124,A388
Н	HEAVY	MTOW≥136	B763,A346
Μ	MEDIUM	7 <mtow<136< th=""><th>AT45,B738</th></mtow<136<>	AT45,B738
L	LIGHT	MTOW≤7	SF34,LJ35

Table 1: ICAO	wake turbulence	categories ⁹
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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.

In order to improve this conservative approach, Eurocontrol designed a new categorization methodology for aircraft with respect to their impact on wake turbulence¹⁰. This project was named Wake Turbulence Re-categorization for Europe (RECAT-EU). Comparing the RECAT-EU scheme with the original 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: RECAT-EU wal	ke turbulence categories ¹⁰
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Identifier	WTC	MTOW[kgx1,000]	Wingspan[m]	Example Aircraft
Α	SUPERHEAVY	MTOW≥100	72 <wingspan<80< th=""><th>AN-124,A388</th></wingspan<80<>	AN-124,A388
В	UPPERHEAVY	MTOW≥100	60 <wingspan<72< th=""><th>B744,A346</th></wingspan<72<>	B744,A346
С	LOWERHEAVY	MTOW≥100	Wingspan<60	MD11,B763
D	UPPERMEDIUM	15 <mtow<100< th=""><th>Wingspan>32</th><th>B738,A320</th></mtow<100<>	Wingspan>32	B738,A320
E	LOWER MEDIUM	15 <mtow<100< th=""><th>Wingspan<32</th><th>AT45,E190</th></mtow<100<>	Wingspan<32	AT45,E190
F	LIGHT	MTOW≤15	-	SF34,LJ35

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 3.

Table 3: Distance-based standard separation minima (nm) for arrivals according to R	ECAT-EU ¹⁰
() indicates minimum radar separation.	

	Trailing	aircraft				
Leading Aircraft	SUPER	UPPER	LOWER	UPPER	LOWER	LIGHT
	HEAVY	HEAVY	HEAVY	MEDIUM	MEDIUM	
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

B. 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 restrictive for flight operations at an airport. At major airports, governments have 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 surroundings¹¹.

To 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.

To minimize noise exposure caused by arriving aircraft, certain lateral and longitudinal 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.

C. 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.

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 Doganis¹¹ and IATA¹², fuel costs cover over one-fourth of the VDOC of an airline.



Figure 1: Airport Ground Chart Heathrow¹³

III. Flight Operations at Heathrow

London Heathrow (LHR), as shown in figure 1, 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 2016^2 . 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.

Heathrow's daily operations are restricted by 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 to 15:00 and the second half being from 15:00 p.m. until the last departure of the day around 23:00. At 15:00, the airport switches segregated arrival and departure operations between the northern and the southern runway in order to equally divide noise emission over the populated areas in the vicinity of the airport and give areas a time of low noise. However, this strict operational strategy limits operations from being fuel and noise efficient and is not the most optimal for most stakeholders.

As prescribed by the Department of Transportation¹⁴, 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 4. 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. The noise annoyance produced by aircraft is generally higher for departures than for arrivals, especially if the arrivals use continuous descent approaches. Therefore, it is more beneficial to use the noise budget by operating arrival flights as their QC is lower with respect to a departure of the same aircraft type.

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.

_	Noise Classification (EPNdB)						
	84.0-86.9	87-89.9	90-92.9	93-95.9	96-98.9	99-101.9	>101.9
Quota Count	0.25	0.5	1	2	4	8	16

Table 4: Quota Count per noise classification at Heathrow.



Figure 2: Relative frequency of occurrence of different RECAT-EU categories at Heathrow on 3 August 2016.

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. The figure shows a clear relation with Figure 2, 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.



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

Heathrow's Terminal 4 (T4)situated south of RWY 09R/27L, where the other terminals are located north of this runway. Due to this location, operations to and from this terminal come with additional constraints. As Figure 1 illustrates, aircraft can only access T4 by using the taxiways that cross 09R/27L. These taxiways comprise perpendicular runway crossing taxiways as well as high speed exit taxiways. Remarkable is the fact that there are no taxiways that go around the ends of 09R/27L, which obviously has to deal with the limited space available within the airport's property. It is therefore beneficial to have all flight operations, both arrival and departure, from and to T4 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. Nest to the capacity perspective, the taxi time from and to RWY 09R/27L is lower compared to the northern runway for airlines operating at Terminal 4. As a result, operations on this runway for T4 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 preferred for operations to and from T4.

IV. Separation Modeling

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 3 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 ATC. The sixth

Table 5: ICAO	wake t	urbulence	categories ¹⁵
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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

category, however, is excluded as no light aircraft operate at Heathrow.

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 time an aircraft occupies a runway. This 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, of which most 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 52 shows the DROT and AROT for each RECAT-EU category, respectively.

In association with independent parallel runways as described in Section 2.1.2, three operating modes can be defined. These modes comprise i) simultaneous independent parallel approaches, ii) simultaneous independent parallel departures, and iii) segregated parallel approaches/departures. The third can be used in several ways, such as one runway being exclusively used for approaches, while the other runway is 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 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; Arrival-Arrival (AA), Departure-Departure (DD), Departure-Arrival (DA) and Arrival-Departure mode (AD).

According to ICAO⁹, 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.

V. Noise Modeling

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 amount 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 thought the advent of 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 Integrated Noise Model¹⁶ as designed by the Federal Aviation Authority (FAA) was intentionally designed to model and evaluate the impact 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 approach speeds, runway types. configurations, flight tracks, grid areas and population data of the airport to be



Figure 4: Population London Heathrow area [5] [10]

analyzed.

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 spreading of this enormous population is illustrated in Figure 4. This plot is generated by data obtained from the Global Rural-Urban Mapping Project (GRUMP) database^{17,18}.

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 does so. Therefore, the data that is obtained as an output of the INM is preprocessed making the data applicable for linear optimization.

VI. Fuel Burn Modeling

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.

A. Standard Instrument Departure (SID)

Table 6: SID runway combinations

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. 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 indicates the length of each departure trajectory, specified per departure runway and SID indicator.

	Track	length (nm)	
SID	09L	09R	27L	27R
ВРК	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

Table 7: IAF runway combinations

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

B. 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. Table 7 indicates the length of each approach trajectory, specified per arrival runway and Initial Approach Fix (IAF) indicator.

C. Taxi Times

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 1.

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 to be operating from a specific terminal at Heathrow as specified in the operational schedule. The results of the taxi time estimation can be found in Table 7.

Inbound Taxi time (minutes)			Outb	ound T	axi tim	ne (min	utes)				
Runway	T1	T2	T3	T4	T5		T1	T2	T3	T4	T5
09L	2	6	9	11	11		12	14	8	15	5
09R	8	2	9	2	10		17	11	8	10	4
27L	10	7	5	6	5		7	4	11	4	12
27R	7	10	4	11	5		4	7	11	10	12

Table 7: Taxi time per terminal runway combination

D. Aircraft Performance Parameters

Apart from the routing parameters, aircraft characteristics play an important role in the amount of fuel burnt. 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) v3.11. 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, fuel flow and approach speed, which are therefore obtained from BADA for each specific aircraft in the flight schedule.

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. The delay factor is applied 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.

VII. Linear Programming Model

In general, an optimization problem consists of resources and activities. Relating 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, mixed integer linear programming is applied in such a way that the optimization process allocates a certain runway to a specific flight. This allocation has be performed optimally 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.

A. Objective function

$$Z = \alpha.n_f \sum_{f \in F} \sum_{r \in R} \sum_{d \in D} c_{f,r,d}^F . x_{f,r,d} + \beta.n_n \sum_{x,y \in P} P_{xy}^G g_{xy}$$

The objective function in the runway allocation process is described by two different 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 part (α) relates to the fuel burn as a consequence of the chosen route and delay for each flight. The second part (β) relates to the amount of people per grid point where the noise level is exceeded.

B. Constraints

The constraints used in this research are of type: equality constraints, inequality constraints, and non-negativity constraints.

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

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.

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

The runway availability constraint, is an equality constraint and concerns the allocation of every flight on a runway that is available within the simulated time frame.

$$\sum_{f \in F} \sum_{d \in D} n_{f,r,d,t}^{DM} \cdot x_{f,r,d} \le 1 \forall r \in R_{conflict}, t \in T$$

The runway occupancy 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 between various runways can be defined. This is done by applying dependency matrices.

$$\sum_{f \in F} \sum_{r \in R} \sum_{d \in D} L^G_{xy, f, r} \cdot x_{f, r, d} - M \cdot g_{xy} \leq L_{\text{limit}}$$

The noise limit switching constraint adds all the AEL-values (L) corresponding to all flights at each grid point and checks whether the noise limit is exceeded at each grid point. If so, the grid point variable g is activated, meaning it will have a value 1 instead of 0, and will be taken into account in the objective function.

VIII. Results

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

Figure 5 shows the pareto optimal solutions for a run of the peak hour between 10 am and 11 am. The boundaries, illustrated in purple and green, show the number of households exposed to 55 dB LDEN and total fuel burn results for the defined runway alternation configuration scheme, which leads to a total of 45,443 exposed households and 155,070 kilograms of burned fuel. The proposed Pareto optimal solution indicated 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%.

Figure 6 shows the runway allocation scheme belonging to the Pareto optimal solution as selected in figure 5. 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 beneficial 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.



Figure 5: Pareto front for operations between 10:00 a.m. and 11:00 a.m



Figure 6: Runway allocation and occupancy scheme for flights between 10:00 a.m. and 11:00 a.m. for a selected Pareto optimal solution

Figure 7 shows in which areas of the grid the L_{DEN} noise limit of 55dBA is exceeded for that solution. 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 LDEN noise level higher or equal to 55 dB. The locations being exposed to a noise level that exceeds the prescribed 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 for a particular runway end.



Figure 7: Noise exposure grid for flights between 10:00 a.m. and 11:00 a.m. for selected Pareto optimal solution based on a LDEN

Figure 8 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, because delay is directly related to fuel burn. 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: Assigned delay distribution of flights between 10:00 a.m. and 11:00 a.m. for selected Pareto

Next to the full flex scenario, also scenario's are created for which runway operations are restricted to westbound or eastbound operations only, due to wind conditions. Based on the obtained results obtained, 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. 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 19:00 - 20:00 and 22:00 - 23:00 respectively. This is done by using the same Pareto-optimal objective weight set as for the illustrated scenario. The results of these scenarios are compared to their respective runway alternation scenario and displayed in Table 3. While savings for both fuel and noise are higher for full flex, as and westbound operations still show in increase in both.

Fuel Consumption Saving (kg %)			
Time frame	Full Flex	East Flex	West Flex
10:00 - 11:00	17,670 11.4	790 0.5	4,950 3.2
19:00 - 20:00	32,580 19.2	1,370 1.0	4,530 2.8
22:00 - 23:00	20,810 14.9	1,100 0.9	4,680 3.4

Table 3: Summary of savings obtained from Improved Flex compared to a regular runway alternation strategy in calm weather conditions.

IX. Conclusions

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.

X. Recommendations

It is 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.

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.

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.

As Terminal 4 is located south of RWY 09R/27L, aircraft operating from or to this terminal are 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.

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