Multi-Stakeholder Aircraft Scheduling Problem

Performance Evaluation and Fairness Analysis at Schiphol Airport

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Technische Universiteit Delft

TU Delft Delft University of Technology

Challenge the future

Multi-Stakeholder Aircraft Scheduling Problem

Performance Evaluation and Fairness Analysis at Schiphol Airport

by

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Preface

This Master Thesis has been written within the educational programme of Transport, Infrastructure and Logistics, a joint Master's program offered by CitG, 3mE and TBM department of TU Delft, with Engineering Logistics specialisation.

My thesis is in the field of airport management, specifically the performance and fairness analysis of the routing and scheduling decisions by Air Traffic Control. The research was conducted at the university, TU Delft, and the evaluation was conducted at Schiphol and the data used was sourced from public domain. The report describes the thesis work sequentially by introducing the problem statement, literature survey, methodology, experimental design and finally concludes with conclusion and recommendations including future scope of research.

I would like to thank my supervisors; Dr. Francesco Corman and Dr. Scott Cunningham for all their help and guidance during the project. I learnt a lot from them and gained invaluable insight from their expertise in all the aspects of the project ranging from operations research, game theory, statistics and multi-actor system analysis. This project would not have been possible without their time, effort and support towards the same. I would like to thank Prof. Gabriel Lodewijks for his help and constructive inputs to enhance the quality of the project work; his guidance was invaluable in completing a successful graduation project work.

Finally, I would like to thank my mother, wife, family and Viktor for their never ending support and encouragement which enabled me to undertake and successfully complete this graduation project.

Manish Tripathy
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Executive Summary

The growth in the aviation industry means that with existing constraints, operational efficiency has to be improved in order to be sustainable. The bottlenecks at airports are usually the runways and consequently, the routing and scheduling decisions from the ATC pertaining to the route and order of the incoming and outgoing flights are of paramount importance. The objective of this research was to evaluate an advanced optimisation algorithm at Schiphol using publicly sourced data on different aspects, which were dual in nature, one was performance as compared to the incumbent practises and the other was fairness which dealt with the fair distribution of the decisions from the ATC for different airlines depending on cost incurred by each airline. The advanced algorithm was devised by drawing an analogy to job shop scheduling problem and solving the same using graph theory and associated (Meta) heuristics. The financial and fairness analysis was carried out through analogising game theory.

The experimental design was set up through running the data through an optimisation model followed by financial analysis. The data consisted of schematics of Schiphol, so as to determine the time to traverse resources like approach air segment, glide path and runways, details of the aircraft and time of entry into the terminal control area of Schiphol along with expected time at gates. In total 49 data sets were evaluated through the model in different configurations. The configurations were as follows,

1. First Come First Serve (Incumbent)
2. Solver Scheduling
3. Solver Routing and Scheduling – the proposed algorithm
4. Equity 1 (Priority KLM) – proposed algorithm being partisan to KLM
5. Equity 2 (Priority Non- KLM) – proposed algorithm being partisan to non-KLM airlines

The output was in the form of delay for individual aircraft which were then consolidated to delays for airlines. The delay(s) were the result of the decision which was based on the configuration used; this aspect was used to compare the performance of the various algorithms. Furthermore, the delay(s) for different airlines was used to analyse whether decisions which resulted in the delays are commensurate with the payments made by the airlines.

The findings were quite consistent with the expected outcome of the experimental set-up. The proposed algorithm, in its normal and original state, performed the best amongst all other configurations. In all the data sets, there was improvement in the performance, by using the proposed algorithm, at a global level i.e. for the whole system as a whole. The factor of improvement from the incumbent practise depended on the initial status of the system. Having established the superior performance of the algorithm, the distribution of decision amongst airlines was analysed to establish fairness. The delays for the airlines were monetised using the value of time specific to aviation operation and the situation was analysed using a cooperative game theory approach, where airlines could agree to implement the proposed algorithm by forming a grand coalition or not agreeing thereby reverting back to the incumbent system for all. Only taking the operational cost incurred by the airlines and performance analysis conducted previously, the Shapley Value gave the fair distribution of the costs based on the marginal improvement each airline brought to the system. For all data sets, the Shapley Value was consistent and comparable to the actual costs albeit with minor inconsistencies; in some cases a few airlines paid more than what they

should pay and in some cases they paid less than what they should pay. To tackle the inconsistencies a financial redistribution framework was proposed. The airlines paying less than what they should pay, contribute the default amount to a common fund and then, the money from the fund is redistributed amongst the airlines paying too much according to their Shapley Value ratio to minimise their loss. This system created a system wherein no outside interference is required and by transferring money internally, a sense of fairness could be introduced into the system. Also, this system took care of the local optimal after a global optimal had been established and in fact improved upon the global optimal. In all the data sets, the number of times an airline paid too much or too little was evenly distributed. Also, the grand coalition, wherein all the airlines agree to implement the new algorithm, was inherently stable due the game being inherently convex and the Shapley Value being present in the core. However, owing to the scale of operation of KLM, KLM could impact the performance of the whole system and actually benefitted the most from the proposed algorithm.

To summarise, the proposed algorithm can be implemented to give a superior performance in terms of minimising the delay experienced by the whole airport. However, a further detailed study of the financial agreements between the airlines and Schiphol is required so as to align the actual financial transactions with that of the ideal or the fair financial transactions. Also, for any financial framework or agreement between Schiphol and various other airlines, the interests of KLM should always be taken into account since KLM is a dominant player whose individual (local) performance affects the global performance. Hence, it can be concluded that the proposed algorithm is definitely an improvement over the existing system and also a sense of fairness can be introduced in the decision support system to ensure participation of all the airlines.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Due to ever increasing aviation throughput, capacity constraints and the inherent stochastic nature of operations, (re)scheduling, keeping in view delays, in a fair, efficient and equitable manner is the need of the hour. This assumes even more importance due to the advent and subsequent adoption of the policies, at all major airports, which involves sharing of information between all stakeholders and Air Traffic Control (ATC). This implies and necessitates fairness and diminishing anti-competitiveness.

There were two aspects of managing airport, the policy aspect and the operational aspect. The policy aspect deals with the implementation of certain operational strategies in the airport, namely, defining the objectives & the stakeholders of the airport and determining the hierarchical relationship between the stakeholders. Most importantly, the information sharing between the stakeholders was also the prerogative of the policy makers. Also the policy aspect has direct ramifications on the competitiveness and efficiency of the airport. The operational aspect deals with the choice of algorithm and operational strategy with respect to sequencing, scheduling and resource utilisation.

In all major airports, more so in hub airports, planning was done at a strategic level and that corresponds to determining the Origin and Destination pairs and the frequency. At a tactical level, the individual flight plan was determined and scheduled, sequenced and finally allotted a runway for either landing or take-off by the respective ATC. Now due to growing demand of air travel, limited capacity of airports and stochastic nature of air travel due heavy dependence on external agents like weather, scheduling and sequencing assumes critical importance and was often the bottleneck in airport operations. And if a flight was delayed, it affects all the subsequent connecting flights and necessitates rescheduling and re-allotment of airport resources. The role of Air Traffic Controllers was to manage the traffic in an airport in the most efficient manner possible while maintaining the required safety standards.

The most standard sequencing and scheduling algorithm was the First Come First Serve (FCFS) algorithm. It simply refers to the fact that, the order in which the aircraft enters the Terminal Control Area (TCA) and demand service was the order in which they would be allowed to land or take-off. This might sound fair from the point of view of the airline operators but, from the point of view of the ATC, it may not be fair and efficient because the primary function of ATC was defined as managing the operation efficiently while maintaining regulations (FAA). Therefore, there have been, and still continuing, several studies to determine different algorithms to optimally manage the operations. The effectiveness of an algorithm was usually determined by comparing the output to the output when employing FCFS. However, a crucial aspect, that was, fairness has not been studied much in the context of optimal solution. Fairness, while taking different definitions for different contexts, in this case refers to not being anticompetitive and promoting business and meaning fair distribution of decisions.

As mentioned earlier, different algorithms have been studied to manage the sequencing and scheduling operation in the airport and consequently, the operations were formulated as the objective function and were formally known as the Aircraft Scheduling Problem (ASP). The most common formulation was in the form of a Mixed Integer Linear Programming (MILP) problem. The objective function can be minimising make span or maximising throughput and the constraints were usually the minimum separation required between subsequent and any pair of aircraft due to safety reasons. The problem belongs to the class Non-Deterministic Polynomial-Time Hard (NP-Hard) and thus complexity was always an issue along with practical implementability, as with the increase in number of aircraft, the complexity and solving time increases. Consequently, (Meta) heuristics were more often than not the best approach to solve these problems and produce almost optimal output.

Although, the problem can be formulated as a travelling salesman problem or a queuing theory problem, the most relevant formulation was as a Job Shop Scheduling Problem (JSP). This was most relevant because it was also sequence based, time based and takes into account the original schedule of the aircraft into the decision making process. And most importantly, the safety separation requirements can be easily formulated into the problem (Hoffman & Ball, 1997) (Krishnamurthy, 1991).

Of the many formulations to solve the job shop scheduling problem, the most relevant in this case was the disjunctive/alternative graph formulation and solution. The disjunctive graph formulation essentially determines all the possible sequences while keeping in mind the minimum separation requirement and constraints, and finally choosing the path with the minimum make span. This methodology was location specific and depends on the airport architecture, runway design, and throughput and ground operation facilities.

Therefore, for this research, a combination of disjunctive graph formulation methodology was used specific to the Schiphol Airport, Amsterdam by creating the schematics for the graph formulation and adapting the time horizon. The objective of this research was to solve and evaluate an ASP by using the above mentioned formulation. The key factor was to establish that such a formulation was indeed an improvement over the standard practice of FCFS. Having established the efficiency of the algorithm, by comparing the make span, delay costs and resource utilisation, it was important to analyse the fairness of the algorithm from a multi-stakeholder's perspective. This was important in order to gain acceptance from the users of the resources as well as be more attractive to potential new users.

The data set for the project was based on real data from Schiphol with respect to the number of take-off and landings in a specific time period. By using a probability value, different class of aircraft were defined having different Wake Vortex. To the scheduled aircraft, three types of delays were added to simulate the delay to uncertainty due to weather or any eventuality, ranging from small to medium to heavy delays. Because the original number of flights was based on real data, the simulation of delay creates every possible scenario for the algorithm to be tested.

The actual algorithm consists of Branch and Bound (B&B) algorithm, FCFS algorithm for comparison and benchmarking purposes and a heuristic in the form of TABU search to find a near optimal solution. The output of the algorithm was the delay value for the system. Again based on real data, monetising the delay and assign probabilistic distribution, the impact on various airlines was analysed to determine the fairness of the algorithm.

The output was then analysed from the point of view of ATC and then different relevant stakeholders. The operational aspect of operations management was used to frame an algorithm, the management aspect of the said algorithm and its impact and it was analysed for fairness, effectiveness and competitiveness. The fairness was determined by using a cooperative game concept called Shapley Value and the Core.

The organisation of the report follows the methodology of the project closely. Chapter 2 and 3 define the problem statement and context of the problem statement. Chapter 4 and 5 present the relevant standard practices and an extensive literature survey of all the previous work that has been done in this field. Chapter 6 and 7 present the algorithm and the methodology for the project. The experimental set up has been described in Chapter 9. Chapter 10 provides the result and the subsequent analysis. Chapter 11 presents a discussion on the results obtained. Finally the report concludes with Chapter 12 and 13, which presents the conclusion, recommendation and future scope of research.

Chapter 2. Problem Statement

The primary aims of this project was to test and evaluate a scheduling algorithm at Schiphol Airport, Amsterdam and specifically study the impact of delays in the decision system and the consequent impact on the stakeholders with respect to fairness. The algorithm, in this case, was essentially formulated to solve the ASP, with objective to minimise delay, which included sequencing, scheduling, runway assignment and taxiing. While solving, the objective function was to minimise the direct delays while ensuring safety regulations were complied in both scenarios, with and without delay. The methodology included alternative graph formulation, B&B, and TABU search heuristic and a comparison with FCFS algorithm. Also included was an analysis of the fairness and equitable nature of the whole decision making process. Fairness here means that, from the point of view of ATC, the decisions from the algorithm with respect to routing and scheduling have to be commensurate with the operational investments/payment of the airlines, in other words fair distribution of decisions. This was due to the fact that the decisions of the ATC translate to the aircraft being early or later than the scheduled time, which has financial implications. Hence it was necessary to evaluate that the decisions result in benefits commensurate with payments failing which, a framework to offset financial loses was required.

The research question can be stated as follows -

“What is the impact of implementing an alternative graph based job shop algorithm to solve the Airport Scheduling Problem at Schiphol Airport, Amsterdam, on the global control system, operational efficiency, equity and fairness amongst stakeholders, under various conditions of operational delay.”

To help answer the primary research question, certain sub-questions have to be solved, which may be stated as follows –

1. How the current system in place was not sustainable and what were the problems?
2. What was the impact due to the centralised (global) control system employed in the TCA on the operational efficiency?
3. What was the effect on delay of the operations of the airport and financial implications of same?
4. What was the hierarchical representation of the stakeholders in context of the said algorithm?
5. How much fairness can be incorporated into the decision making process by using the proposed algorithm?

2.1 Scientific Relevance/ Contribution to Literature

This project work uses the work of Marcella Sama and D’ariano by utilising the optimisation solver developed for two major airports in Italy, Rome and Milan. To that end, this project uses the solver, compiled including solving approaches/algorithm, to solve the test instances and evaluate traffic instances at Schiphol. However, that work focuses on the airside operations only and since land side activities like taxiing also impact the schedule, those aspects were conceptualised and introduced in this research. Also, two further analyses were carried out, monetising the delay and fairness analysis of the said algorithm with respect to incumbent practises. The following were the specific contribution from this project work –

1. New test case at the Schiphol Airport with increased traffic for statistical robustness
2. Analysis of the properties at Schiphol with respect to mapping the resources used by the aircraft and utilising those information in the algorithm
3. Introducing extra operations on the ground, taxiing time and gate approach time
4. Financial Analysis in the form of financial implications of delay
5. Monetise time and use these values for performance analysis through various indicators
6. Fairness Analysis using game theoretic approach

2.2 Practical Relevance

With the focus of the aviation industry firmly on collaboration and improving efficiency, the objective of airports nowadays was to improve the efficiency of the airport node in the network, maximise throughput and utilise resources efficiently. But, the operational implementation, which deals with primarily routing and scheduling, was still done by the FCFS logic, which has been studied to be not optimal. Hence, this research aims to evaluate a different and advanced algorithmic approach to routing and scheduling so as to improve efficiency, minimise delay and ensure all regulations, safety and policy based, were met. The output of the research was the study of the impact of the implementation of an algorithm, which was expected to improve efficiency by minimising delays, on the operational level activities at Schiphol and also on the operations of the stakeholders. The impact on the stakeholders was analysed through game theoretic tools and reflect the group dynamics and the system as a whole. Hence, this study was important because this was the initial step to develop a complete decision support system by analysing the scheduling and routing and the associated impacts.

2.3 Deliverables

The deliverables for the project work were –

1. Defining the test case of the Schiphol Airport in terms of resources used by aircraft and identifying appropriate properties for the same.
2. Using the test case for an algorithmic evaluation at Schiphol airport with real traffic scenario.
3. Evaluating the algorithm for a specific time horizon and compare it with the incumbent approach for operational efficiency and fairness.
4. Analysing the impact and advantages of the said algorithm.
5. Analysing the impact on the stakeholders and their respective hierarchical relationship.
6. Drawing analogy with a cooperative game theory scenario to analyse the type of collaboration between the stakeholders.
7. Evaluating the fairness of the algorithm through the game theory analysis by framing the problem as a cooperative game and using Shapley value as a tool to evaluate fairness distribution.
8. Monetizing the output of the algorithm and using the above analysis to design a financial mechanism to offset any unfairness inherent in the algorithm.

Chapter 3. Context

The primary objective of this project was to evaluate a specific algorithm for Schiphol, operate it using real time data and assess the impact and advantage of the same. The specific algorithm here refers to an advanced optimisation algorithm for traffic control, proposed to be used by ATC in the TCA, tested against real traffic data set. Owing to the nature of aviation operations, there a lot of constraints involved as well as a lot of performance indicators like make span and cost function. Hence it was important to define the objective function and the perspective of analysis of this project work.

Although cost was the most important factor in almost any operation, in the aviation industry, cost was usually a derived function of time and hence the algorithm focuses on minimising the make span and consequently the delay. Apart from minimising the total delay, the average delay for a given time horizon can also be examined to gain a perspective into the effect on the various stakeholders. The primary beneficiary of this project would be the ATC, Schiphol. This makes sense as well because one of the jobs of ATC was to manage the airport efficiently while maintaining all regulation thereby making the network of airports efficient through minimising queuing and utilisation of airport resources. So, the primary stakeholder of this project was the ATC and the objective function was to minimise the make span and consequently, delays.

Since the input for the algorithm will be real time schedules of flights to and from Schiphol, another interesting aspect can be visualised and analysed, the impact of delay on the operations. In other words, how the decision making process, based on an algorithmic principle was affected by delays. It was interesting to see, how the algorithm works out the optimal solution in case of a large number of delays and whether the solution was in fact a local or a global optimal solution. Also it was interesting to note how delays for specific airlines result in scheduling. An important consideration here was that, delay in air was more expensive than delays on ground, with the difference studied to be almost double (Inniss & Ball, 2004) and hence, in case of a conflict, arrivals always take precedence over the departures. This also defines and scopes the project work as focussing more on the operational scheduling.

Another aspect that was considered important in gauging how efficient an airport was the utilisation of resources. Again, the algorithm was primarily designed based on defining the TCA into resources and assigning properties to them and resolving conflicts in order to minimise the make span. Efficient utilisation of resource leads to higher throughput, which was one of the objectives in the agenda of the airport.

Although it was difficult to negotiate and utilise user preferences in case of aviation operation due to the inherent safety requirements, it was important to see the dynamics between the stakeholders. As mentioned earlier, the algorithm's primary beneficiary would be the ATC but given the sharing of information, the collaboration with ATC and internally with other airlines would tend to work only in case of a sense of parity. Hence the impact of the said algorithm assumes importance in view of the hierarchical relationship between the stakeholders, both with ATC and with other airlines as well.

To conclude, the context of the problem statement can be defined as to solve an aircraft scheduling/routing problem with the objective of minimising the delays and ATC as the primary stakeholder. Apart from the above mentioned focus of the project, the project also focuses on the impact of delay in a similar context and the hierarchical interaction/dynamics of the stakeholders. And furthering the stakeholder's analysis was an analysis on the fairness of the algorithm using a game theoretic approach, Shapley value. Figure 1 presents the context of the project work and Figure 2 presents the operational context of the project work.

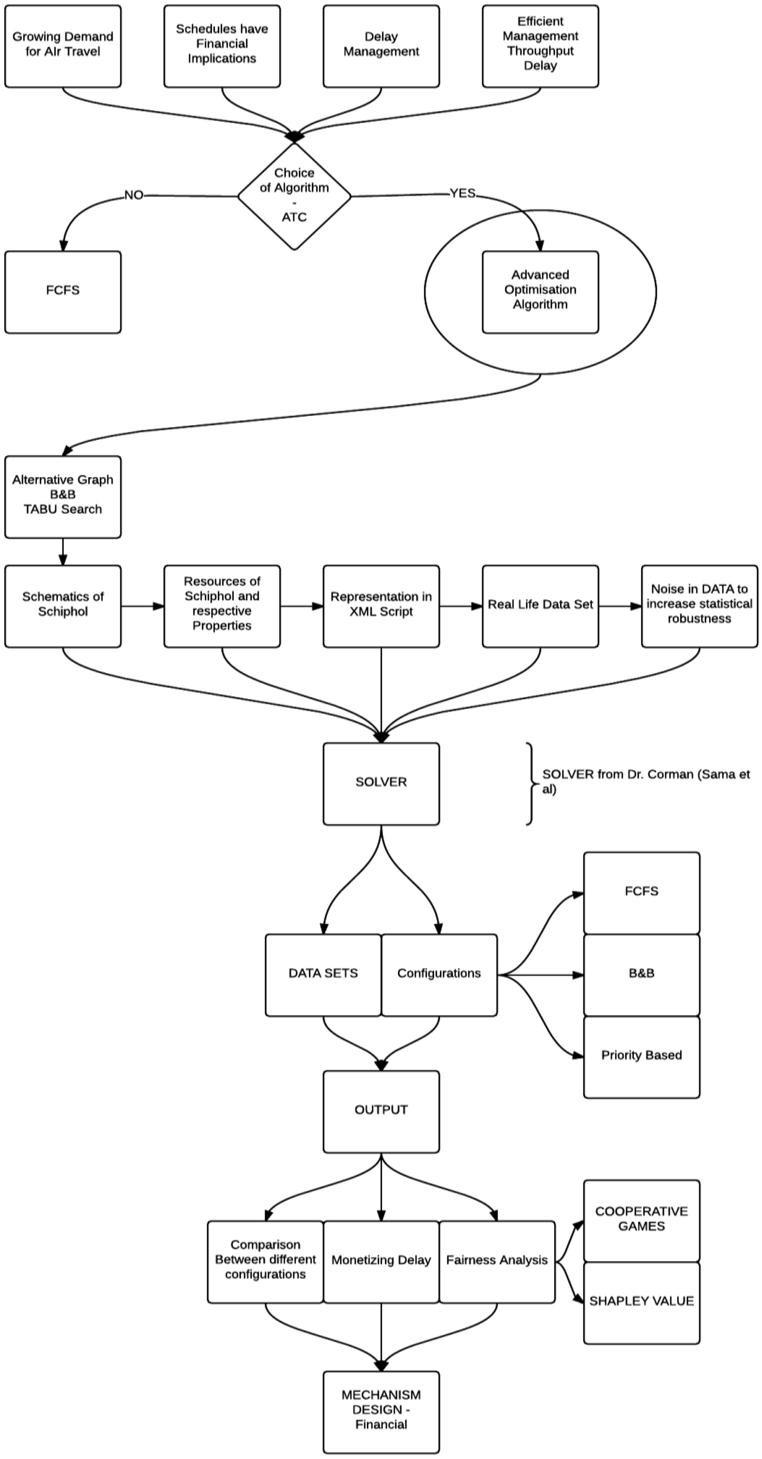

Figure 1 Context of the Project

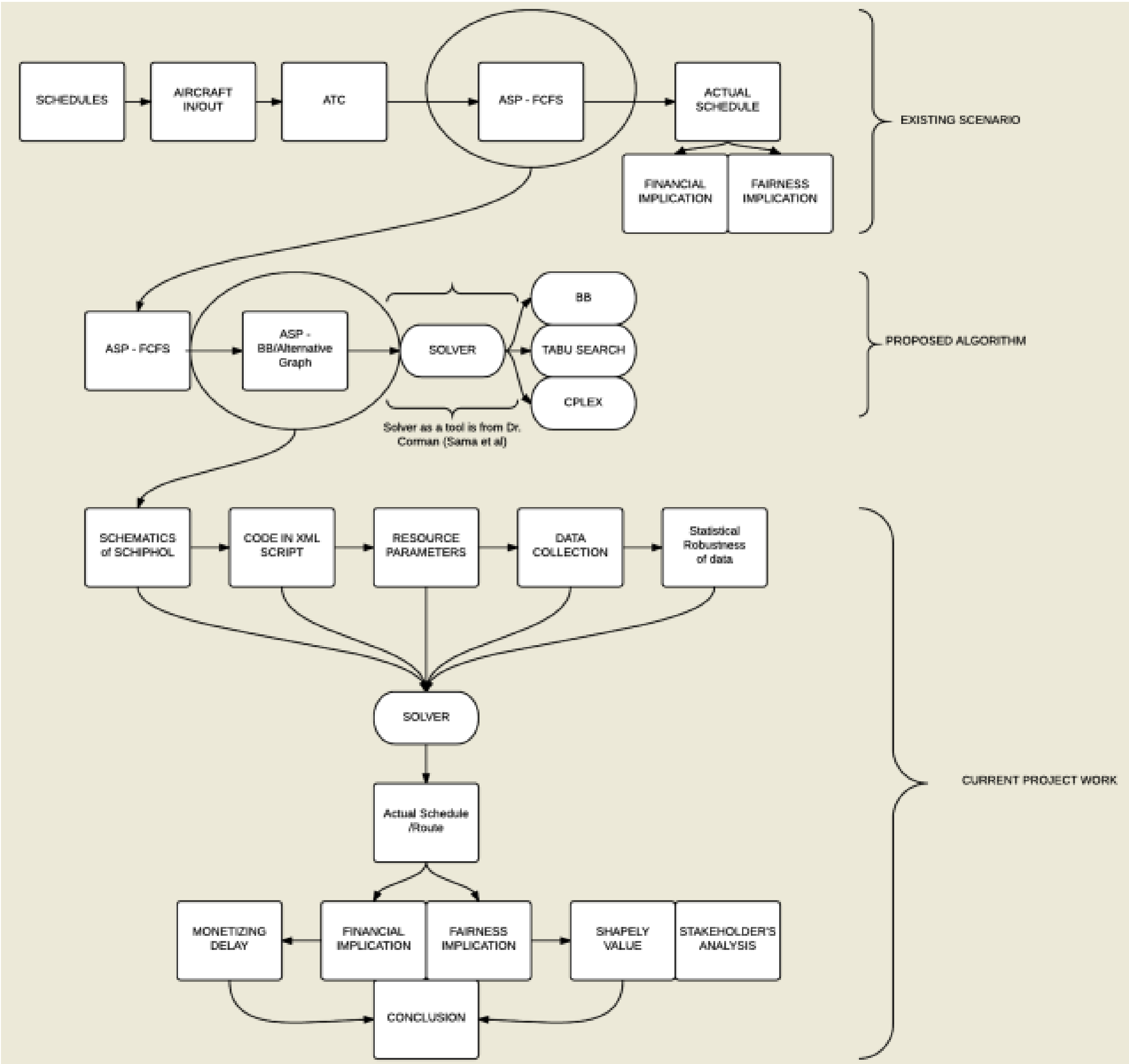

Figure 2 Operational Context of the Project Work

Chapter 4. Standard Practices

This chapter describes the standard practices pertaining to the scheduling agreements, gate allocation and hierarchical nature of the aviation operation.

4.1 Schiphol Operations and Schematics

Schiphol is the primary airport in The Netherlands and one of the major airports in Europe both in terms of passenger traffic and cargo throughput. It also serves as the primary hub for KLM airlines as well as KLM City Hopper. The Schiphol airport was designed as a single terminal layout with three major departure halls. Consistent with growing traffic trend in global aviation throughputs, Schiphol has been consistently witnessing growth in both passenger and cargo segments. In the year 2014, almost 55 million passengers were served at Schiphol, which, apart from being a huge number, was a growth of around 3% compared to previous years. Almost 1.5 million tonnes of freight were processed at Schiphol. The economic and social impact was valued at 27.3 billion euro (Schiphol) (Statistics Netherlands, 2014) (Aeronautical Information Publication, 2014).

4.1.1 Runways

Schiphol has 6 runways which cater to both civil and general aviation. The runways are described as follows –

1. 18R/36L Polderbaan (3800 m)
2. 06/24 Kaagbaan (3500 m)
3. 09/27 Buitenveldertbaan (3453 m)
4. 18L/36R Aalsmeerbaan (3400 m)
5. 18C/36C Zwanenburgbaan (3300 m)
6. 04/22 Oostbaan (2014 m) (Primarily used for general aviation, hence, excluded from the analysis)

Figure 3 Runway Layout (B)

Polderbaan	**18R – Landing**	**36L – Take Off**	**24 hour operation**
Zwanenburgbaan	18C – Takeoff/Landing*	36C – Takeoff*/Landing	*Daytime Operation
Kaagbaan	06 – Takeoff/Landing	24 – Takeoff/Landing*	*Daytime Operation
Buitenveldertbaan	09 – takeoff/Landing	27 – takeoff/Landing	Daytime Operation
Aalsmeerbaan	18L – Takeoff	36R – Landing	Daytime Operation

Table 1 Details of Runway

Figure 3 depicts the runway layout and Table 1 provides a detail of runway. Owing to Schiphol's location and standard practices, the selection of runways and orientation was determined by the wind direction and wind velocity. Since the aircraft always takes off and lands towards the wind, because headwind provides lift, the direction of wind determines the orientation. The operations which are decided owing to the wind orientation are usually of two kinds –

1. North-South Operation
2. South-North Operation

The orientation and usage of runways was determined based on the above two categories while the number of runways was determined by the time of operation i.e. peak or non-peak.

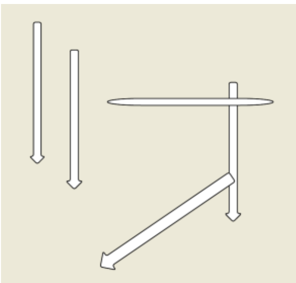

Figure 4 2+2 North South Operation

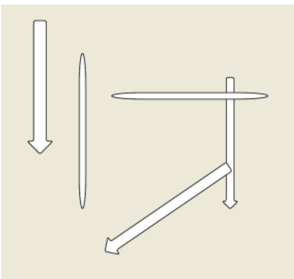

Figure 5 2+1 North South Operation

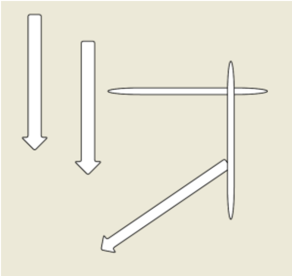

Figure 6 2+1 North South Operation

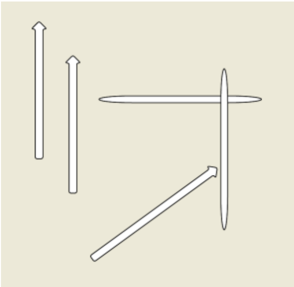

Figure 7 2+1 South North Operation

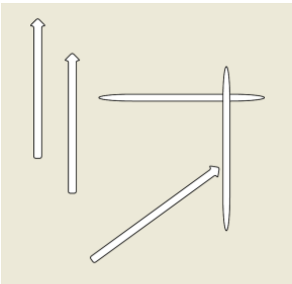

Figure 8 2+1 South North Operation

Figures 4-8 show the direction of the headings of the aircraft that land and takeoff at Schiphol. Usually the configuration that was used was 2+1, alternately assigning two or one runways from landing and take offs, depending on the arrivals or departures peak or non-peak operations. Sometimes when the capacity was over stretched, the 2+2 configuration was used, meaning two for arrivals and two for departures.

4.1.2 Terminal Control Area (TCA)

There were clearly demarcated regions or areas which fall under the aegis of the Schiphol ATC. Figure 9 shows the extent of the ATC area and the demarcations with other neighbouring ATC's.

Figure 9 TCA Schiphol

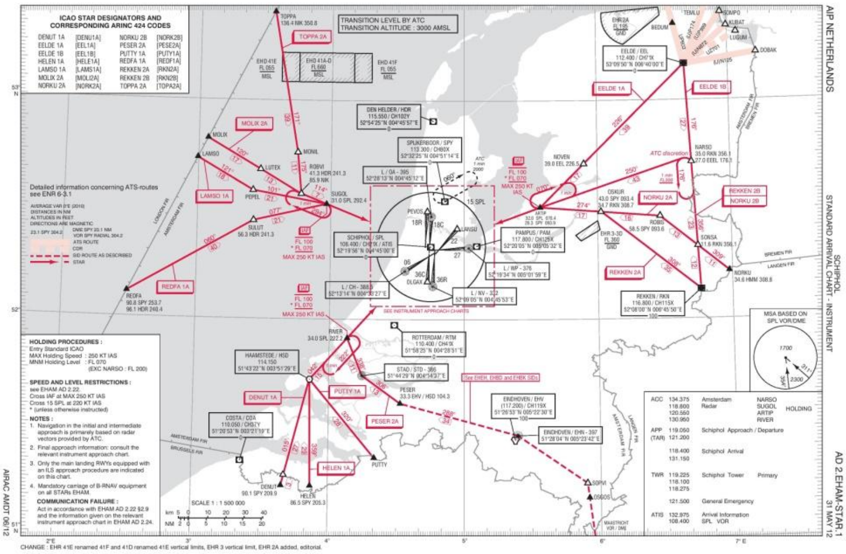

Figure 10 Schiphol ATC control area and arrival pathways (Schiphol)

The decisions pertaining to scheduling and routing were taken for every aircraft once it enters the control area of the relevant ATC, which in this case was Schiphol. Figure 10 shows the waypoints that every aircraft follows to land at Schiphol. Depending on the origin of the flight, the runway assigned to it, other traffic and weather, the aircraft follow one of the approaching glide path, do a holding manoeuvre if required and then land on the assigned runway. As explained earlier, the routing and scheduling was done at an operational level using the FCFS rule. The air corridors were well defined as per the RADAR that was monitoring them and the speed, altitude and rate of descent was well defined for each manoeuvre and corridor. The same procedures were followed for departures as well, but since there was no conflict in any land or air corridor for departures, those aspects were not considered in this research.

4.1.3 Landing/Departure Procedures

In the above chapters, the tactical and strategic planning was explained which was used by the airport authorities and various political organisations to negotiate a schedule through bilateral and/or multilateral treaties. However, due to the inherent stochastic nature of the operations, at an operational level, more often than not, there were changes to the schedule. The changes may be due to delays, weather or even some incident. Therefore, the common understanding was that the landing decisions were usually taken on a FCFS basis. The departures, unless faced with some specific instance of incident, follow largely the schedule in terms of scheduling.

4.1.4 Schematic Representation

For the purpose of this research, the Schiphol TCA was divided as resources and the resources were defined by the properties of the aircraft utilising them such as speed of the aircraft and the time taken to traverse the resource. Based on the arrival chart, the focus area can be divided in to the following resources –

1. Approach air segments – The approach air segments can be defined as the RADAR waypoints which identify the route of an aircraft after it enters the TCA on its approach to Schiphol. They were named by the RADAR used to monitor the aircraft utilising the said resource.

Depending on the origin of the aircraft and the runway configuration used by Schiphol, the aircraft may utilise any of the 12 air segments for approaching. The three regional approaching segments were named as SUGOL, RIVER and ARTIP which is presented in Figure 11.

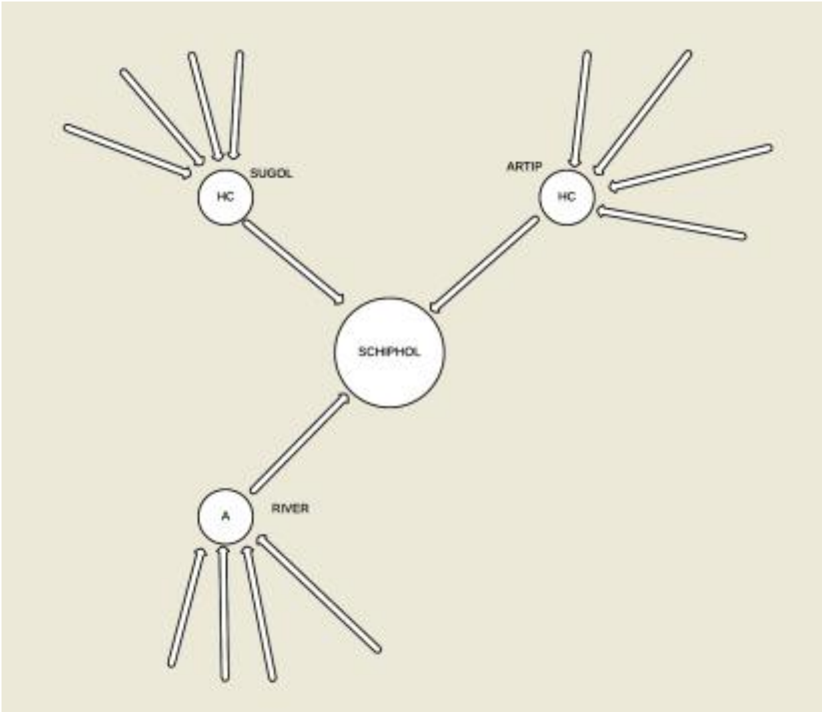

Figure 11 Approach Segment and Common Glide Path

2. Common glide path – After using any of the above mention air segments, the aircraft goes through common glide paths, which were three in numbers and were also named same as above. Figure 12 presents sample glide paths and approach segments of ARTIP.

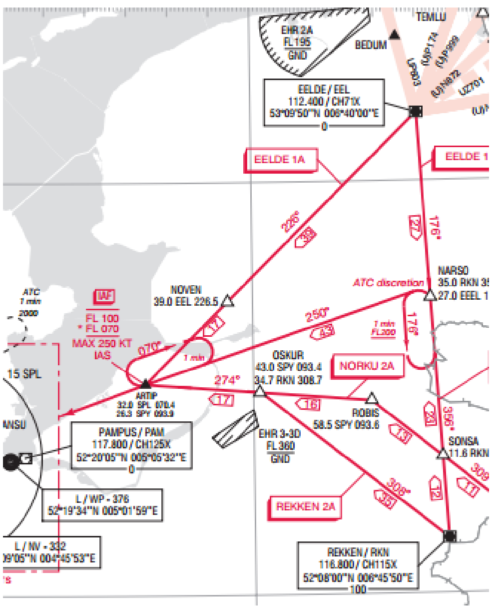

Figure 12 Sample Glide Paths and Approach Segments (ARTIP)

3. Holding pattern – Manoeuvre for orientation with proper runway. The holding circles were effectively used when the aircraft has to spend some extra time in air due to the runway or any other land resource not being ready for its own use. However, in this case, the holding pattern refers to the manoeuvre that an aircraft has to undertake in order to have the right orientation with the runway being used for landings.
4. Glide path specific to the runway – The glide path specific to each runway was the path where the aircraft undergoes constant descent approach and immediately afterwards lands on a specified runway. Figure 13 presents the holding pattern and glide for runway 06.

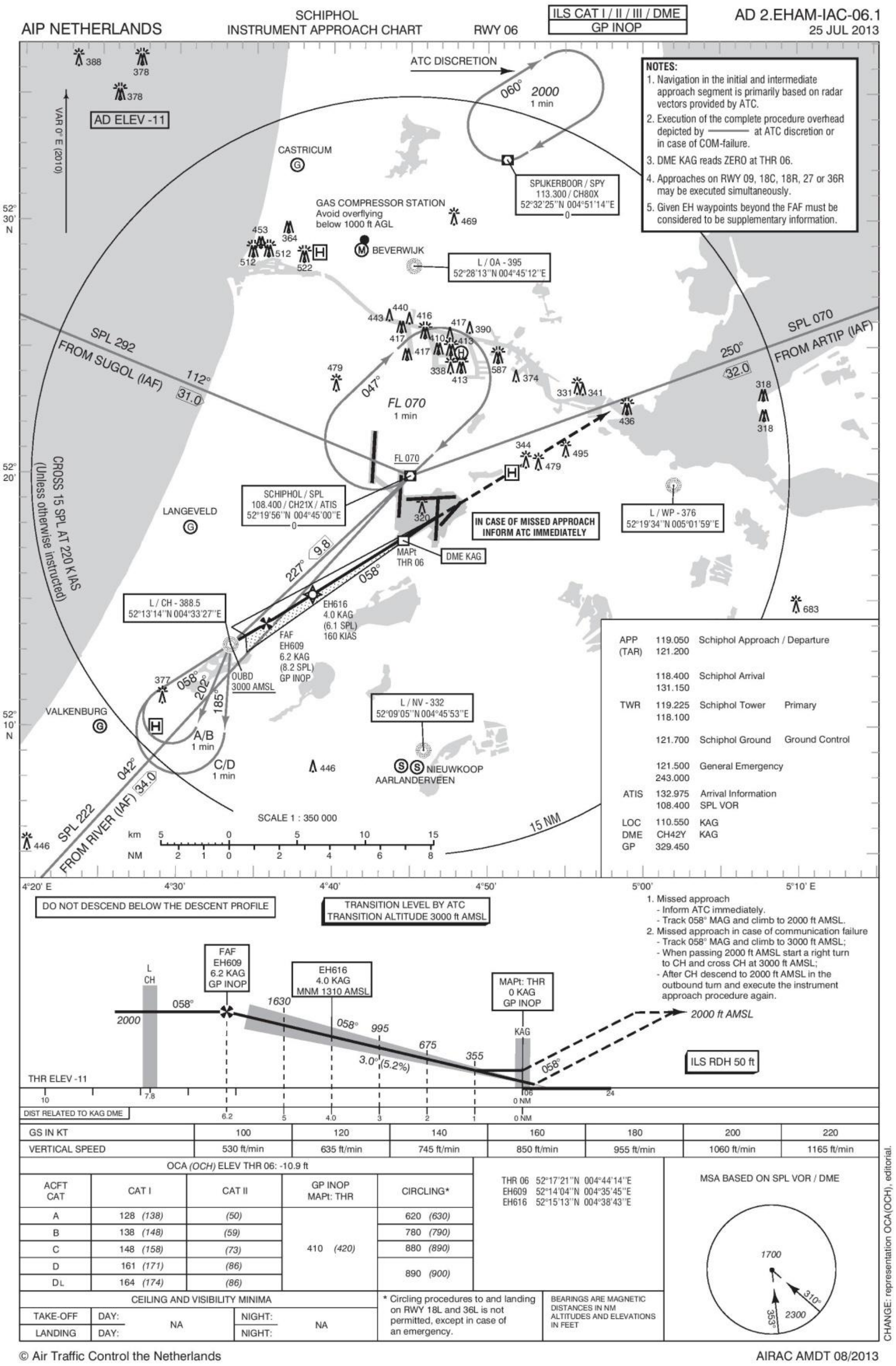

Figure 13 Holding pattern and Glide for Runway 06 (Schiphol)

5. Runway – Arrivals
6. Taxi ways – Arrivals

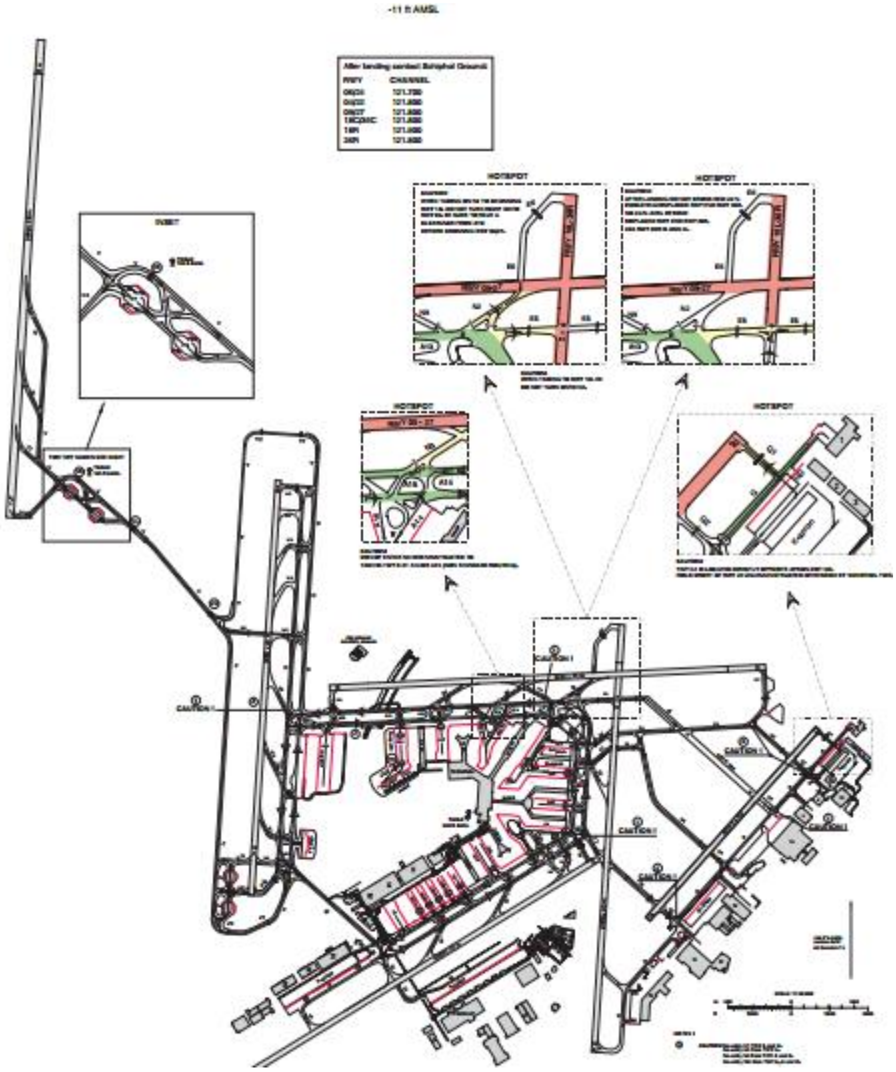

Figure 14 Ground Movements (Schiphol)

7. Gates
8. Turn Around Time
9. Taxi ways – Departure
10. Runway – Departure

Table 2 provides a summary of all the resources for Schiphol TCA.

approach air segment	common glide	Holding pattern	glide path	runway arrivals	taxiway arrivals	gates	taxiway departures	runway departure
SUGOL1	SUGOL	SIMILAR	GLIDE PATH 1	06K	Time Specific	Infinite Resource	Time Specific	06K
SUGOL2			GLIDE PATH 2	09B				09B
SUGOL3			GLIDE PATH 3	18CZ				18CZ

SUGOL4			GLIDE PATH 4	18RP				18L
RIVER1	RIVER		GLIDE PATH 5	24K				24K
RIVER2			GLIDE PATH 6	27B				27B
RIVER3			GLIDE PATH 7	36CZ				**36C**
RIVER4			GLIDE PATH 8	36RA				36L
ARTIP1	ARTIP							
ARTIP2								
ARTIP3								
ARTIP4								

Table 2 Details of resources for Schiphol TCA

4.2 Aviation Operation

The aviation operation, since the de-regularisation of the aviation industry, has grown in leaps and bounds and continues to do so at a very robust rate.

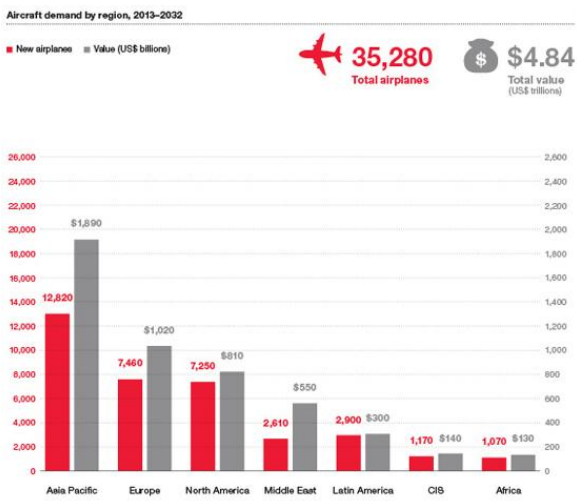

Figure 15 Aircraft Demand/Growth (Boeing, 2013) (IATA, 2013)

Figure 15 shows the demand of aircraft in the time horizon till 2032 depending on the region including the financial value of the expected growth and it clearly shows the robust growth. Owing to the growth, it was essential that the airports handle the enhanced traffic in an efficient manner so as to be an efficient service provider while being financially viable at the same time. Being competitive and financially viable assumes critical importance due to the two factors, intense competition as well as an enforced collaboration between all the airports, which can be seen as nodes in a network representing aviation. Hence, for the whole network to operate efficiently, individual nodes must function efficiently in processing the incoming and outgoing traffic to and from the said airport/node. Each airport has three kinds of operations along with the corporate identified mission/vision which are as follows –

Mission/Vision – This sets the purpose of the business and defines the goal towards which the company progresses through its actions.

Strategic Action – The strategic actions set the direction of the company. This means that all corporate level decisions including negotiations were done at this level. For the airport, this usually means the location, type of service provided, types of airlines served, throughput estimates and profitability estimates. The timeframe of such actions was usually measured in years and the implementation of any decision was gradual and takes time.

Tactical Operation – This was the intermediate set of actions which functions to align and link the strategy with the operational or day to day activities of the airport.

Operational Action – The operational actions take care of the day to day operation of the airport and were critical to the functioning of the airport. The actual implementation of the strategies occurs at an operational level and the time frame of the operational actions can vary from hours to days, depending on the kind of operation. This project work focuses on the operational actions of an airport and more specifically on the routing and scheduling of aircraft with an objective function, either minimise delay or maximise throughput, on a day to day basis with hourly time horizons.

The details of the three levels of action are summarized in Table 3.

		Mana-gement level	*Dredging organisation*	*Time horizon*	*Scope*	*Level of detail*	*Relates to*
The overall organisation	**Mission**	Top	Board of directors	Long	Broad	Low	**Sustainability, survival, profitability,**
	Strategy	Senior	Plant / Area management	Long	Broad	Low	**Growth rate, market share, environmental goals**
Production/ Operations	**Strategic**	Senior	Plant / Area management	Moderate to long	Broad	Low	**Product design, choice of location, choice of technology (cutter or dredger, which vessel)**
	Tactical	Middle	Project office	Moderate	Mo-derate	Mo-derate	**Employment levels, output levels, equipment selection,**
	Opera-tional	**Low**	**Vessel**	**Short**	**Nar-row**	**High**	**Scheduling personnel, adjusting output rates, inventory management, purchasing**

Table 3 Operations Management Decision Levels (Davis & Heineke, 1991)

4.2.1 Operational Aspect

The scheduling arrangements between airlines and the corresponding airports were done at a corporate level and involve negotiation with all actors involved including civil aviation authorities, as and when required. These can be categorised as the strategic and tactical actions. Consequently there was a schedule in place and, ideally, the aircraft follow the schedule. But owing to any event or disturbance, they do not enter the TCA in the same order as they were expected at Schiphol. Now, due to this situation, the ATC job was to manage the incoming and outgoing traffic and ensure all operations were carried while ensuring safety regulations were met. To do this, the ATC use the FCFS methodology, which was not the optimal algorithm from the point of view of efficiency and delay minimisation. This activity was done at an operational level and this project was aimed at improving the efficiency of these set of activities which include resource allocation, scheduling/routing and gate allocation.

4.3 Delay

It was important to analyse the impact of delays on the aviation operations because the performance of aircraft was usually measured by its compliance with the existing schedules, failing which there was a financial implication. An aircraft might be delayed due to variety of reasons ranging from weather or accidents to simply mismanagement or human error. However, a delay has widespread implications, which can be described as follows –

1. Maintenance – This aspect of delay cost comes from the fact that owing to delay, both en-route or on land, the aircraft has to undergo more fatigue than intended. Hence, this was taken into account during the maintenance operations contributing to the costs.
2. Fuel – This was result of en-routes delay through holding circles or longer re-routes owing to delay at destination airports. Owing to the high price of fuels, this contributes most to the cost of delay while the scheduling was changed en-route. The usual price was 0.8 Euro/kg (Energy Information Administration, 2010).
3. Crew
4. Passengers Hard
5. Passengers Soft
6. Reactionary – The knock on costs incurred due to a delay in the first place. These can be incurred due to gate/slot allocation, connecting passengers or effect on the pliability of the aircraft in that particular route.

The distributions of costs are described in Figure 16.

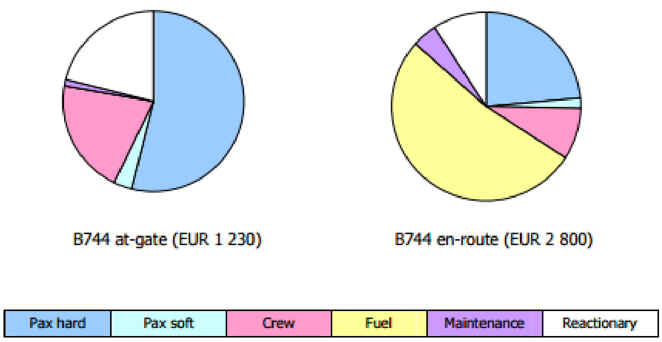

Figure 16 Cost of Delay distribution (EURCONTROL, 2011)

However, for the purpose of financial implications of delay in this research a consolidated value of cost of delay was enough. The algorithm's output and further calculation of fairness were done taking into account the value of delay by monetizing the delay. The value of delay can be seen in the table as represented in Figure 17.

Aircraft	Low scenario	Base scenario	High scenario
B733	1 620	2 850	4 260
B734	1 680	2 940	4 400
B735	1 520	2 690	4 030
B738	1 730	3 100	4 850
B752	2 250	3 870	5 730
B763	3 170	5 390	8 470
B744	6 100	9 480	13 700
A319	1 670	3 000	4 540
A320	1 750	3 120	4 880
A321	2 050	3 650	5 490
AT43	500	920	1 440
AT72	660	1 220	1 900

Figure 17 Total cost of Delay based on aircraft (Euro) (EURCONTROL, 2011)

4.4 Stakeholder Analysis: Preliminary

There are a lot of tangible and intangible stakeholders who were involved in an aviation operation and consequently airport operations. Each of the stakeholders has different objectives and sometimes, owing to that, conflict might arise. Also, in the aviation industry, a clear hierarchical relationship exists between the stakeholders, and consequently it was important, before introducing any innovation, to prioritise and analyse the stakeholders and their perception of the proposed objective of the innovation or policy. The primary aim of this section was to identify all the stakeholders who have an interest in the aviation operation in the context of this project work and describe their objectives and interest in the project. It was important to note that the current scenario was a Multi Actor System (MAS) which means that a lot of actors were involved with varying degrees of involvement, interest and impact on the project.

Based on the multiple characterisation and categorisation, a list of stakeholders was enumerated and they were further analysed in terms of their objectives and potential alignment or misalignment with each other. Table 4 illustrates the stakeholders involved in the Schiphol operations with respect to this project and their objectives.

NAME	OBJECTIVE(S)	COMMENTS
ATC	Minimise Delay Efficient Operation Ensure regulation were met (Safety)	ATC has absolute authority when it comes to decision with respect to any aircraft manoeuvre in the TCA
Airline – KLM	Minimise Delay Profitability Optimal Use of Resources	KLM was the Hub Airline at Schiphol and operates almost 60% of the aircraft in any given time horizon. Financial Contributor
SCHIPHOL GROUP	Profitability Attractive to users and airlines Maintain efficiency in the aviation network	Schiphol owns the airport at Schiphol and has tie-ups with government and municipality. Financial Contributor

	Optimal use of resources	
Operations Employee	Availability of Information Situational Awareness Compliance to labour regulations	This group will both benefit from and contribute to the operational efficiency at Schiphol.
Other Airlines	Minimise Delay Fair allocation of resources through agreements (gate and other aviation resources like air segments)	The other airlines operating at Schiphol should be attracted to conduct operations at Schiphol, through maintaining a balance between the payments and the revenue generation. Financial Contributor
Civil Aviation – NL	Ensure competitiveness of Schiphol through bilateral agreements Determine policy aiming to manage aviation in NL Determine and execute government's role in terms of policy and funding. Support KLM	Policy framing and execution Financial Contributor
Civil Aviation - Other	Support their airline through agreements and negotiation with civil aviation authorities at NL	Policy framing and execution
Municipality of Amsterdam	Ensure attractiveness of Schiphol Manage Noise Regulation	Financial Contributor
Passengers	Minimum Delay Maximum flexibility Minimum cost to passengers Choice of airline/Maximum choice	Financial Contributor

Table 4 Stakeholders involved in Schiphol operations

4.5 Scheduling

The current practice at airports with respect to scheduling is that it is done through various stages of negotiations and agreements. The strategic/tactical level of scheduling is done at a corporate level by various airlines through their respective civil aviation authorities which are represented in Figure 18 and 19. The vertical position represents the power with the agency and the arrows represent the negotiations amongst the agencies. Through agreements between the government authorities and airlines, the types of services are agreed upon ranging from flight services to ground support. This is where Schiphol group comes in and, as mentioned in Table 3, all the stakeholders have their own objectives and try to find a common ground for the services expected and rendered. However, at an operational level, there are a lot of factors which affect the scheduling agreements in place and accordingly they must be resolved. This is the domain of the ATC and it takes responsibility of landing or taking off the aircraft at the airport, Schiphol in this case, efficiently and by complying with all regulations. The aircraft are allowed to use the resources of the airport in the same order as they requested to use them and by comparing with their expected time of departure or arrival, the delays can be calculated.

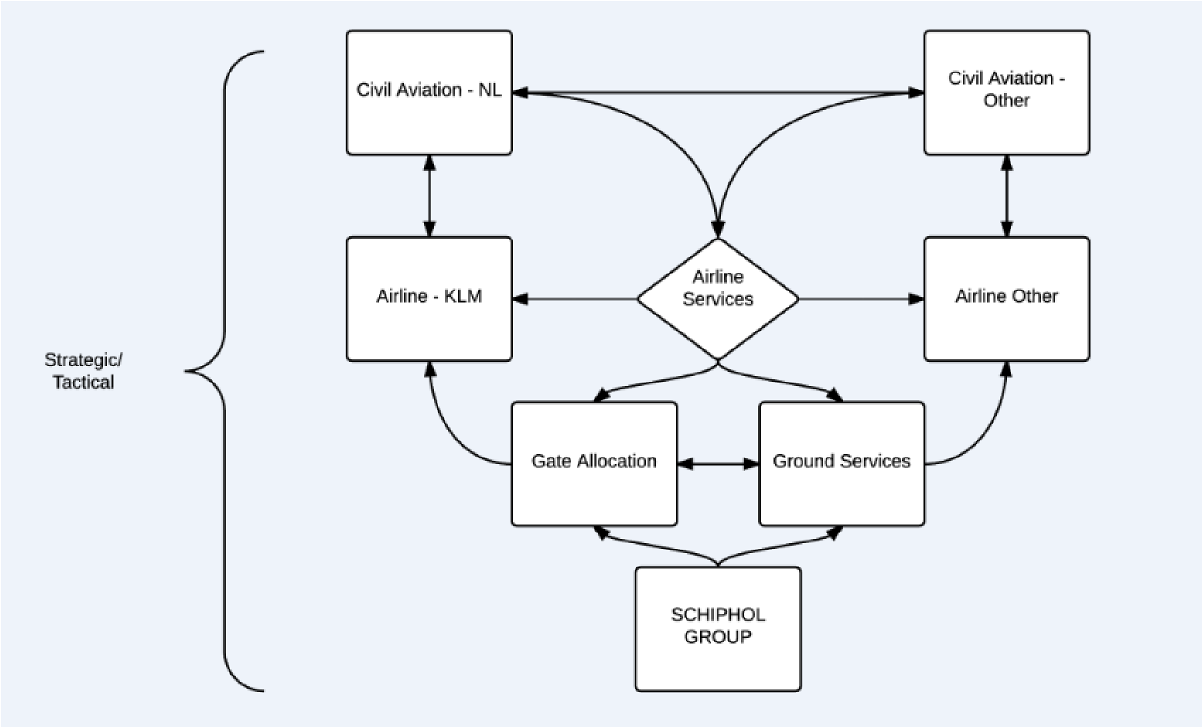

Figure 18 Strategic and Tactical Actions

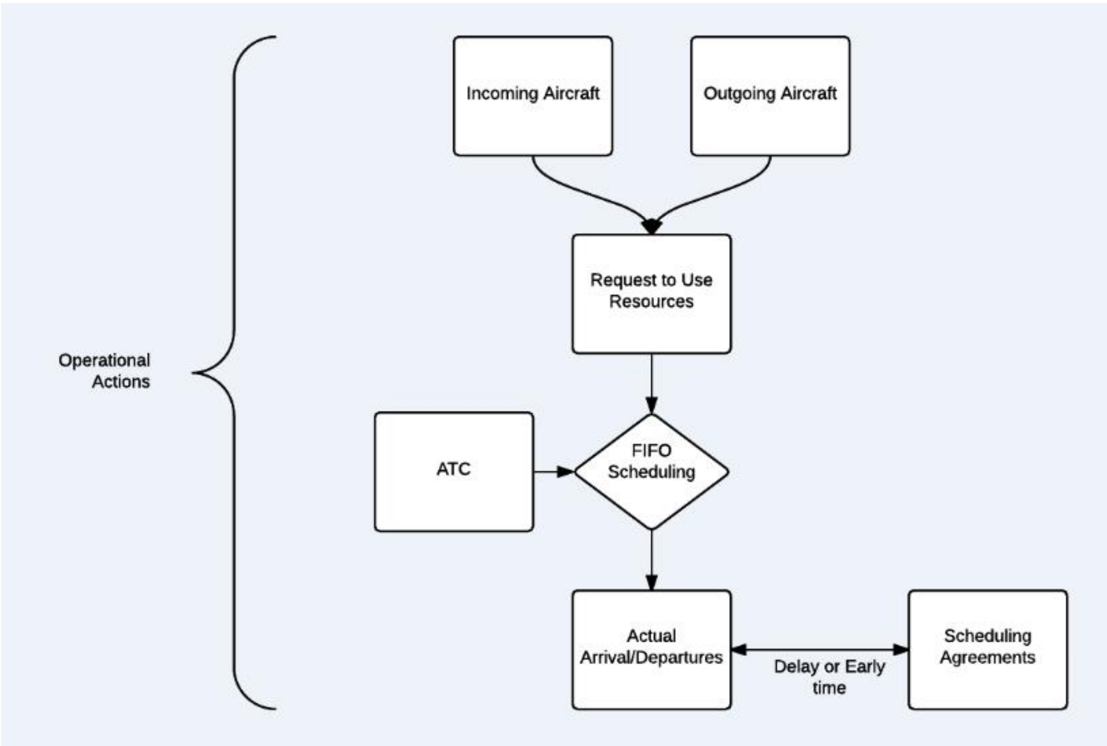

Figure 19 Operational Actions

4.6 Hierarchy

The hierarchical relationship of the stakeholders was important in this type of operations because often, regulation and policy take precedence over operational aspects. There were two types of relationship between the stakeholders, one at a strategic level and the other at an operational level which is presented in Figure 20. At a strategic level, the civil aviation authorities and government authorities from aviation and trade departments negotiate in the preliminary stages to discuss the services between the respective countries and by extension to airports. The Schiphol group and the municipality, Amsterdam in this case, come in at this stage. The Schiphol group provides the services like infrastructure and ground support and they negotiate for sustainability and profitability while the municipality takes care of environmental aspects such as noise and impact on real estate. After this stage, airlines like KLM, the hub airline, and other airlines enter into agreements with the Schiphol group with respect to gate allocation, slot allocation and ground service availability. As before, the negotiations take into account financial viability, sustainability and profitability. At this stage, the ATC and the end users have little or no say at all.

At an operational level, the relationship between the stakeholders was different because regulations and safety criteria were important. So, at this level, ATC was the absolute authority and has the function of scheduling and routing the aircraft. Schiphol group negotiates the gate and slots with the airlines, KLM and others, but the actual usage was moderated and controlled by the ATC. Hence, ATC has the highest priority in the operational level, followed by the airlines. The users, as before, don't have a say in the management of the operations at the airport. The users have a choice in terms of choosing specific airlines, depending on their service. Hence, the airlines primary objective was to provide efficient service in terms of pricing, seating and delay. This project focuses on minimising the delay.

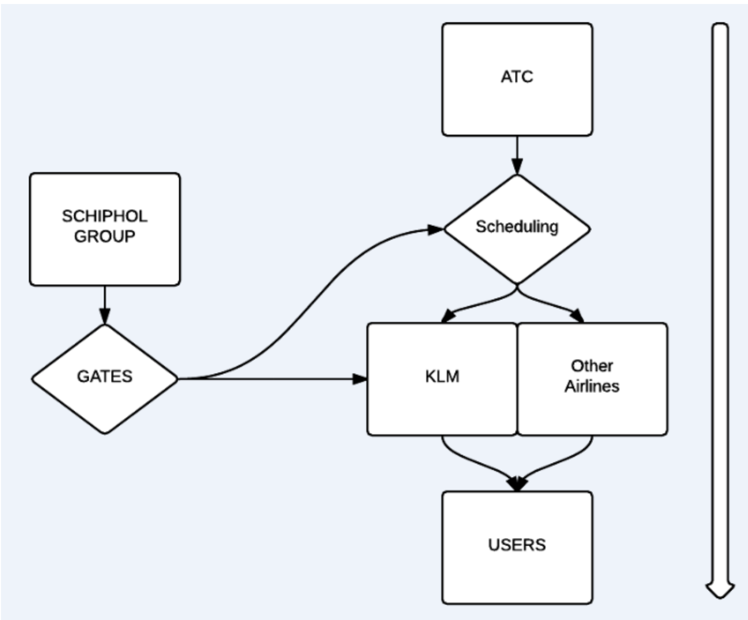

Figure 20 Hierarchical Relations - Operational Action

4.7 Causal Diagram

The nature of the aviation operation is vast and has many aspects which impact the overall decision making process and the global control system. And, since, at each stage a lot of different stakeholders are involved with non aligned objectives, conflicts arise and the decision taken cascades through the hierarchical structure of the system. Within the context of this research, the focus was on the operation scheduling aspect of the aviation operation. The key aspect here was that the decision made by ATC, although pertaining to only scheduling and routing, have wide ranging consequences, primarily financial. Now, since airlines were investing in the airport and also pay for landing and resource usage, it was critically important that the decisions and the consequent financial outcomes were commensurate with the payments so as to maintain fairness and attractiveness of Schiphol from the business point of view. This is best represented through a causal loop as seen in Figure 21.

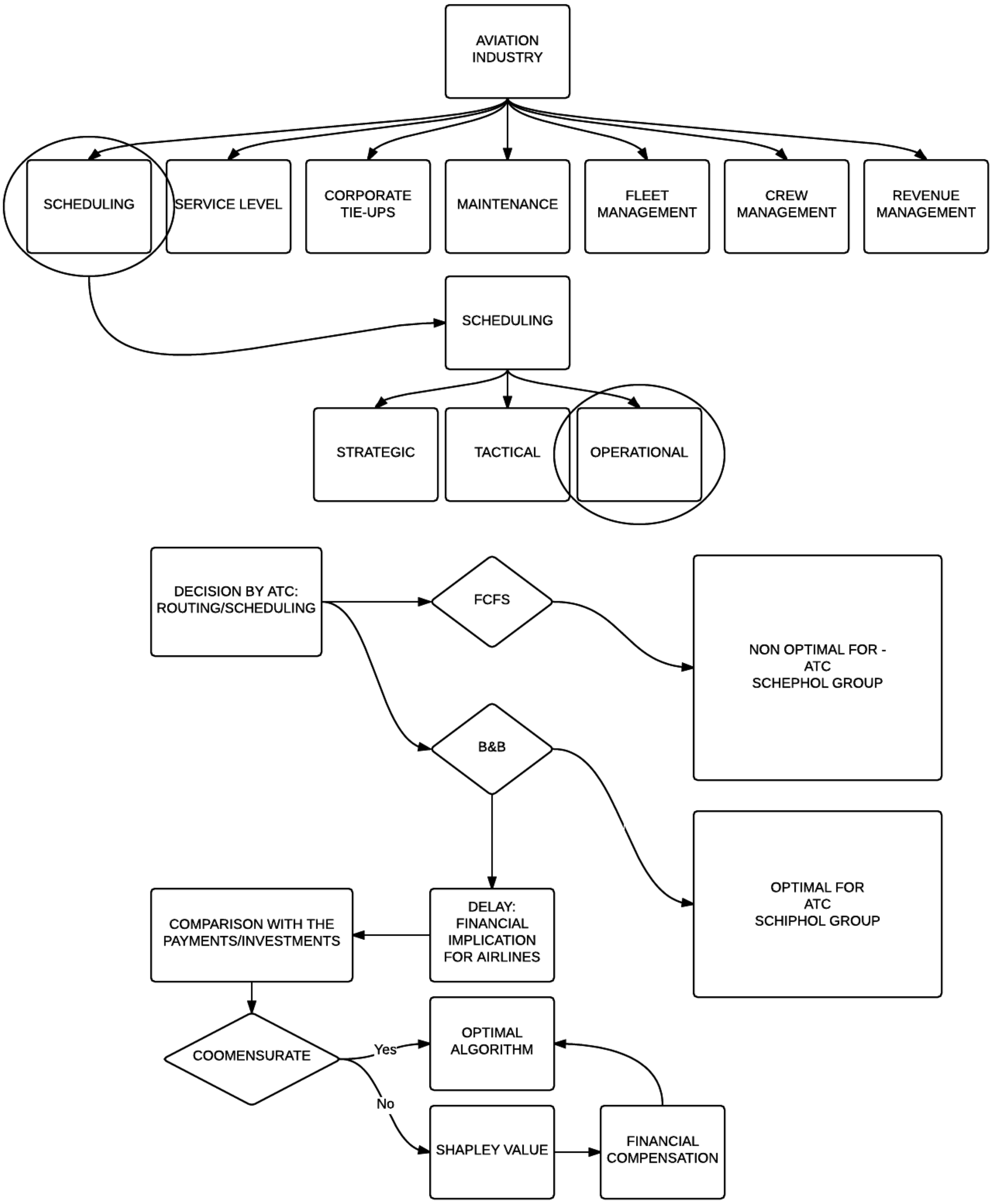

Figure 21 Causal Diagram

4.8 XLRM Model

The XLRM framework was developed by the RAND corporations to aid the decision making process while negotiation with the stakeholders over any project, which was to be implemented. The XLRM framework structures the analysis around key uncertainties, options, metrics and models. This was a useful analytical tool because it represents, at a glance, the whole process flow of the project. And, by identifying, the above mentioned parameters, it was easier to execute and evaluate any process. Also, it was helpful while negotiating the decision strategy with the stakeholders. The XLRM model can be described having the following properties –

1. Exogenous Uncertainties – These are a set of factors which affect the ability to achieve a certain objective.
2. Response Packages/Policy Levers – Management strategies available to the agents which can be used to achieve the defined objective.
3. Models – Models to produce metrics of performance (M) for each strategy (L) in the face of ensembles of uncertainties (X) as can be seen from Figure 22.

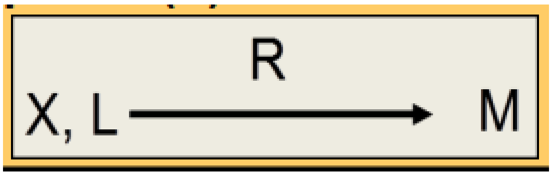

Figure 22 XLRM: Models (Lempert, 2012)

4. Performance Metrics – These are the outputs of interest which reflect the decision maker's goals.

Now, in the context of the current project, Table 5 shows the various aspects of the XLRM model prior to the experimental design.

EXOGENOUS UNCERTAINTIES 1. Delays due to weather, accident or some other issue. 2. Schedule agreements between airlines and Schiphol group 3. Perception or alignment of objectives of different actors 4. Fair distribution of the decision from ATC	**RESPONSE PACKAGES** 1. Minimise delay globally 2. Minimise delay locally 3. Use another advance algorithm instead of FCFS 4. Prioritise KLM in the algorithm 5. Prioritise other airline in the algorithm 6. Implement Fair Distribution through Shapley Value **7.** Implement financial compensation through utility redistribution
MODELS 1. Advanced Optimisation Algorithm using alternative graph formulation with modifications. 2. B&B, FCFS, TABU Search, CPLEX 3. Game Theoretic Analysis 4. Financial Framework	**PERFORMANCE METRICS** 1. Delay for each aircraft translating to delay for each airline 2. Financial output with respect to the operational costs – landing, delay, noise charges 3. Distribution of the cost amongst the airlines – Shapley Value 4. Redistribution of the costs amongst the airlines – Financial Framework

Table 5 Stakeholders involved in Schiphol operations (Lempert, 2012)

Chapter 5. Theoretical Background and Literature Survey

The ASP has evolved over the years; from being considered for a green field project to managing existing infrastructure or capacity in the most efficient manner. Consequently, the various aspects of the problem concerning the objective function have also changed. The ATC was the principal stakeholder and manages the airline operations in the TCA, being the highest authority in the hierarchy of stakeholders. ATC operation can be termed into the following operations and it is presented in Figure 23.

1. Aircraft Scheduling Problem (ASP)
2. Aircraft Landing Problem (ALP)
3. Aircraft Take-off Problem (ATP)

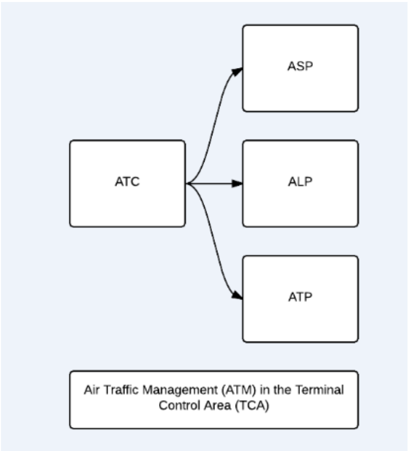

Figure 23 ATM in TCA

The following sections detail the development of each aspect of Air Traffic Management (ATM), leading to the background and basis of the current research work.

5.1 ATC Operation

The ATC, as mandated by the International Civil Aviation Authority (ICAO) (ICAO), is responsible for the efficient operation of the aircraft in the airport premises, TCA, and in the air up to 5 nautical miles (nm) and 3000 ft above ground level, while ensuring the separations, both vertical and longitudinal, within subsequent and any pair of aircraft was maintained (FAA ATC). Figure 24 gives an overview of ATC. This was done due to the presence of Wake Vortex, a form of air turbulence, which was the signature of a jet engine (Tether & Metcalfe, 2003) (Beasley, Sonander, & Havelock, 2001). Apart from the ground and local control mentioned above, the ATC has to coordinate the En-route and Approach control as well to facilitate smooth operation. This was done by the following, and as a whole they manage the complete journey.

1. Terminal Radar Approach Control (TRACON) - 40 nm and 10000 ft form the airport.

2. Air Route Traffic Control Centres (ARTCC) - En-route Traffic Management (de Neufville & Odoni, 2003)

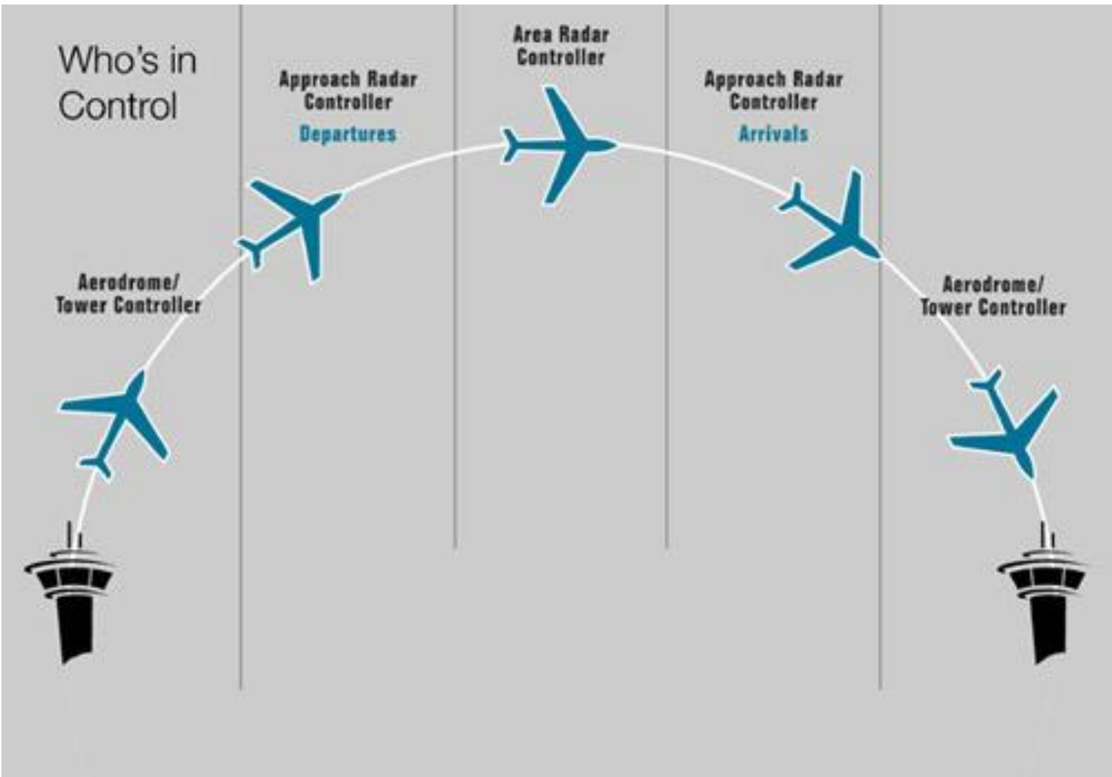

Figure 24 ATC

The above mentioned operations can be broken down to three tasks –

1. Sequencing - This aspect consists of determining the sequence of aircraft landings and take-off from a set of feasible sets, following an algorithm, while satisfying the pre-defined objective function as well as associated constraints.
2. Scheduling - Designating the Scheduled Landing Time (SLT), the Scheduled Take-off Time (STT) and assigning the operational window to each of the activity.
3. Runway Assignment - In most of the major airports, multiple runways were the norm, and so this aspect was concerned with assigning a suitable runway to the scheduled traffic based on ground situation and future operations (Brinton, 1982) (Ernst, Krishnamoorthy, & Storer, 1999) (Bianco, Dell'Olmo, & Giordani, 1997).

Consequent to the sequencing and scheduling, two types of planning activities have been studied for the ATC –

1. Tactical Planning - The sequencing and ground operations were planned a few hours before the actual landing or take-off, for example, a calculated time of take-off (CTOT) or Scheduling Landing Time (SLT) was assigned through EUROCONTROL (EUROCONTROL, 2005) at Brussels when airlines use a busy hub airport.
2. Strategic Planning - This was micro aspect of the above macro planning and refers to the planning and operations in the terminal control area (Atkin, 2008) (Atkin, Burke, Greenwood, & Reeson, 2008). The scheduling in this case can be done by choosing any appropriate algorithm (Balakrishnan & Chandran, 2006).

A key characteristic, important to the ATC operations and to this project was the management of the air operations in the TCA. This refers to the situation where there was imbalance between the traffic demand and the available resources. Usually, the runway was the bottleneck in an airport (Idris, et al., 1998a) (Idris, Delcaire, Anagnostakis, Hall, & Pujet, 1998b). In such a scenario, since aircraft have to maintain a minimum speed for physical and safety purposes, it becomes necessary to manage the queue formation prior to runway assignment and subsequent landing (Brinton, 1982). Such a manoeuvre requires either *Vector for Space* or *Holding Pattern* (Artiouchine, Baptiste, & Durr, 2008) (Bianco & Bielli, 1993).

Consequently the objectives of the ATC can be enumerated as follows –

1. Safe and efficient operation of the airport.
2. Maximise the runway throughput.
3. Minimise the approach time.
4. Minimise the workload on the operatives in the airport and comply with the regulatory authority standards.
5. Minimise the taxiing time and consequently delay of each aircraft.
6. Maximise the fairness of operation in terms of scheduling and resource allocation to different airlines (Idris, et al., 1998a) (Fahle, Feldmann, Gotz, Grothklags, & Monien, 2003) (Lee & Balakrishnan, 2008).

5.2 Aircraft Scheduling Problem (ASP)

The ASP along with its various components like ALP has been studied quite extensively. The objective function of the problem, while varying due to being solved from different stake holder's perspective, has been saturated. Current research was dedicated to finding most optimal heuristics, reducing complexity of the algorithm and incorporating as much practical elements as possible.

The basic approach was framing the problem as a Mixed Integer Linear Programming (MILP). Owing to the fact that it was NP-Hard, the complexity increases with the increase in the number of aircraft. As a result, in order to make the solution implementable, heuristics and Meta heuristics were used.

The Travelling Salesman Problem (TSP) can be modified to solve the ASP. The original problem can be described as finding the shortest route for a salesman who was supposed to visit *n* cities only once and finishing at the city of origin (Schrijver, 2005). The single runway ASP can be defined as a time-dependent TSP, each city was an aircraft, the distances were the safety mandated separation and the time windows were the landing time windows. A similar scenario can be built for a multiple runway airport (Luenberger, 1988).

Another approach was to analyse the ASP as a queuing system and solving it accordingly. Again the parameters were based on the different types of aircraft, separation time and number of runways; each of them corresponding to types of customer, service time and number of servers respectively (Bauerle, Engelhardt-Funke, & Kolonko, 2007).

In most literature, a JSP was used to adapt and solve the ASP (Beasley, Krishnamoorthy, Sharaiha, & Abramson, 2000) (Carr, Erzberger, & Neuman, 1998). The JSP was a sequence dependent problem where a fixed number of jobs have to be completed in a fixed number of machines and the times involved were set-up time and operation time, objective function being make span or tardiness. Frequently included was the penalty for early or late jobs, with respect to time windows. Table 6 provides a comparison between JSP and ASP.

JOB SHOP SCHEDULING	AIRCRAFT SCHEDULING PROBLEM
Job	Landing operation
Machine capacity	Runway
Release time	Expected landing time
Start time	Actual landing time
Completion time	Freeing if runway
Sequence dependent processing time	Safety requirements of separation between aircraft

Table 6 Job Shop Scheduling vs Aircraft Scheduling Problem

The most important difference between the two formulations was that in the ASP, the minimum separation has to be maintained not just between two successive jobs but between any pair of jobs (Lenstra, 1977) (Ernst, Krishnamoorthy, & Storer, 1999). For the purpose of this research, the job shop formulation would be used to solve the ASP.

5.3 Solving Approaches

As mentioned earlier, the ASP belongs to the class of problems designated as NP-Hard and hence, more often than not, heuristics were used to solve them and implementation was important from practical point of view. The standard approach was to use one algorithm as the base scenario and then compare other algorithms with respect to various parameters such as delay, costs and complexity.

5.3.1 First Come First Serve (FCFS)

The FCFS is a scheduling algorithm and is self explanatory in itself. The jobs are processed in the order they arrive to the machine and correspondingly, the aircraft are provided slots for landing in the order they arrived at the TCA. The Scheduled Landing Time and the flight trajectory are all taken into account (Neuman & Erzberger, 1991). In practice, this is hardly used in entirety, as the ATC might change some of the order due to a potential sequence of light aircraft behind heavy aircraft. However, it has been studied that FCFS is not an efficient and practical algorithm (Capri & Ignaccolo, 2004). Part of it stems from the fact that it doesn't take other information into account such as cost constraints or safety considerations (Carr, Erzberger, & Neuman, 2000). Also, to follow FCFS implicitly would not be considered fair by the ATC since the objectives of ATC and airlines differ.

But with advancement in computing abilities and reducing complexities, FCFS algorithms serve an important role, that of a benchmark. The usefulness of any other algorithms can be demonstrated by how it performs as compared to the FCFS algorithm. The parameters like cost, delay and throughput are the output of any scheduling algorithm and based on their comparison, an indication of effectiveness of the said algorithm can be determined.

5.3.2 Dynamic Programming (DP)

Dynamic Programming is an optimisation methodology for making sequential decisions. ASP can be modified as a dynamic programming model because of the importance of sequence and separation.

ASP was closely related to TSP and has been solved using the DP approach (Psaraftis, 1978). Based on the DP approach for solving the TSP, Psaraftis developed three algorithms for the static case of ALP to examine two alternative objectives, the Last Landing Time (LLT), and the Total Passenger Delay (TPD) with respect to FCFS discipline. Another aspect, runway throughput, has been studied with a static case, fixed aircraft, using the DP approach (Balakrishnan & Chandran, 2006). This draws from earlier work concerning Position Shifting, which refers to the limit of maximum number of rescheduling revisions, Maximum Position Shifting (MPS). As is standard, the number of changes in position is calculated from a FCFS algorithm. The Constrained Position Shifting (CPS) method uses the constraint to move aircraft from one position to another (Dear R. , 1976) (de Neufville & Odoni, 2003) (Malaek, 2008).

Complexities of the problem and relevant heuristics have been the aspects which have been studied most within dynamic programming approach (Balakrishnan & Chandran, 2006) (Bianco, Dell'Olmo, & Giordani, 1999). A slight variation was to minimise the holding pattern time generated by circling in a single runway airport. A dynamic programming algorithm and linear programming algorithms with relaxation and rounding based were used in the main algorithm. The approximation algorithms alternatively approximate the sum of arrival times of all the aircraft (starting time of all jobs) and the arrival time of the last aircraft (make span) with relative weightings of 5 and 3, respectively. As different classes of the aircraft were not considered, the required separation between landings was independent of the aircraft type (Bayen, Tomlin, Ye, & Zhang, 2004).

A number of studies focusing on the ALP formulation as a JSP have been conducted with the objective of comparing different approaches to solve afore mentioned problem. The algorithms used were FCFS, Heuristics and Dynamic Programming and the output has been compared using a software base (Brentnall, Aircraft Arrival Management, 2006) (Brentnall & Cheng, 2008).

5.3.3 Heuristics

As explained earlier, due to complexity issues, heuristics were almost the best approach to solve the ASP. A heuristic approach to the aforementioned CPS problem has been formulated and solved (Dear & Sherif, 1989) (Dear & Sherif, 1991).

Meta Heuristics like genetic algorithm (GA) and ant colony optimisation have also been used to solve the ASP. After the early genetic algorithm approaches (Stevens, 1995), modified versions of the same problem have been solved by comparing various chromosome parameters (Ciesielski & P, 1997) (Ciesielski & Scerri, 1998).

A variation of GA was used to a modified formulation of ASP. The separation was fixed based on three aircraft varieties with a constraint that it was not possible to land before the estimated landing time (Cheng, Crawford, & Menon, 1999). Further continuation of this work was based on examining the efficiency of the chromosomal formation and comparing it with other previous results under same assumptions (Hansen, 2004). Modifying the objective function to reflect three parameters, aircraft class, maximising system capacity and minimising the sum of all landing times, GA has been used to solve it under simulated conditions with 30 flights with different arrival intervals (Bianco, Dell'Olmo, & Giordani, 1997) (Capri & Ignaccolo, 2004).

Another study focussed on the air borne delay for an aircraft which amounted to the difference between the actual and estimated landing time. The methodology used was the Receding Horizon

Control (RHC) based GA analogous to the model predictive control. Also included was a comparison between the RHC and other optimisation strategies (Hu & Chen, 2005a) (Hu & Chen, 2005b).

A few studies focussed on the comparison between several heuristics and also with FCFS. Notably, successive algorithms resulted in improved results and all the objective function parameters were satisfied and the results were presented for a scenario with 500 aircraft and 5 runways (Beasley, Krishnamoorthy, Sharaiha, & Abramson, 2000) (Fahle, Feldmann, Gotz, Grothklags, & Monien, 2003).

5.3.4 Software

Although there were a lot of software that were available to the ATC operators which aid in the management of the operations, many of the crucial tasks and scheduling operation were still done manually.

Most of the software were a representation of the various parameters involved in the management of ATC and to some extent perform or aid in micro decision making rather than a complete decision support system.

5.3.4.1 CTAS

CTAS, otherwise known as Centre-Terminal Radar Approach Control (TRACON) - Operating System, was the result of the collaboration between NASA Ames Aviation Centre and the Federal Aviation Authority (FAA). Its aim was to aid the ATC in managing traffic flows while improving safety and efficiency. The input for the above software was the real-time flight plan, track data for all relevant flights and weather information (Erzberger, 1992) (NASA Ames Aviation) (FAA).

The two main parts of the software system are as follows –

1. Traffic Management Advisor (TMA) - This is a time based planning tool that aids in sequencing and scheduling of the arriving aircraft taking into account the throughput and capacity of the airport. The outputs are estimated & scheduled arrival time and delays.
2. Final Approach Spacing Tool - This advices on runway assignment and sequence of landing, taking into account the final descent and safety requirements.

5.3.4.2 AMAN

AMAN refers to Arrival Manager and is a decision support tool that sequences the arriving flights. The process is initiated by assigning every arriving aircraft a runway and then modifying the flight plan to minimise the total delay while also doing it in a fair and unbiased manner (EUROCONTROL, 2005) (Soomer & Koole, 2008).

5.3.5 Relevant Heuristic/ Approach

In this section the heuristics and approaches are covered which are very relevant to the current project work and are used extensively.

5.3.5.1 Branch and Bound (B&B)

Branch and Bound is an algorithm for combinatorial optimisation problem that employs a state search, not unlike a decision tree, and then searching through the branches of the said tree and employing lower or upper bound, as and when required to find the optimal solution (Land & Doig, 1960) (Little et al, 1963).

The versatility of this approach can be seen from the wide area of application of the algorithm (Clausen, 1999). Of particular relevance to this project, is the branch and bound technique developed to schedule modes in a traffic network (D'Ariano, Pacciarelli, & Pranzo, 2007) (Sama, D'Ariano, & Pacciarelli, 2012).

5.3.5.2 Tabu Search

Tabu Search is type neighbourhood search Meta heuristic used to solve combinatorial optimisation problems (Glover, 1987). The methodology involves creating a list of solutions, for a period of memory of the type short, intermediate and long term, which are not searched to avoid being stuck in the poor optimal area or plateau region.

5.3.5.3 Disjunctive Graph

Disjunctive Graph is a methodology to solve complex job shop scheduling problems. Consequent to the ASP being formulated as a JSP, disjunctive or alternative graphs can be used to solve them. The most important factor which makes this method particularly suitable is the way the scheduling and the timing constraints are handled.

The sequence of the tasks and the utilisation of the resource or machine can be represented through a set of directed or undirected graphs which also includes the constraints. A valid schedule for the disjunctive graph may be obtained by finding an acyclic orientation of the undirected edges – that was, deciding for each pair of non-simultaneous tasks which was to be first, without introducing any circular dependencies – and then ordering the resulting directed acyclic graph. The ultimate aim was to minimise the make span (Mason & Oey, 2003) (Gröflin & Klinkert, 2002). Disjunctive arcs result from the fact that two operations i and j on the same machine cannot overlap in time. Since there is a one-to-one correspondence between feasible semi-active schedules and feasible selections in a disjunctive graph, an optimal schedule minimizing make span can be found be determining a feasible selection that minimizes the length of a longest path in the associated graph (Gröflin & Klinkert, 2002) (Roy & Sussman, 1964).

5.3.6 Game Theory

A game, in the context of Game Theory, can be seen as a scenario where all the involved actors have interests in a particular project, which is the game. Each of the players has their individual objective which they want to fulfil but are bound by the operational constraints. This means that, the constraints are the rules of the game. Now to fulfil their objective, within the constraints, each player has a set of strategies which they employ and consequently get the results in the form of either tangible or intangible outcomes like financial implication or long term deals or simply profit or loss. Any scenario can be analysed if the scenario can be formulated as a game with players, objectives and strategies. This is a very important tool to analyse a situation, quantify the outcome of the various strategies and eventually formulate long term strategies and uses concepts from economics, political science and operations research/ advanced mathematics. The description above is of a simple game without any further analysis, however, in reality there are many ways to classify any game and for the purpose of this research, cooperative and non-cooperative games are discussed.

5.3.6.1 Cooperative Games

A cooperative game can be described as a scenario where the players collaborate in some manner during the operation with the understanding that this collaboration will be beneficial as compared to operate individually. The nature of cooperation can vary widely depending upon the nature of operations and the alignment between the stakeholder's objectives, ranging from active sharing of information/resources to using same resources to only complying with guidelines. This branch of game theory models how agents compete and cooperate as coalitions in unstructured interactions to create and capture value and it must be stressed that this analysis was not an assessment of the degree of cooperation among agents in the model: a cooperative game can model extreme competition as well (Chatain, 2014) (Ferguson).

5.3.6.2Non- Cooperative Games

Non-cooperative game models the actions of agents, maximizing their utility in a defined procedure, relying on a detailed description of the moves 2 and information available to each agent (Chatain, 2014) and hence these kinds of games can be called as procedural. It differs from cooperative games in many ways, primarily, the entity analysed is an agent rather than the group and there might be cooperation amongst the agents, hence the nomenclature is not simply a literal translation (Parkes).

5.3.6.3 Biform Games

Biform games are a blend of Cooperative and Non-cooperative games which model the intuitive distinction between shaping the game and playing the game. These comprise two phases. In the first phase, modelled and solved non-cooperatively, agents independently take actions that determine the value they can create as coalitions (i.e., the characteristic function). In the second phase, modelled and solved as a cooperative game using the core, agents create and capture value. Biform games are well suited to model business strategy where decisions are about a firm's ability to create value and to influence the environment to improve value capture, while de-emphasizing tactical decisions (Chatain, 2014). This is in line with the current research and analysis methodology wherein both aspects are used to analyse the output and draw conclusions.

5.3.7 Fairness of Algorithm

Owing to the involvement of various stakeholders in the aviation operation, to ensure cooperation, it was essential to establish that the scheduling algorithm was fair. The fairness aspect had been neglected, but there have been few studies that focussed on this aspect recently. One approach was to take in the preferences of the airline while scheduling (Soomer & Franx, 2005). This creates the perception that any algorithm used was fair since the airline decide which aircraft to prioritise, but this assumes a high volume of operation for each airline, whereas, in reality this was not the case. Hence, a different approach was required which was more realistic. Including the cost of delay into the scheduling was another approach which describes the cost of scheduling an aircraft and its impact on the airline. Another approach, stemming from game theory, was to analyse the operation as a cooperative game and analyse the Shapley vale to determine the fairness quotient of the algorithm and iteratively use a mechanism design to come up with the fairest algorithm (Skowron & Rzadca). This approach was pertinent here, because, essentially the stakeholders collaborate with each other, at least with respect to information sharing with ATC, and all contribute to a common financial ecosystem wherein if the system benefits, they all stand to benefit, necessitating the use of Shapley value.

5.3.8 Shapley Value

Shapley value is a solution concept in the field of cooperative game theory. To each cooperative game it assigns a unique distribution (among the players) of a total surplus generated by the coalition of all players. This means that, every player contributes to a common fund to utilise common resources, and eventually depending on the marginal contribution each player makes to the group as a whole, they each receive the benefits. Fairness is essentially an important aspect in this methodology since the benefits are always commensurate with the investments each player makes to the whole cause (Shapley L. S., 1953). This concept has been used in the aviation industry as well, although for a differently framed problem, focusing on the role of runway as a bottleneck (Littlechild & Owen, 1973). Also, game theory in general is a very useful analytical tool to undertake stakeholder's analysis involved in a decision making process and various studies have been undertaken in that direction (Hermans, Cunningham, & Slinger, 2014).

The Shapley Value is a unique distribution of savings in a cooperating game satisfying several criteria like efficiency, super-additive and linear. The Shapley value is one way to distribute the total gains to the players, assuming that they all collaborate. It is a fair distribution in the sense that it is the only distribution with certain desirable properties listed above. According to the Shapley value, the amount that player *i* gets given a coalitional game (v, N) can be formally written as shown in Figure 25.

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\;(n-|S|-1)!}{n!}(v(S \cup \{i\}) - v(S))$$

Figure 25 Shapley Value (Shapley L. , 1953)

N= Total Number of Players; S = Subsets; i = Player

This can be interpreted as the marginal contribution of each player to the cost structure in every possible permutation.

Chapter 6. Algorithms Used and Process Flow

Of the methodologies described in the previous chapter, some were of critical importance to this project and were used to formulate the problem, solve, analyse the output and eventually draw conclusions. The following flow chart as presented in Figure 26 explains the process flow for the algorithmic part of the project.

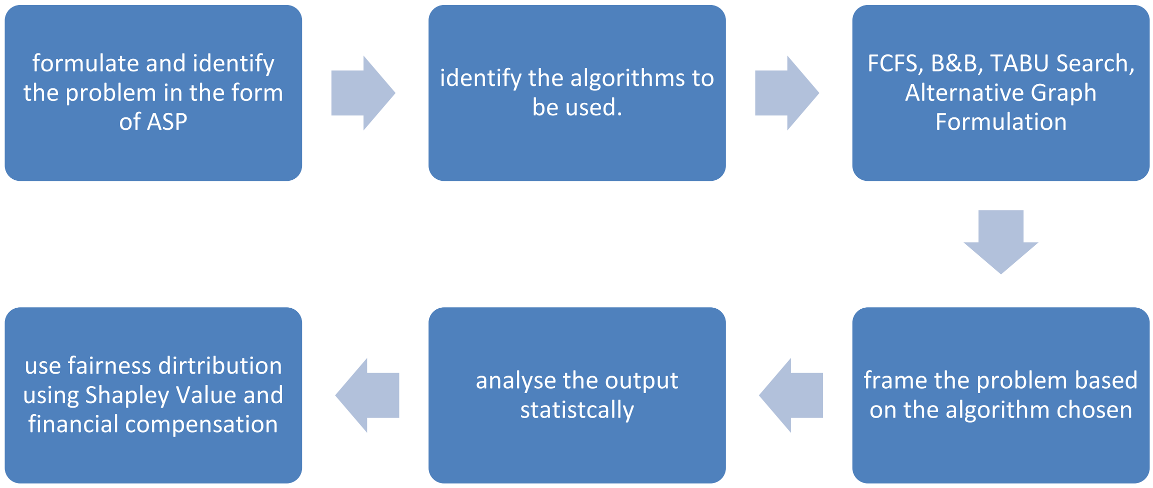

Figure 26 Algorithms used and process flow

The following algorithms were used to evaluate the test case and generate output for further analysis-

1. Job Shop Scheduling
2. Alternative Graph Formulation
3. Graph Theory
4. Branch and Bound Heuristics for solution
5. TABU Search to eliminate sub-optimal solutions
6. FCFS for the base (worst) case scenario and bench marking purposes
7. Shapley Value

Figure 27 demonstrates the algorithm used at each stage and the software used for the computation.

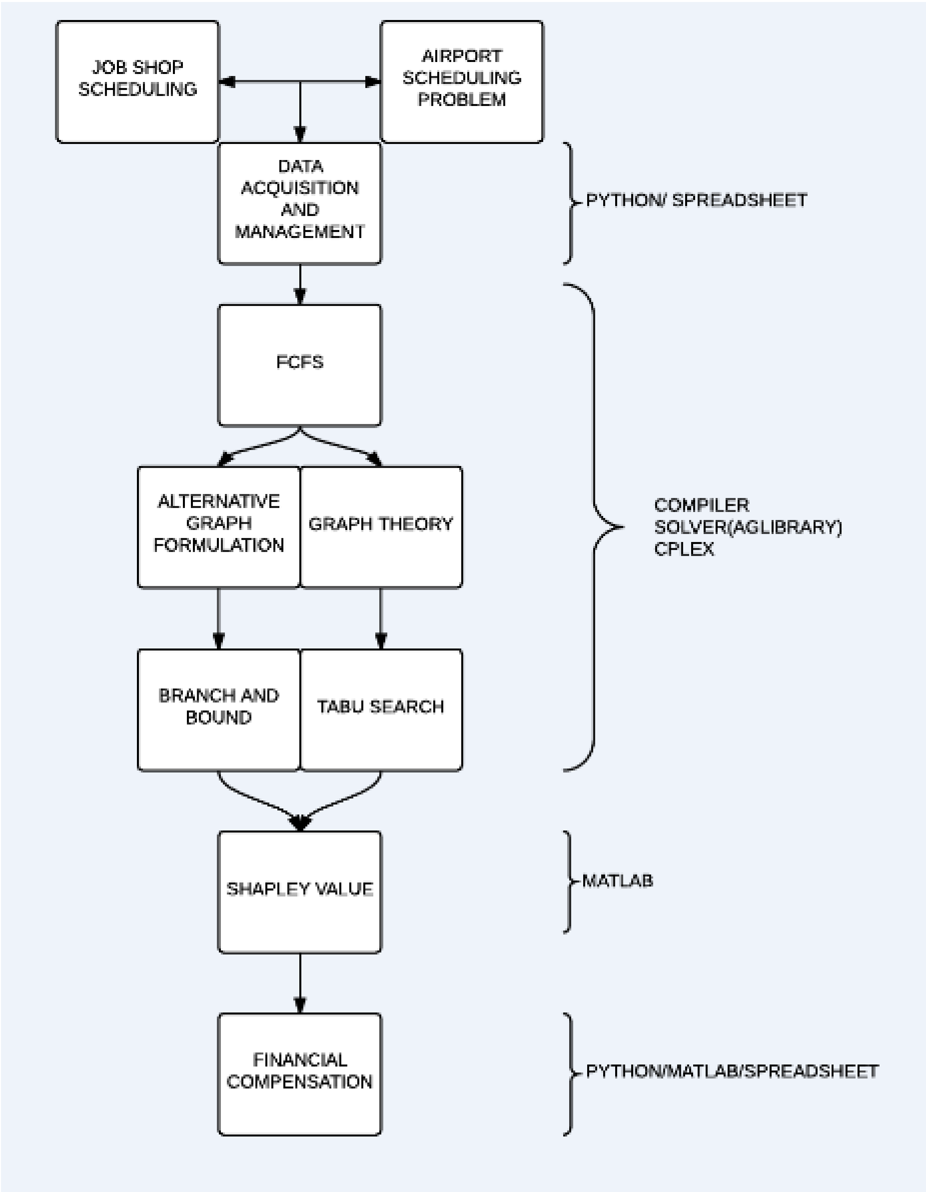

Figure 27 Algorithm and computation details

6.1 An Example

This section demonstrates the algorithms used with the help of an example.

6.1.1 Job Shop Scheduling

Job Shop scheduling problem can be described as the assignment of specific jobs to specific machines at particular times which optimises the objective function which is usually minimising the make span. The make span is the total length (unit being time) of the schedule, that is, when all the jobs have finished processing. The basic problem can be represented in Table 7.

Jobs	Machine Sequence	Processing Times
1	1,2,3	$p_{11}=10$, $p_{21}=8$, $p_{31}=4$
2	2,1,4,3	$p_{22}=8$, $p_{12}=3$, $p_{42}=5$, $p_{32}=6$
3	1,2,4	$p_{13}=4$, $p_{23}=7$, $p_{43}=3$

Table 7 Example Problem

6.1.2 Graph Theory: Alternative Graph

The previous problem can be represented using the alternative or disjunctive graphs and solved using heuristics. Figure 28 presents the conjunctive graph and Figure 29 presents the disjunctive graph. Prior to solving the problem, the representation requires to be done, which is done as follows –

1. Directed graph G, nodes N, arc sets A and B, G=(N,A,B)
2. There exists a node for each operation (i,j)
3. Conjunctive arcs A represent routes of the jobs
4. Arc (i,j) $\longrightarrow$ (k,j) denotes that operation (i,j) precedes (k,j) (defined for two operations of the same job)
5. Disjunctive arcs B represent sequence of jobs on a machine
6. Arc (i,j) $\dashrightarrow$ (i,k) denotes that operation (i,j) precedes (i,k)
7. Arc (i,j) $\dashleftarrow$ (i,k) denotes that operation (i,k) precedes (i,j)
8. Arcs in both directions exist, only one of the two is selected in a feasible schedule(defined for two operations on the same machine)
9. Length of an arc is the processing time of the operation from which the arc originates
   $(i,j) \xrightarrow[p_{ij}]{} (k,j)$
10. Add a source node U and a sink node V
11. Connect U to the first operation of each job by a conjunctive arc (going out of U) of length 0
12. Connect V to the last operation of each job by a conjunctive arc (going into V)
13. A *feasible schedule* corresponds to a sub graph S such that
    a. S contains all the conjunctive arcs A
    b. For each pair of disjunctive arcs between the same nodes, exactly one arc is contained in S
    c. S contains no directed cycle

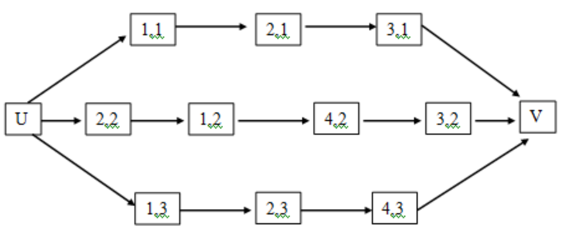

Figure 28 Conjunctive Graph

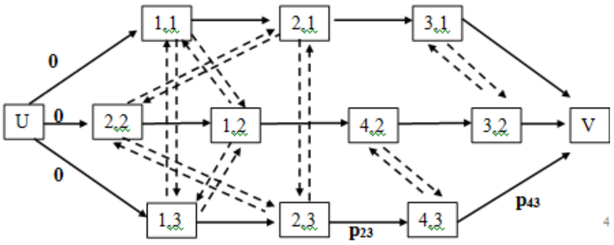

Figure 29 Disjunctive (Alternative) Graphs

The formulation to solve the objective function, which is to minimize the make span is described below—

Variables:

t_{ij} = start time of job j on machine i,   for all operations (i,j)

Min C_{max}

Subject to

$C_{max} \geq t_{ij} + p_{ij}$ for all $(i,j) \in N$

$t_{kj} \geq t_{ij} + p_{ij}$ for all $(i,j)\ \tau\ (k,j) \in A$

$t_{ij} \geq t_{ik} + p_{ik}$ or $t_{ik} \geq t_{ij} + p_{ij}$ for all (i,j) and $(i,k) \in N$

$t_{ij} \geq 0$ for all $(i,j) \in N$ (Columbia University IEOR) (Pacciarelli, 2000)

6.1.3 Branch and Bound and TABU Search

The algorithm explores branches of a rooted tree, the network of graphs in this case, which represent subsets of the solution set. Before enumerating the candidate solutions of a branch, the branch is checked against upper and lower estimated bounds on the optimal solution, and is discarded if it cannot produce a better solution than the best one found so far by the algorithm.

1. Initialization
   AO = first operation of each job, $r_{ij} = 0$ for all (i,j) in AO
2. Machine Selection
   Calculate $t(AO) = \min_{(i,j) \text{ in } AO}\{ r_{ij} + p_{ij}\}$ and let i^* be the machine corresponding to the operation that minimizes $r_{ij} + p_{ij}$
3. Branching
   The branching techniques can be varied and were drawn from the below listed techniques and is represented in Figure 30.
   a. Depth First
   b. Breadth First
   c. Lower Bound Min First
   d. Lower Bound Max First

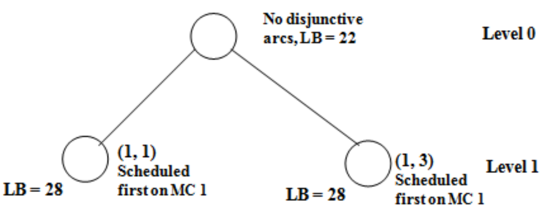

Figure 30 Branch and Bound: Branching

4. Bound
   The initial solution of BB, the upper bound (UB) is obtained from the best solution execution a set of heuristics presented above for branching. The lower bound is calculated for each section and will be used to evaluate partial selections graph. Other key factors for the speed of the algorithm of BB are the rules of implications that allow reducing the number of branches necessary to find the optimal solution. Figure 31 presents the solution of the example problem.

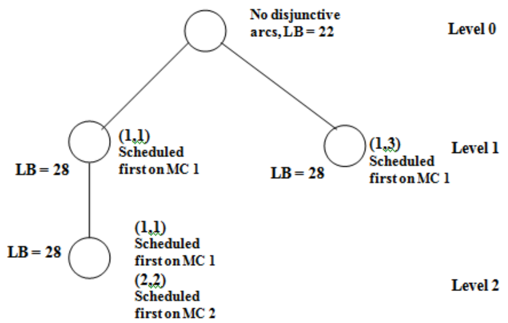

Figure 31 Branch and Bound: Solution

The Tabu Search (TS) is a meta-heuristic deterministic based on local search. This process is a logical extension of the Branch and Bound methodology and is based on storing a restricted set of solution which provides sub optimal output. At each step, the best solution of this set is selected, and becomes the starting solution for the next step. References to such solution are stored in a taboo list used by the algorithm to avoid visiting solutions already explored previously (Sama M. , D'Ariano, D'Ariano, & Pacciarelli, 2014).

6.1.4 Shapley Value

There are three players, a, b and c and the costs incurred are as follows-

V(a) = 6	V(a,b) = 12	V(a,b,c) = 42
V(b) = 12	V(a,c) = 42	
V(c) = 42	V(b,c) = 42	

The coalition involving all the players is called the grand coalition. The Shapley value, indicating the fair and unique distribution of the costs amongst the players, was the following set-

[2 5 35]

This means that the player “a” should bear 2 units of the cost, player “b” should bear 5 units of the cost and the player “c” should bear 35 units of the costs. The sum of the Shapley values is equal to the value of the grand coalition. The framing of the project scenario into a Shapley value problem would be done in the section, fairness analysis.

Chapter 7. Methodology

This chapter describes the methodology followed to solve the research question and analyse the output and provide meaningful conclusions and recommendations. There are four aspects of the project, the overall process flow which is a macro view of the project work, the algorithmic part, the analysis of the output of the previous part and finally the impact analysis part.

7.1 Overall process flow chart

The process flow chart presented in Figure 32 describes the methodology that was followed to undertake this project work.

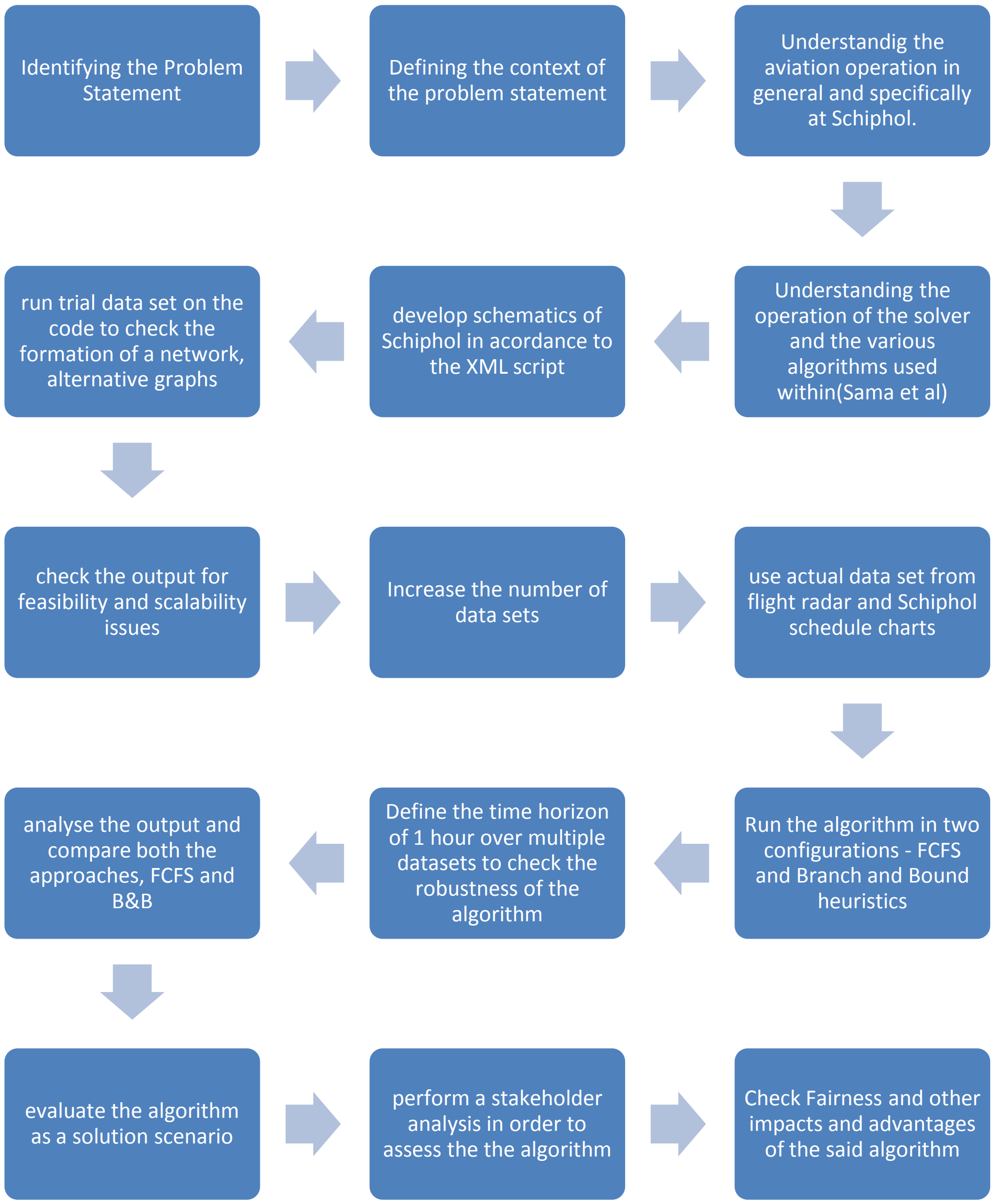

Figure 32 Process flow chart for the project

7.2 Methodology for the Experimental Design

The algorithm was designed to minimise the make span and demonstrate decisions with respect to routing and scheduling of the aircraft. And more importantly, the code necessitates all the data to be specific for Schiphol. The first task was to define the airport TCA as resources and use a unique nomenclature for each of them. Having defined the resources, the next task was to define the properties of the aircraft in the resources, like speed and time taken to traverse. The next step was to identify the users, in this case, the aircraft and chart their routes and schedule details. All the above was done using a XML script in the proper format. The next part, in this particular step, was to run the compiler using various scheduling parameters like FCFS or B&B as per requirement and getting an output. The methodology for the experimental design is presented in Figure 33.

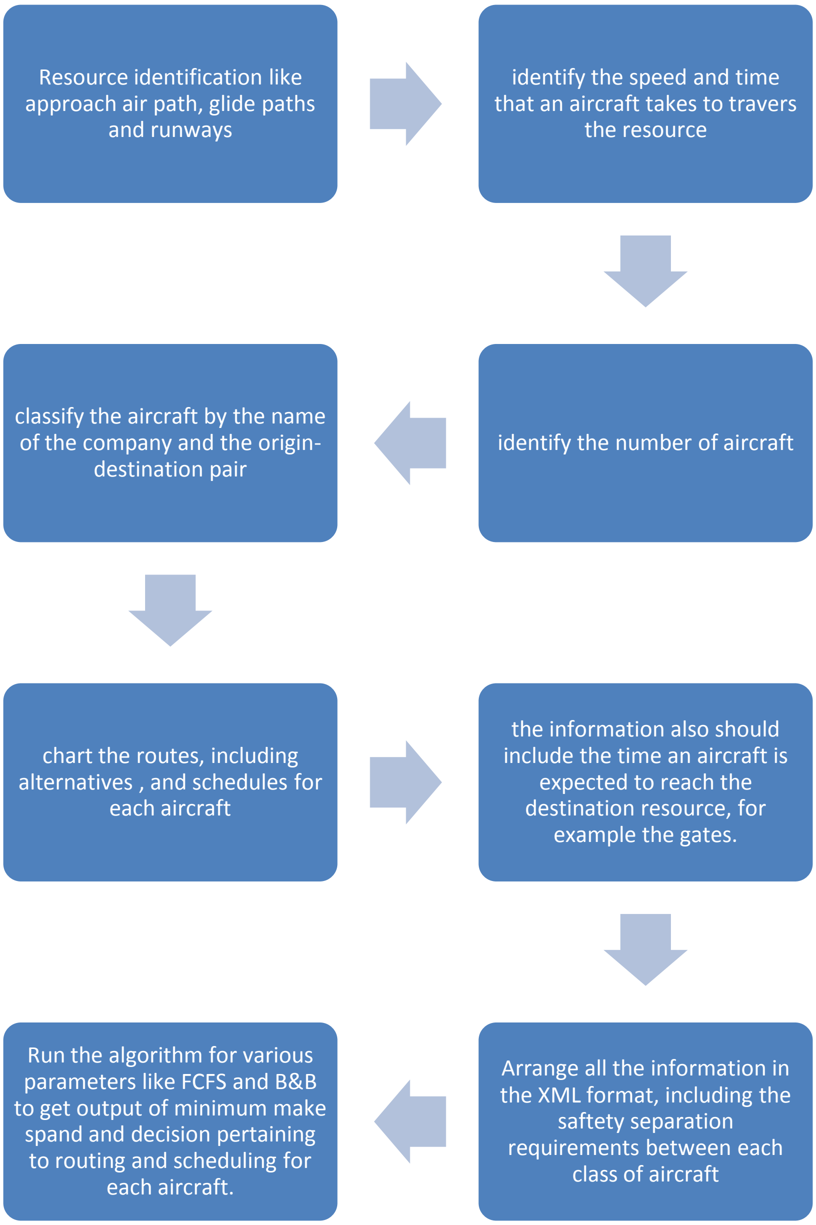

Figure 33 Methodology for the algorithm

7.3 Methodology for the analysis of the output

The output of the algorithm was the details of the delay, depending on the objective function chosen. The total delay, consecutive delays and individual delays of each aircraft were separately created and stored. The analysis of these numbers gave an indication of the efficiency of the algorithm. The process for the analysis of the output is described in Figure 34.

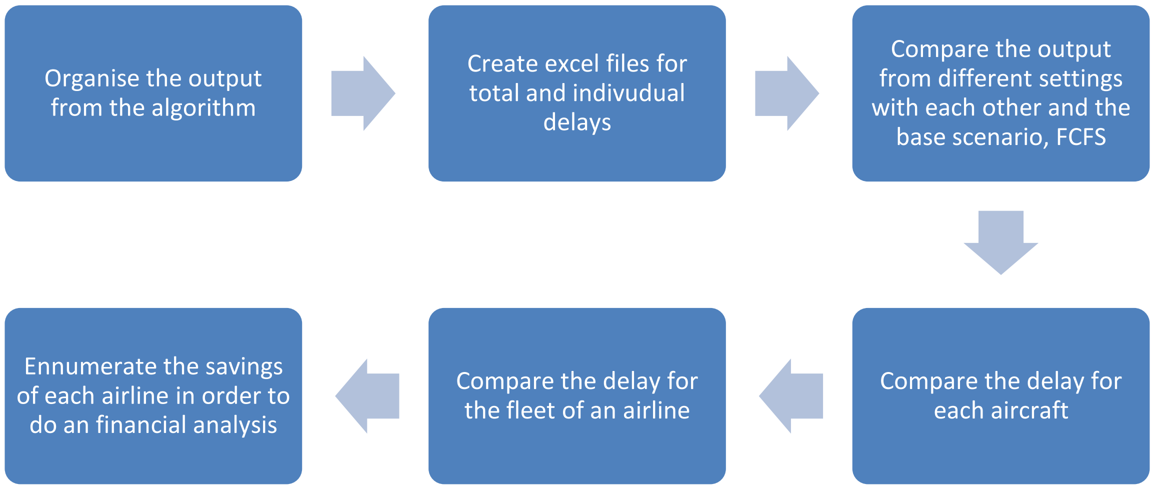

Figure 34 Methodology for output analysis

7.4 Methodology for the impact analysis

Since there were a lot of stakeholders involved in the aviation operation, it was important to analyse the impact of the algorithm on the various stakeholders from the point of view of fairness and financial sustainability. The methodology for impact analysis is described in Figure 35.

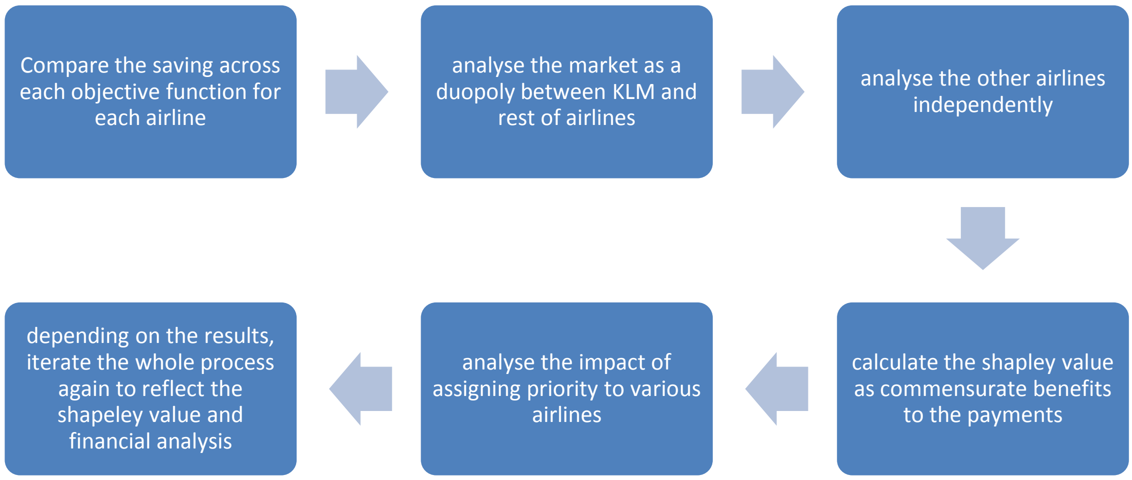

Figure 35 Methodology for impact analysis

7.5 Methodology for Fairness Analysis: Shapley Value

The cost incurred by the airlines depends on the landing fees charged by the airport, the number of aircraft that they operate in the given time horizon and the kind of passengers that the airlines was carrying and all these can be categorised as the operations cost of each airline. Since performance wise, FCFS was the worst case scenario as well as the incumbent standard operating procedure, it can be assumed that if the airlines do not cooperate, each of them will incur the operational cost independently. Now, when they cooperate, in other words adopt the Routing and Scheduling algorithm, each of them experience a certain value of delay which may or may not be different from the delay in the case of FCFS. However, the Routing and Scheduling was expected to be the best case scenario and consequently, it was expected that the delays and costs of each airline will be less than FCFS scenario. The next step was to enumerate all the possible coalition between airlines in each test instance. This was done to calculate the marginal incremental benefit each of the coalition brings about to the system. The best case scenario was where everyone cooperates and the Routing and Scheduling algorithm was adopted fully, which improves the system efficiency and reduces cost. By calculating the marginal contribution of each airline as it joins the coalition, the Shapley value was calculated, which was nothing but a unique distribution of the costs over all the airlines in the coalition. This value was then contrasted with the costs incurred by the airlines using FCFS and Routing/Scheduling to assess the fairness of the Routing/Scheduling algorithm. The process can be represented in the flowchart as shown in Figure 36.

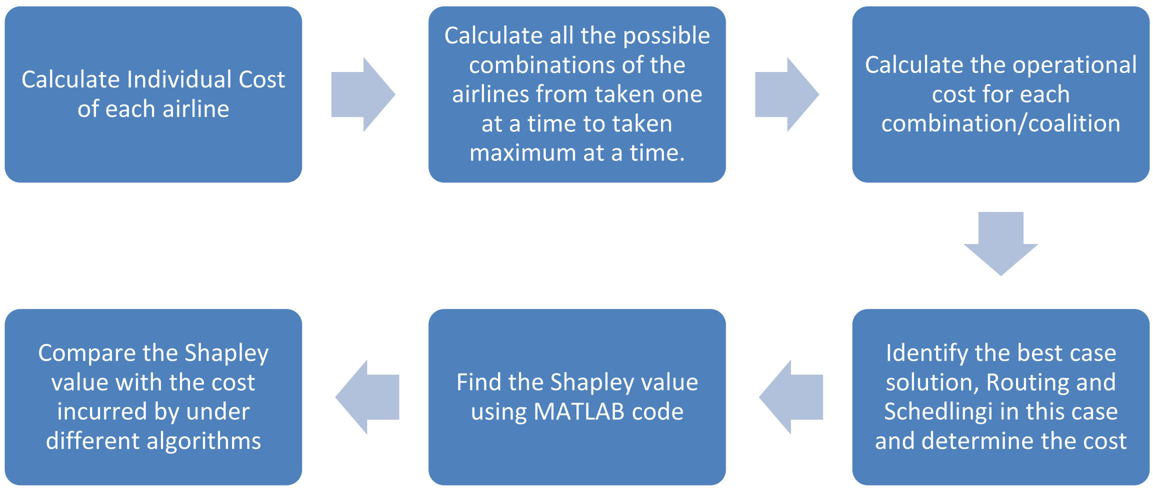

Figure 36 Flowchart for Shapley Value calculation

To calculate the Shapley value, a MATLAB code was used wherein the value of payoff of all permutations was used as input and the output was the Shapley value in the form of a matrix. A similar approach was used in the current project. The input for the code was the financial analysis/payoff quantity. The output was the Shapley value that gives the unique distribution of costs amongst the players which leads to eventual benefit sharing. This value was also tallied with the volume generated by the player individually to check whether the analysis was practical or not.

7.6 Methodology for Financial Compensation

In this research, in the above few steps, the Shapley value and the financial analysis was carried out for each text instances. As explained above, the function of the financial compensation was to device a methodology to make the pay off more attractive and the coalition stable. The steps for this part of the design can be represented in Figure 37.

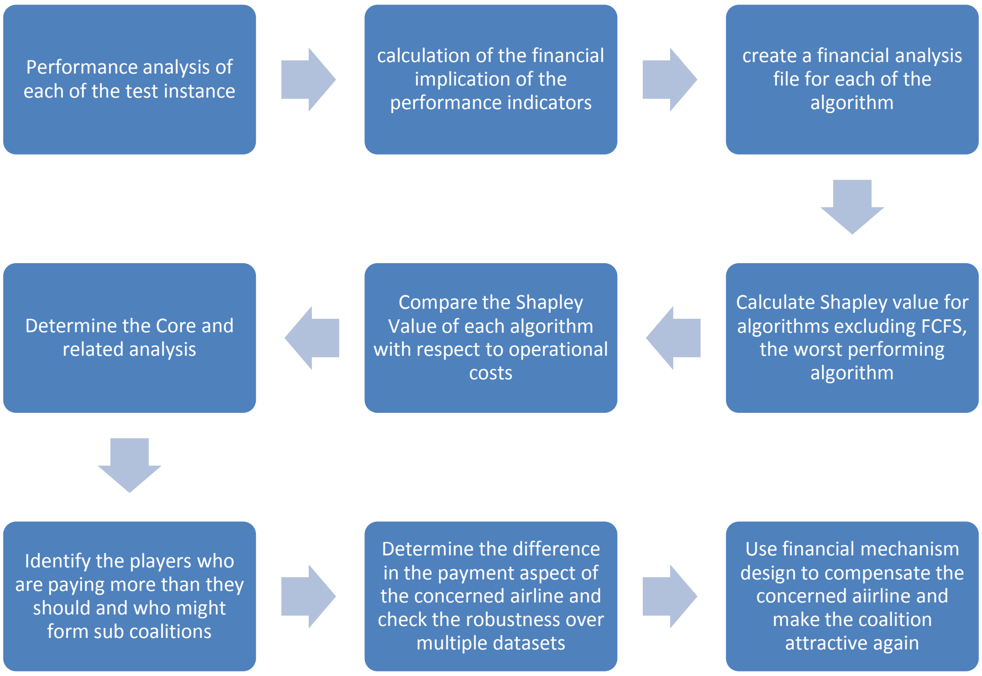

Figure 37 Framework Design

As mentioned above, the function of this financial compensation framework was to promote stability to the system. Due to the variable nature of the operation, the Shapley value varies greatly amongst the actors and also might not be present in the core, leading to instability. Hence, whatever be the Shapley value and whether it's present in the core or not, if the loses were offset by financial compensation, the system and consequently the coalition would still be attractive, stable and sustainable.

Since, it was established earlier that this was a transferable utility game; a framework can be formulated to redistribute the utility after the Shapley value analysis to promote fairness. The process can be described in steps as presented in Figure 38.

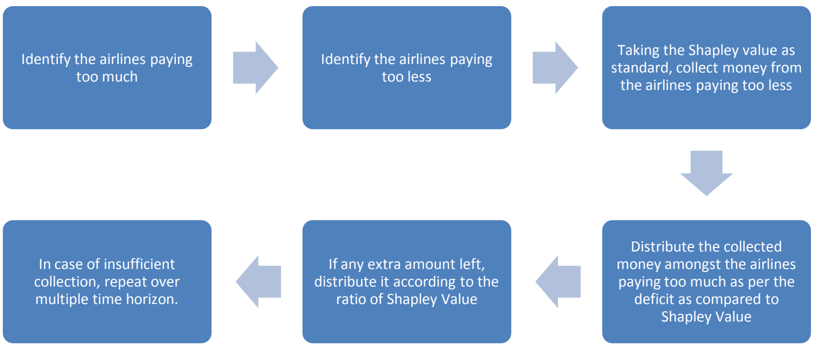

Figure 38 Framework Methodology

Chapter 8. Data

Due to the specific nature of the operations, the data for the project had to be procured specifically for Schiphol. There were various kinds of data which were required to render a decision on the operational aspect of aviation. For this project the data that were important was described in further sections of this chapter.

8.1 Airport Resources

The airport resources refer to the air corridors used by incoming and outgoing flights at Schiphol within the control area of Schiphol ATC. The initial data requirement was the distance of the approach air segment when the aircraft enters the TCA. Coupled with the distance in nautical miles and the velocity of the aircraft in that particular segment, the time taken to cover the said segment can be calculated. The next resource was the common glide path stemming from the approach segments, and the requirement was same as before, distance and the speed of the aircraft in the segment. After the common glide path has been traversed, the next resources were the glide path specific to individual runways. The glide paths also include manoeuvre related holding circles and other spatial manoeuvres. Subsequently the next resource was the runway followed by taxi ways. For the purpose of the project, the most important thing was to find the time blocks for each resource; hence, it was suffice to know the time that it takes for an aircraft to cover the taxi way to the gates. The gates were treated as infinite resource in the sense that infinite number of planes might arrive and depart from it without any conflict. Most of the data can be found using the publicly available aviation charts from Schiphol. The rest can be sourced from Flight Radar and similar resources. The resources were described in Table 8 which provides information about the data and its respective sources.

Name of Data Set	Source	Link
Schiphol Aviation Air Corridors	Schiphol Group	Aviation Charts
Taxi Data	Luchtverkeersleiding Nederlands	Functional Design of Dynamic Taxi-time Prediction Sub-project of Timeline at Amsterdam Schiphol Airport
Speed of Aircraft	Luchtverkeersleiding Nederlands	Radar Data
Runway Details	International Virtual Aviation Organisation, Schiphol Group	Schipol Ground Movement Charts
Gates	Schiphol Group	Schipol Ground Movement Charts

Table 8 Data and respective sources

8.2 Terminal control area safety requirements

Due to the fluid dynamics and a phenomenon called Wake Vortex, a minimum separation has to be maintained between two successive aircraft. This separation has to be maintained in all the axes, namely horizontal, vertical as well as longitudinal due to safety concerns and regulations that cannot be avoided or circumvented. The wake vortex was dependent on the class of aircraft and its properties like mass, velocity and engine specifications. This safety requirement has an important bearing in any routing and scheduling decision because this takes the form of a constraint and often becomes the bottleneck constraint. For the purpose of this project, four classes of aircraft were defined and based on the technical specification, as defined the manufacturer, the minimum distance between the aircraft was defined. Table 9 describes the separation time in seconds.

Class of Aircraft	1	2	3	4
1	51	70	38	42
2	38	42	38	42
3	38	42	51	70
4	38	42	38	42

Table 9 Minimum Separation Data

8.3 Aircraft Schedule Data

Since the project work focused on improving the efficiency of routing and scheduling by introducing an algorithm, a real life schedule was required which was then optimised and compared under various parameters to deliver the best output based on a given objective function. The required schedule should be computationally feasible as implementation was an important criterion of assessment for any algorithm. This requirement translates to exponential increase in computational complexity with a linear increase in the number of data points; hence the time horizon for the algorithm was restrictive. For the purpose of this research, the time horizon considered was 30 minutes to 45 minutes which translates to about 30 arriving aircraft. The aircraft was recorded at the moment they enter the Schiphol air space and consequently routing and scheduling algorithm was used to come up with a decision. This specific time point was chosen to record the aircraft in order to ensure that the data/schedule was not the result of any previous decision system; the intended algorithm will take a decision on the routing and scheduling from this point and undertake further comparisons with base scenario. To gauge the robustness, sensitivity and consistency as an algorithm a set of 40 such data sets was recorded, 10 of which were actual data set and 30 were artificially created, introducing noise with respect to actual arrival and consequently delay. The noise was a uniform distribution of delay in three categories namely, small delay, medium delay and large delay. The value of delays ranged from 300- 2000 seconds. The schedule was sourced and validated from three sources –

1. Flight Radar
2. Schiphol App/ Schiphol Website
3. Luchtverkeersleiding Nederlands

Chapter 9. Experimental Design

This chapter describes the experimental setup that was used to run the algorithm based on the data on airport, aircraft and schedules mentioned in the above chapters. The experimental design of all the above mentioned data were defined accordingly. The following can be described as the properties of the experimental design –

1. The analysis was carried out in the TCA of Schiphol airport, which has been described earlier.
2. The resources in the TCA have been defined along with their respective properties using the data from Schiphol group and Flight Radar.
3. The algorithm's objective function could be changed as per requirements. Primarily, for the purpose of analysis, the objective function would be to minimise the total delay or make span. However, for instance, to analyse the impact of one airliner having a huge throughput, the objective function van be changed to minimise the average delay.
4. Since routing and scheduling fall under the aegis of ATC in the current scheme of things, the primary user and the primary stakeholder in this research work would be ATC Schiphol. Consequently, their objectives, mission and vision would be used as primary perspective for while setting the objective function.
5. The data to be used as input, schedule, was actual data and was sourced from the Schiphol App and validated through flight radar.
6. The code for the input to the solver was written in XML script.

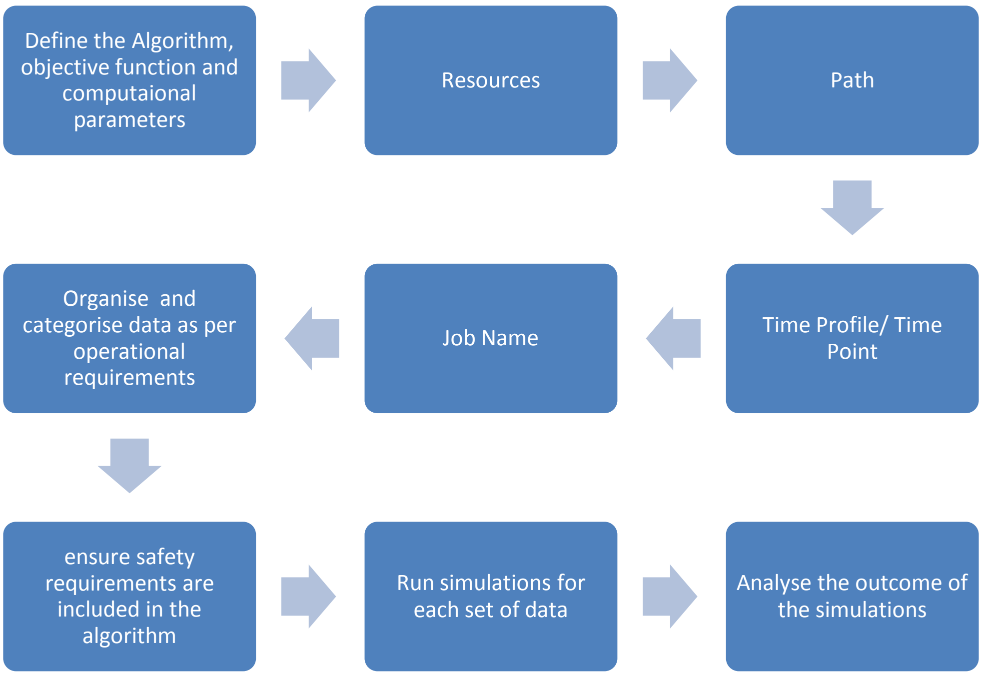

Figure 39 Steps of experimental setup

The following steps describe the experimental setup by utilising the information and premises described above and specifically describe the code and the details therein. Figure 39 presents the steps of experimental setup in a more comprehensive manner.

9.1 Objective Function

The first task in the experimental design set up was to identify the objective function, describe the properties of the algorithm and represent it as a header file which was common for all the experimental runs. The order of the script, the scheduling and routing parameters used, the time of execution (complexity) and parameters to be considered was all included in this section of the code, in the XML script.

The objective function can be anything, varying from minimising total delay to prioritising certain airlines during the run of the algorithm. The properties include which optimisation methodology to follow like the type of cut within Brand & Bound methodology.

9.2 Resources

The next step was to identify the resources at Schiphol, include the relevant information and parameters and use appropriate nomenclature. The resources here mean the components used by the aircraft to make a landing or takeoff at the airport, and these were represented by the approach air segments, common glide path, holding circles, glide manoeuvre for runway, runways, taxi ways and gates and it is presented in Figure 40. The information required was the time taken by the aircraft to traverse a particular resource and that information was derived from the distance of the specific resource and the speed of the aircraft at that point of time.

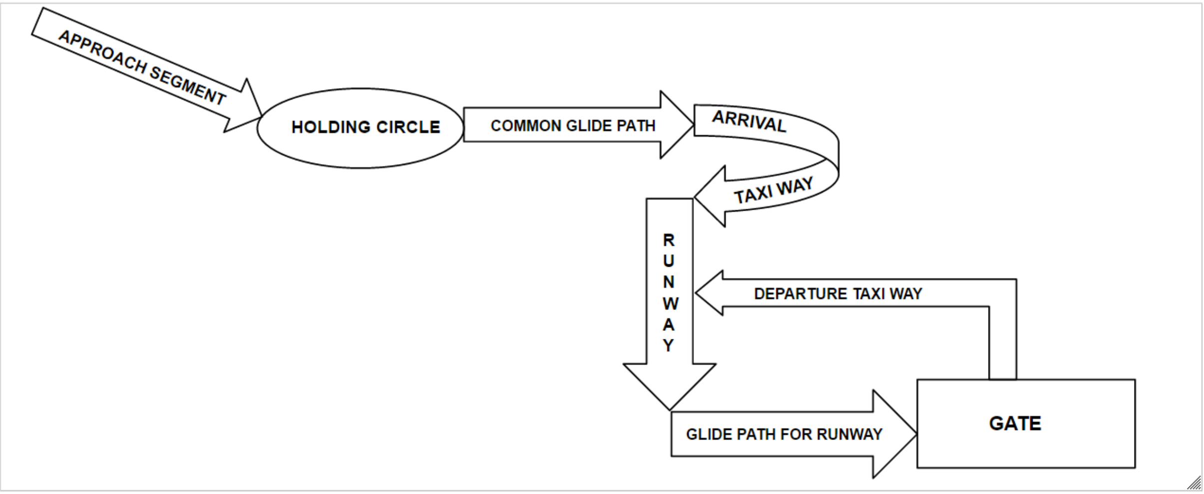

Figure 40 Resource in the code

9.3 Pathway

The next step was to chart the path each arriving or departing aircraft takes to either land or takeoff from Schiphol. This was done by identifying the approach air segment an aircraft takes and then subsequently tracking the glide path and the corresponding runway. This essentially means that this part of the code was a collection of sequentially aligned resources taken by the aircraft to undertake any manoeuvre like landing or takeoff. In the code, the path represents the designated path of each aircraft and it can be depicted from Figure 41.

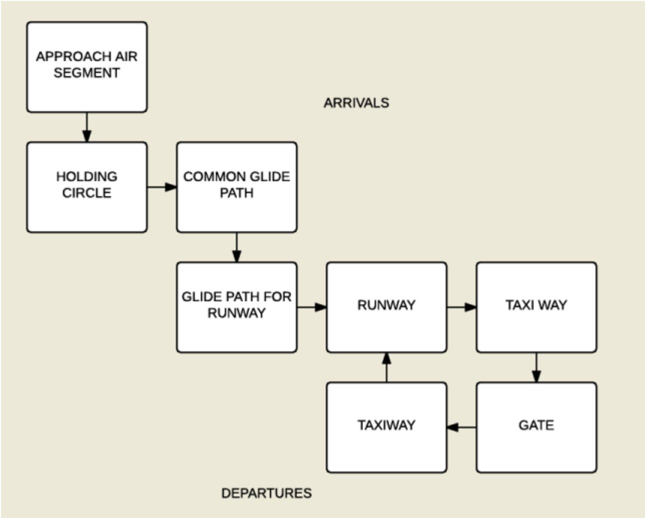

Figure 41 Path of an aircraft in the code

9.4 Time Profile of Aircraft

The next step in the experimental design was the description of the time profile of the aircraft. This includes the time of arrival of the aircraft at the TCA, time taken to traverse the resources over a designated path and finally the expected arrival time at the gates. This is presented in Figure 42. In the context of the time profile, the following terms were introduced and used to convey critical information to the solver –

1. Release Time – This was the time of entry of an aircraft into a specific resource recorded at the node before the resource.
2. Processing Time – This was the time an aircraft takes to traverse from one node to another, thereby utilising a resource. For example, the processing time for the resource glide path represents the time taken to enter and exit the resource glide path.
3. Perishability Time – This was the time which represents the weight at which rate the value of a job decreases if not processed immediately after completion. In other words, for any resource, this time was the processing time plus the lax allowed for that resource. In case the lax was zero, which means a strict no wait/delay timeframe.
4. Due Date Time – This was the expected time of the aircraft at the final destination, the gates in this case for arriving aircraft and departure runway in case of departing aircraft (Sama, D'Ariano, & Pacciarelli, 2012).

The above mentioned details regarding the aircraft take into account the schedule in place and schedule or route based on the objective function, as defined in the header section.

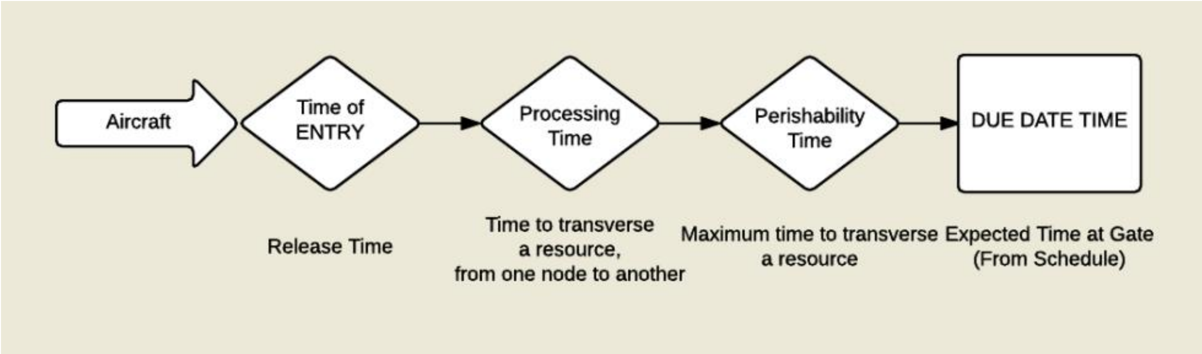

Figure 42 Time profile and Time points in the code

9.5 Aircraft Identification

This step was designated to list all the aircraft that were arriving or taking off from Schiphol as per their name, origin, make and airline company information. This step ensures that the post analysis was conducted with enough numbers and so that each player was identified properly for the analysis.

For example,

Job1 – KLM1

Job2 – KLM2

Job3 – Etihad1

Job4 – Germanwings1

9.6 Run Algorithm

Having structured the code so far thus, the next step was to organise the data in the required format to run the algorithm. As mentioned earlier, the data was sourced from various sources and was a real time representation of traffic at Schiphol. The data corresponds to the number of aircraft utilising the resources to either take-off or land at Schiphol. So, basically every aircraft was linked to the above mentioned points like time of entry, designated path and expected time of arrival/departure. The aircraft was recorded the moment it enters the TCA and from that point, there were two decisions possible, one through FCFS and the other using the proposed algorithm with a pre-defined objective function. In order to achieve a robust algorithm, 40 data sets were used. Furthermore to achieve consistency of the output, deliberate noise was introduced in 30 of the data sets, by manipulating the time of entry into the TCA, thereby simulating delay, and then observing the impact on the output, through comparison. 10 sets of data were the real time data with 30 more with noise introduced, as mentioned above. The 10 set of data sets were calculated over 10 time instances spread over two days in order to ensure that they were representative data.

9.7 Test Case Scenario, Experimental Run and Simulation

Subsequent to setting up the experimental design, the next step was to decide on the methodology to utilise the data to run the simulation under various scenarios. This entails primarily modifying the objective function, so as to quantify and analyse the output in terms of financial implications. To achieve that, configurations were defined in which the data was the same but the objective function and parameters like importance of delay and priority of airline were changed to acquire different output for analysis. The post analysis parameters also play a factor in determining the configuration. The test cases can be described in Table 10.

1	**FCFS on the complete dataset**
2	Routing and Scheduling on the complete dataset
3	Routing and Scheduling KLM priority
4	Routing and Scheduling Other Airlines priority
5	Routing and Scheduling with Holding Circles

Table 10 Test Case Instances

All the test instances or the data sets were run for each of the configuration to create a set of output which can then be analysed, compared and from where, inferences can be drawn. The details of the various configurations for the algorithm were defined as follows in the subsections.

9.7.1 Configuration 1

FCFS – This scenario was the base scenario which was used to compare all other scenarios and analyse the impact of the algorithm through different scenarios. This was the standard practice that was employed in the airports currently wherein the resources were allocated in the order the aircraft demands the use for the resource. The actual schedule or expected time of arrival was not important here because the order of arrival into the TCA takes precedence.

9.7.2 Configuration 2

Branch and Bound Algorithm – The objective function in this scenario was to minimise the maximum delay of the whole system. Also, the average delay was calculated for all the instances. Then by applying weights or priority to the specific airlines, again, average and maximum delay were calculated.

9.7.3 Configuration 3

Branch and Bound Algorithm and TABU search – The objective function in this scenario was to minimise the maximum delay of the whole system. Also, the average delay was calculated for all the instances. Then by applying weights or priority to the specific airlines, again, average and maximum delay were calculated.

9.7.4 Configuration 4

CPLEX Scheduling– This configuration transforms the said problem into a “Mixed Integer Linear Programming (MILP)” file (.lp extension) which was solved using CPLEX, concentrating only on the order of the aircraft i.e. scheduling. The objective function in this scenario was to minimise the maximum delay of the whole system. Also, the average delay was calculated for all the instances. Then by applying weights or priority to the specific airlines, again, average and maximum delay were calculated.

9.7.5 Configuration 5

CPLEX Routing and Scheduling – This configuration transforms the said problem into a “MILP” file (.lp extension) which was solved using CPLEX, concentrating both on the order of the aircraft and the routes alternatives i.e. scheduling and routing. The objective function in this scenario was to minimise the maximum delay of the whole system. Also, the average delay was calculated for all the instances. Then by applying weights or priority to the specific airlines, again, average and maximum delay were calculated.

Table 11 provides a summary of all the configurations for simulation.

Configuration 1	FCFS
Configuration 2	B&B
Configuration 3	B&B with TABU Search
Configuration 4	CPLEX Scheduling
Configuration 5	CPLEX Routing and Scheduling

Table 11 Configuration for Simulation

Based on the above description of the scenarios, all the instances were run and the output was compiled in an excel file to perform the financial analysis to analyse the feasibility of the proposed algorithm and also check the fairness aspect of the algorithm.

Chapter 10. Results

The results from the above specified configurations and test case instances were in the form of total delay, be it average and maximum, and also individual delays of specific aircraft. The latter was most interesting because that output deals with the financial implications to the airlines. So, for the next part of the analysis, namely fair distribution, financial implication and subsequent mechanism design, the delays of the individual aircraft were used.

The raw data was just a collection of numbers and have to be organised and ordered before they could be analysed and presented. The organisation part of the output was done by storing the output as file with the ".csv" extension. This ensures that the file could be opened by excel spreadsheet where the ordering of the data was carried out. The results were spread over 40 datasets, with each dataset having the output of delay as a result of algorithm including FCFS, B&B and Priority B&B for each aircraft. Priority here means that the aircraft of a certain airline would be treated as "landing and delayed", thereby giving it priority in case of conflict against other airlines. The following steps were followed to analyse the output from the algorithm—

1. Comparison between FCFS and B&B (Scheduling and Routing)
    a. for all aircraft
    b. for all airlines
2. Comparison between FCFS and B&B
    a. Priority given to KLM – EQUITY 1/ EQUITY KLM
    b. Priority given to other airlines – EQUITY 2/ EQUITY Others
3. Comparison between B&B
    a. Normal and Priority to KLM
    b. Normal and Priority to Other Airlines
4. Comparison of Time Gain or Loss
    a. Between different airlines

10.1 Comparison Procedure

To get an understanding of the difference between the various configurations, first, the benefits of each configuration were calculated against FCFS configuration. The following steps were followed to format in each of the presented results –

1. Calculate the delay of each airline under various scenario and configuration like FCFS and B&B.
2. By comparing the delay from each configuration, calculate the benefits or losses of each airline due to specific configuration like FCFS vs Scheduling and FCFS vs Routing/Scheduling.
3. Present the benefits or losses graphically for each airline.
4. Repeat the above process with a slight modification, giving priority to KLM and in another case giving priority to other airlines.
5. The negative values signify loss and positive values signify gains.
6. The unit of the measurement at this stage was seconds. The monetizing of the time benefits was done at a later stage, for the financial analysis.

Table 12 presents the result of the algorithm for one of the test instance and displays various configurations.

NAME	FCFS	BB	benefit	ROUTING	benefit	klm weight routing equity 1	benefit	other weight routing equity 2	benefit
klm	-2083	-691	-1392	-4077	1994	-2934	851	-900	-1183
etihad	88	88	0	0	88	39	49	-356	444
chinas	553	210	343	-571	1124	20	533	-869	1422
cathay	390	255	135	105	285	105	285	105	285
malaysian	285	0	285	0	285	200	85	0	285
delta	91	106	-15	256	-165	256	-165	-245	336
united	376	106	270	256	120	456	-80	-245	621
german	-141	-6	-135	-410	269	10	-151	-150	9

Table 12 Output for Test Instance 1

10.1.1 Scheduling B&B

Figure 43 shows the time gain or loss of each airline, in seconds, due to the utilisation of the scheduling algorithm over the utilisation of the FCFS scenario. It could be seen that by implementing only scheduling, all the airlines expect KLM and Delta enjoy time savings or benefits.

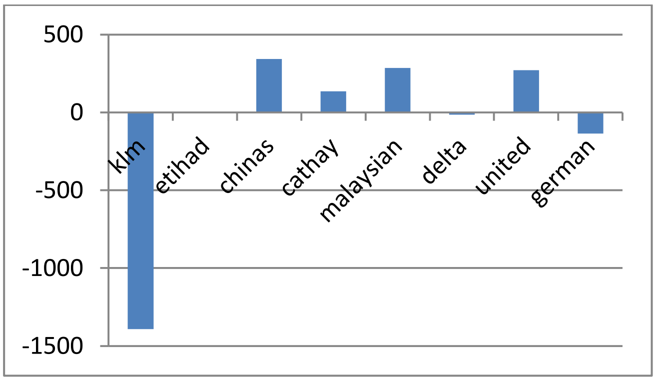

Figure 43 FCFS vs Scheduling Benefits (seconds) dataset1

10.1.2 Routing and Scheduling B&B

Figure 44 shows the time gain or loss of each airline, in seconds, due to the utilisation of the scheduling and routing algorithm over the utilisation of the FCFS scenario. It can be seen that by implementing routing and scheduling, all the airlines, expect Delta, enjoy time savings or benefits.

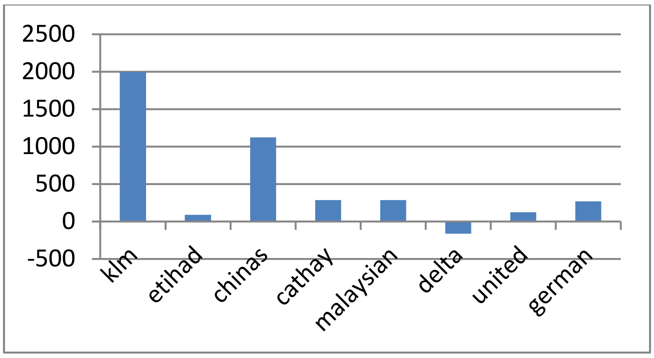

Figure 44 FCFS vs Routing/Scheduling Benefits (in seconds) dataset1

10.1.3 Priority KLM

Figure 45 shows the time gain or loss of each airline, in seconds, due to the utilisation of the scheduling and routing algorithm, with priority given to KLM, over the utilisation of the FCFS scenario.

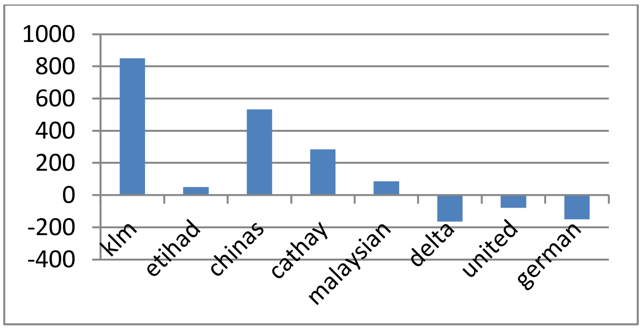

Figure 45 FCFS vs Routing/Scheduling Priority KLM dataset1

10.1.4 Priority Other Airline

Figure 46 shows the time gain or loss of each airline, in seconds, due to the utilisation of the scheduling and routing algorithm, with priority given to non-KLM, over the utilisation of the FCFS scenario.

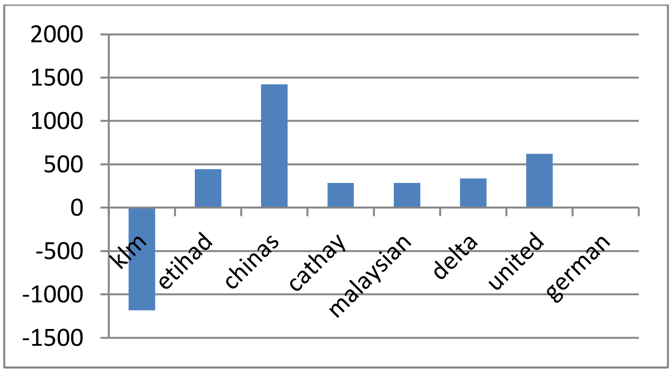

Figure 46 FCFS vs Routing/Scheduling Priority Other Airlines dataset1

10.1.5 Routing/Scheduling benefits: Priority KLM vs Priority others vs Normal

This analysis was done by comparing the benefits of the configuration where all the airlines were treated equally to the configuration where KLM was given priority or where Other Airlines were given Priority. This was important to assess the impact of the algorithm on the decision making process, fairness analysis and most importantly the sensitivity analysis of the algorithm. Figure 47Figure 48 represent the consolidated comparison between equity 1 and equity 2.

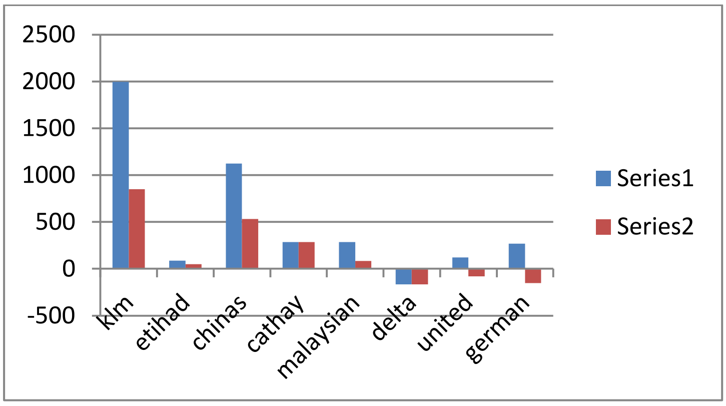

Figure 47 Consolidated Representation for Equity 1

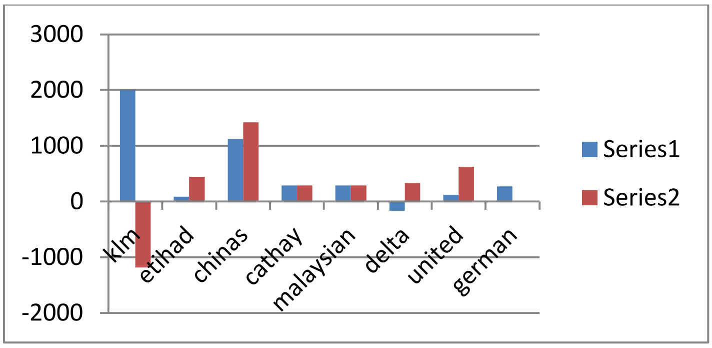

Figure 48 Consolidated Representation for Equity 2

10.2 Output Analysis

In this section the output was analysed in a more rigorous manner while laying emphasis on the operational, financial, fairness and sensitivity aspects. This analysis will be necessary to evaluate the impact of the algorithm, within the control system in use, on the various stakeholders like airlines and ATC. The operational analysis deals with the details of time savings and impact on the various airlines. Statistically the benefits and loses of various airlines were represented over a number of datasets to ensure robustness. The financial analysis was basically the monetisation of the operational output. This analysis was done to gain an understanding of the financial implications of the decisions on the operations. Thereafter, fairness analysis was carried out using a game theory tool, Shapley Value. This was a more rigorous way to analyse fair distribution. In Section 10.1, only statistics was used to demonstrate the impact of the algorithm on the airlines, from where it could be inferred the benefits or losses of each airline. But this was not an exhaustive analysis; rather, it was a very superficial way to look at fairness.

10.2.1 Financial Analysis

The financial analysis deals with the monetisation of the delay and representing the output in terms of money, which also serves as input for the next analysis. Since, this research deals with only the operational aspect of the scheduling and routing procedures, the two aspects which were important to this analysis were the landing fees and the value of time in case of delay.

10.2.1.1 Landing Fees

The landing fees were paid by the airline to the airport authorities for each landing or take-off manoeuvre that its aircraft undertake. The value depends on the category of the aircraft and the maximum permissible weight class of the aircraft. For the purpose of this research, the value was consolidated over all the aircraft and was taken at 100 Euros per manoeuvre (Schiphol Group, 2015)

10.2.1.2 Value of time: Delay

When an aircraft was delayed, the impact was predominantly financial and depending on a lot of factors forms a significant chunk of the costs incurred.

However, to quantify the value of time and analyse the financial implication, a value was assigned to delay cost per minute, which was taken at 100 Euros per minute for the purpose of this research (Ball, Barnhart, Dresner, Hansen, & Neels, 2010).

10.2.1.3 Output

The outputs from the algorithm, after the delay being monetised, were represented as costs to specific airlines and are represented in Table 13.

KLM	**1700**
Etihad	246
China S	1121
Cathay	750
malaysian	575
Delta	251
united	826
german	100

Table 13 Cost to Airlines (Euros)

10.2.2 Fairness Analysis

This section deals with the fairness aspect of the algorithm in terms of the financial impact of the decision with respect to routing and scheduling. As mentioned above, a game theoretic approach, using Shapley value, was used to determine the fair distribution and then compare it with existing practices to determine the feasibility of the algorithm. Next, a financial compensation framework was also conceptualised based on the outcome of the Shapley Value.

10.2.2.1 Parallels of Cooperative Games

The above analysis demonstrated the operational, financial and sensitivity aspect of the proposed algorithm. However, the fairness aspect was analysed only superficially without any rigorous method and it has been stated earlier that fairness was an important criteria for any implementation of algorithm. Hence, it was important to examine the output in a more rigorous manner with respect to fairness. This was done by drawing parallels with a cooperative game situation analogy. While, exact parallels cannot be drawn to a cooperative game because of the nature of the operation, wherein ATC, as the agent, holds the highest state in the hierarchical relation, the analysis can still be undertaken because all the stakeholders still cooperate with ATC, albeit owing to regulations, to manage the operations. However it was very important to stress that the airlines don't have choice not to accept any algorithm adopted by the ATC. The point was to demonstrate the inherent fairness of the algorithm so as to be attractive as a business option to airlines.

Analogy with Current Analysis

The airport operations can be seen as a cooperative game where every player cooperates with ATC to manage their own aviation operation at the Schiphol airport. Now, the current scenario was such that ATC uses FCFS to manage the operations like landing and takeoffs. However, better results in terms of minimising delay have been obtained using the proposed algorithm. And this algorithm was financially beneficial to the airlines as well owing to minimising of the delay. However this assessment was the result of a global control system implemented by the ATC, hence, nothing can be said about the effect on individual airlines operating small fleet or humongous KLM. A very powerful tool was to utilise the Shapley value to ascertain the fairness of the algorithm and subsequently design a financial mechanism to offset any unfairness.

This analysis can be done owing to framing the problem as a cooperative game scenario. The key assumption was that by agreeing to the proposed algorithm, the airline improves the overall performance of the system while being profitable and sustainable themselves. The marginal increment in performance, resulting in benefits, was used and analysed to determine benefits commensurate with the investments, through Shapley Value. Also, the scenario can be treated as a case of Transferable Utility cooperative game due to the following reasons –

1. The payoffs to the coalition may be freely distributed amongst the coalition. In this case this refers to the improvements in system efficiency due to a specific algorithm.
2. All members were satisfied when there was a universal currency that was used for exchange in the system. In this case, this takes the form of financial compensation mechanism design.
3. Each coalition can be assigned a single pay-off.

10.2.2.2 Shapley Value

In the previous financial analysis, the payments done by each airline was shown and also the context was set such that it deals with only the landing or take-off costs.

The Shapley value calculation can be represented in Table 14 which is followed by interpretation of the outcome.

Airline	FCFS	Routing/Scheduling	Equity KLM	Equity Others	Shapley Value (R/S)	Shapley Value (Equity KLM)	Shapley Value (Equity Other)
KLM	1700	1700	1700	1700	1663	1648	1678
Etihad	246	100	165	100	85	165	5

China S	1121	200	233	200	297	357	237
Cathay	750	275	275	275	307	397	217
Malaysian	575	100	433	100	134	84	184
Delta	251	526	526	100	451	461	441
United	826	626	960	200	619	549	689
Germanwings	100	100	116	100	66	-14	146

Table 14 Shapley Value - Test Instance 1

The following inferences can be drawn from Table 14—

Technical Analysis

1. The games were additive which means that the value of any two coalitions will be no less than their individual values and that the grand coalition, involving all the airlines, will have the highest payoff.
2. The symmetry axiom of the game was satisfied based on the interchangeable players receiving the same payoff.

$$\text{for all } S \text{ that contains neither } i \text{ nor } j,\ v(S \cup \{i\}) = v(S \cup \{j\})$$

3. The dummy player axiom criteria was also satisfied which states that a player will receive the payoff which was exactly the amount that they can achieve on their own.

$$\text{for all } S \text{ such that } i \notin S,\ v(S \cup \{i\}) - v(S) = v(\{i\})$$

4. The additive axiom was also satisfied which states that if we remodel the setting as a single game in which each coalition S achieves a payoff of $v_1(S) + v_2(S)$, the agent's payment in each coalition should be the sum of the payments they should have achieved for that coalition under two separate games.

Games Analysis

1. The output of the algorithm and Shapley value do not follow any trends with respect to any airline output, rather the output were inherently a part of the algorithm.
2. However, it can be seen that the routing and scheduling algorithm performs better than the incumbent practice of FCFS. The degree of improvement was dependent on a lot of factors like the time horizon, delay in the test case and the number of aircraft.
3. The Shapley value that was calculated for the Routing/Scheduling algorithm, Equity KLM and Equity Others were comparable in quantity to the costs or payments made by the airlines.
4. However, in some instances a particular airline pays more and sometimes less and there was no particular trend for this observation. This affects carrier like KLM which operates around 50% of all volume to a carrier like Etihad which, in this instance, had only one flight.
5. This skewed output with respect to the Shapley value and the actual cost/payment can be addressed through a financial compensation framework.

10.2.2.3 Stability Analysis: Core

The above analysis deems the distribution of cost or benefits amongst the players as fair. But a crucial question was whether the distribution will lead to stability and sustainability of the coalition. This was essential because for some players, forming smaller coalitions rather than the grand coalition might be more beneficial even though it reduces the effectiveness of the overall efficiency of the system.

The core of a coalition was a set of values of payoffs which were most attractive to the players and were conducive towards formation of the grand coalition. They would form a coalition, grand coalition, only when the payment profile was drawn from a set called CORE and is presented in Figure 49.

A payoff vector x is in the core of a coalitional game (N, v) if and only if

$$\forall S \subseteq N, \sum_{i \in S} x_i \geq v(S).$$

Figure 49 Core (Ferguson)

The core has various properties inherent to it and can be non-empty, empty, unique and even non-unique. However, it was extremely difficult to conceive the core due to dimensional constraints although it can be ascertained whether the core was empty or unique. In the case of the two tables above displaying the Shapley value for various algorithms, the Core was non-empty and was not unique. It can be said that the Shapley value was in the core but it was not unique as other distributions might be present in the core which were equally attractive to the players.

A unique situation worth analysing was the game called convex games (Milgrom & Shannon, 1996). This was a sub-class of games which take into account the "snowballing" effect of the game. This can be described in simple words as the incentives of joining the coalition increasing with the increase of the number of players in the coalition and is represented in Figure 50.

$$v(S \cup T) + v(S \cap T) \geq v(S) + v(T), \forall\ S, T \subseteq N.$$

Figure 50 Convex Game (Shapley L. , 1971)

In a convex game, the core was always nonempty and more importantly, the Shapley value was always inside the core. In fact, the Shapley value was the centre of gravity of the core and this arrangement ensures stability and sustainability of the coalition (Shapley L. , 1971). Keeping in view the nature of aviation operations and the expected demand for service, the system will benefit greatly if the coalition was convex in nature as it was both sustainable, inclusive and promotes growth through improved incentives. With respect to this specific scenario, the convex nature can be seen empirically.

10.2.3 Framework: Financial Compensation

As mentioned before, owing to the nature of aviation operation, the attractiveness of an airport with respect to business opportunities was very important. This can be achieved through implementing a system which can be viewed as fair. The primary aim of the framework was to design a methodology to compensate the airlines which were losing money as a result of the decision yet by being in the coalition improve the overall efficiency of the system. Due to the inherent stochasticity, although Shapley value can be computed easily, using the core to determine stability was difficult both in terms of complexity and representation. Hence, financial compensation model was proposed to make the coalition attractive even when the pay off sets was not from the core. Also another important aspect was to use the mechanism design to model the payment structure. Since, a convex game was much more suitable to the aviation industry and especially to a big airport; the payment structure can be modelled in such a manner that the game assumes convexity.

Name	Routing/Scheduling	Shapley Value	Paying Less	Paying More	Re-Distribution	New Loss
KLM	1700	1663		37	30	7
Etihad	100	85		15	9	6
China S	200	297	97			
Cathay	275	307	32			
Malaysian	100	134	34			
Delta	526	451		75	65	10
United	626	619		7	4	3
Germanwings	100	66		34	25	9

Table 15 Financial Compensation

It can be seen from Figure 15 Aircraft Demand/Growth that, after the Shapley Value calculation, a further redistribution based on the deficit or excess payment was done which further reduces the loss of airlines and makes it minimal. This means that the worst case scenario for the airlines, with respect to only operational scheduling/routing, was that they achieve breakeven or keep the losses minimal.

The following Table 16 demonstrates the number of times an airline paid more than it should pay and the number of times an airline paid less than it should.

NAME	Number of Test Instances	Instance where pay too less	Percentage (%)	Instance where pay too much (%)
KLM	49	24	48	52
airline 1	49	22	44	56
airline 2	49	27	55	45
airline 3	49	22	44	56
airline 4	49	19	38	62
airline 5	49	20	40	60
airline 6	49	21	42	58
airline 7	49	23	46	54

Table 16 Distribution of inconsistencies in payments

10.3 Validation

Validation of the results was important so as to align the aim of the project, the expected outcome of the project and the results obtained after the simulation. This assumes even more importance, because the end user would be most interested in this aspect of the project because if the results and the expected results and were aligned and validated, that means the project could be implemented and recreated.

The validation can be described in the following terms-

1. The proposed algorithm improved the performance of the airport as compared to the currently practised algorithm, FCFS.
2. The objective function was to minimise the make span and provide as an output, a globally optimally solution. This meant that the solution was supposed to provide a solution which minimises the total delay of the system as a whole. Consequently there might be some aircraft, which were experiencing no delays previously might face delays under the proposed algorithm so that the system might achieve optimality. This was exactly what was seen in the simulation of the algorithm over all the 40 data sets.
3. The algorithm was also run with two modifications, prioritising KLM (Equity 1) and prioritising other airlines (Equity 2). The expected result was that in Equity 1, the overall performance would be better as compared to FCFS, would be inconclusive with respect to normal algorithm and the performance of KLM would improve. The degree of improvement was deemed to be not so much important as to the presence of improvement. In 80% of the cases KLM's performance improved. In case of Equity2, the corresponding number for the other airlines was at 70%.
4. Consequent to the solution being global and inconsistencies in the individual performances, the fairness of the decisions were evaluated next. This was done by using the concept of Shapley Value. The expectation was that some airlines would be paying more than their corresponding Shapley Value and some would be paying less than their corresponding Shapley Value. Again this was observed over all the data sets and hence a financial compensation framework was designed so as to offset the extra payments by airlines and ensure fairness.

Overall it can be said that algorithm performed along expected lines and the output was perfectly aligned with the aim and objective of the project.

Chapter 11. Discussion

This study was conducted with the aim of evaluating an advanced optimisation algorithm for scheduling and routing of aircraft at a major airport, Schiphol, Amsterdam, in this case with particular focus on the performance, equity amongst stakeholders and fairness of the algorithm in terms of fair distribution of decisions. The algorithm was run over a real set of data from Schiphol which was intended to be representative of the distribution of aircraft belonging to different airlines and analyse their individual performance as well. Basically, the project covered the operational aspects which dealt with performance of the airport in terms of total delay experienced and associated financial implications for the airport and the airlines and fairness aspect which dealt with the analysis of the distribution of the decision with respect to routing and scheduling amongst the different airlines, which was an indicator of the benefits being commensurate with their payments towards operational costs like landing or delay charges. Tools from varied fields like operations research, game theory and economics were used to formulate, solve and analyse the problem.

The methodology comprised of formulating the problem as a job shop scheduling problem, use data of all the incoming and outgoing flights as inputs, form the alternative graphs of all the possible sequence of operations of each aircraft taking into account potential conflicts and eventually rendering a decision based on minimising the make span. These decisions were at the behest of ATC and offer a global optimal solution or a system optimal. However, the airlines performances, which were dependent on the decisions, were also affected due to the decisions and result in a situation where a particular airline might face huge delays in order for the system to reach an optimal. Since, the algorithm was absolute in terms of rendering decisions and the objective function was minimising the make span, the preferences of the airline were not taken into account, the output of the algorithm were analysed for fairness. This was done through a game theoretic tool called Shapley Value by drawing analogy of the current situation to a cooperative game scenario. Thereafter, the Shapley Value was compared to the actual costs incurred by the airlines and the ones paying too much and the ones paying too less were enumerated. Finally, a redistribution of the cost distribution was done by transferring the utility, costs in this case, from the ones paying less to the ones paying too much in the same ratio as Shapley Value.

It was found that the proposed algorithm performed better than the incumbent algorithm, FCFS, over all the data sets. The degree of the improvement did not follow any trend over different data sets and were dependent on the initial delay values of the system, number of aircraft and potential conflicts on the usage of the resources. Also the percentage of the improvement was quite random and was dependent on the initial condition of the test instance. So, it was important to know which conditions prompt what kind of performance improvements. This understanding was not present in this research and it was assumed that the factor of improvement was not important; rather the presence of improvement was important.

Another interesting aspect of this performance analysis was that, the more the system was delayed, the better the improvements could be seen in the system, as a result of the algorithm. This was due to the nature of the operations and the algorithm chosen, disjunctive graph with objective function to minimise make span. This observation had wider implications on the game theoretic analysis of the scenario.

A variation of the algorithm was also studied, wherein the KLM flights were prioritised in case of conflicts. This was done to check whether KLM can get any advantage due to its scale of operation, status as a hub airline or simply getting preferential treatment from ATC. However, the result of this analysis was quite inconclusive and did not follow any trend. The primary algorithm, without any modification, still gave the best outcome, albeit in 20% of cases the solution with respect to KLM improved. The expectation was that the benefits of KLM would increase when Equity KLM was used, but it was observed that while there were benefits, the benefits were less than the normal algorithm. This is due to the fact that in both the cases the KLM experienced no delay and the benefits referred to how much more early than scheduled time can an aircraft be landed. Hence, when in both algorithms, KLM flights are not delayed and before time, prioritising KLM doesn't make much of a difference. However, when non-KLM airlines were given priority, KLM experienced losses and all other airlines gained at its expense. So, the other airlines would prefer an algorithm where priority is granted to them i.e. non-KLM airlines but this would affect the overall performance of the system.

Having established the superiority of the proposed algorithm, the next aspect to be analysed was the fairness aspect of the algorithm. As the objective function related to the global optimal solution, the micro level aspects pertaining to the specific airlines were not addressed. Hence, an analysis was carried out on the output of the algorithm using tools from game theory, specifically Shapley Value. The Shapley Value gave a unique distribution of the costs (benefits) incurred by the airlines which they paid to Schiphol group to use the resources. The next step was to check whether the distribution of benefits was commensurate with the payments the airlines made. The Shapley value was more or less almost equal to the actual costs incurred by the airlines. As expected, there were some variations wherein some airlines paid more than they should and some paid less. This was the primary reason why the Shapley Value was computed in the first place; the algorithm being aimed at global optimal inconsistencies were expected for performance at airlines level. To mitigate this, a financial compensation framework was proposed.

Since it was assumed that this situation was analogous to a cooperative game scenario and formulated accordingly, transferable utility was an important aspect of the analysis for the financial compensation framework. After comparison with the Shapley value, the airlines paying too less were enumerated and asked to pay what was expected of them and the collected money was distributed over the airlines paying too much in the same ratio as the Shapley Value to offset the extra payments. In some instances, the collected money could not offset the extra payments completely, it minimised the cost to the airlines, in other words achieving a local optimal stemming from the global optimal solution. A key assumption here was that the airlines would accept the result even if they end up paying too much in spite of that being the minimum value possible. This can be explained by the fact this project focuses on only the operational costs of the aircraft, the landing fees and the delay values in terms money lost and this was not the most important contributor to the revenue management of the airlines. Passengers were the major revenue source and apart from that all the cost structure was aimed at keeping the costs to a minimum value possible at which operational status can be maintained. Hence, if they can minimise their costs at an operational level, being rational entities, this would be acceptable to them. But it must pointed out that, the other forms of financial agreements between Schiphol group and the airlines were neglected here, like the slots leasing and gate allocation payments. This was done because despite those payments, the airlines still have to pay the operational costs and so the analysis was based on that. However, it can be argued that if those payments were taken into account, the results might change for various airlines owing to various factors like scale of operation and number of aircraft operated, for example KLM might not care too much about the operational costs or maybe due to the above reasons, for KLM, the costs might be offset by other revenue streams.

KLM presented an interesting scenario in all the test instances due to its scale and the nature of objective function. Since, the improvements depended on the initial state of the system and the objective function was to minimise the make span, ATC as well as all airlines preferred a system with minimum or no delays. However, owing to the convex nature of the game, having higher number of fleet would result in higher incentive to join the coalition and would result in better performance for the whole system through global optimal. Hence, owing to its scale of operation, KLM clearly enjoyed a very important status in all the analysis carried out with ATC's interest in mind.

One important consideration that was not explored mathematically but was analysed empirically, was the stability and sustainability of the coalition which was explored through another game theoretic concept called Core. Core can be described as a set of imputations which were the pay off for all the stakeholders for which the grand coalition was the most attractive coalition. Here, it was assumed that a grand coalition will happen, which was the case because the ATC regulations and decisions were binding and the point was to show that they were fair, and that coalition would be the most attractive rather than any sub optimal coalition with smaller players. Here, in this research, the convex nature of the game stemming from the super additivity and satisfying other required criteria, point to the presence of a core which was non-empty. However it cannot be said as to whether the pay off, Shapley Value, was unique or not. Since every test instance was different from each other, the data set can never be exhaustive, so it was essential to know the presence and the uniqueness of the core to assess the stability of the coalition. Also, knowing that, it will be easy to devise a payment structure in the first place which would promote a stable coalition.

Overall it can be concluded that despite the limitations, this research produced results which were practical, important and an improvement over the current practice. Further studies were required to validate the output of this research and also form a consolidated output covering all aspects of aviation apart from scheduling so that advanced algorithm can be tested and implemented at Schiphol.

Chapter 12. Conclusions and Recommendations

This chapter draws conclusion from all the above analysis and proposes recommendations towards the potential implementation of the scheduling and routing algorithm at Schiphol. The analysis comprised of two aspects, the first being operational aspect and the later being impact assessment through game theoretic analysis. This section first draws conclusion from the above analysis, then addresses the sub-questions of the research question and finally proposes recommendations.

12.1 Operational Aspect

This part of analysis dealt with the performance indicators of the operational aspect of the scheduling and routing at Schiphol. The metrics that were used were the value of delay for the overall system, the global optimal, and then at a micro level for the individual aircraft. The details of the aircraft were used to compile the performance of the airlines at a consolidated level, leading to the next part of the analysis.

The following conclusions were drawn from this part of the analysis –

1. The incumbent practice of using the algorithm FCFS, was not optimal and often results in a decision/solution which was not optimal at a global level which can be improved. Since decision pertaining to operational performance of the airport was the prerogative of the ATC, it would benefit from a better and advanced algorithm.
2. The proposed algorithm performs better than the base case scenario which was FCFS. The improvement was in terms of reducing the overall delay experienced by the system. Over all the data sets, the routing and scheduling algorithm always reduces the delay experienced by the system.
3. However, while the proposed algorithm improved the system performance as a whole, the performance of individual airlines varied from gaining to losing due to the decisions of the algorithm. This was a concern because these decisions will impact the presence of the airline at Schiphol due to the financial implications of the decisions.
4. Giving priority to KLM (Equity 1) did improve the performance of the system as well as that of KLM, but the improvement was not as good as the normal algorithm without any priorities. Inherently, KLM and ATC both would benefit from the same objective function.
5. Also KLM, owing to the fact that it operates almost around minimum 50% of all the volume in any given time horizon, enjoys the benefits due to the scale of the operation and in instances where it loses money due to any decision, the loss was usually offset by the other aircraft of the fleet which were benefitted.
6. The previous algorithm was recreated with preference now being accorded to other airlines, non-KLM. The other airlines would prefer this system rather than the normal algorithm because this suits them at a micro level. This inconsistencies needed to be addressed to ensure equity and fairness.
7. Overall, it can be concluded that the routing and scheduling algorithm was a huge improvement over the FCFS, ranging from 85% to 540 %, and produces globally optimal solution for the TCA.

12.2 Impact Assessment Analysis

Having established that the proposed algorithm was in fact a better and improved algorithm as compared to FCFS globally, the next step was to look at the micro level performance of the algorithm with respect to the airlines. The delay values of the individual aircraft were consolidated to get the delay values for the airlines as companies with fleet of aircraft. The following conclusions can be drawn from this part of the analysis –

1. The scenario can be formulated as a cooperative game scenario and tools like Shapley Value and Core can be used to analyse the situation.
2. The Shapley value of the instances was calculated and that represents that decision distribution i.e. cost distribution. The Shapley value was calculated for the entire configuration, routing/Scheduling, Equity 1 and Equity 2 and was found to be comparable to the costs of the airlines. However, some airlines pay more and some less as per the Shapley value.
3. As shown in the output analysis chapter, after the Shapley Value analysis, a financial compensation was carried to compensate the airlines that were paying too much from the airlines that were paying too little. As such, the new situation was better than the incumbent scenario of FCFS, so as long as the losses were kept to the minimum, it was acceptable by the airlines.
4. It was critical to reiterate here that this analysis was only pertaining to the operational aspect of the scheduling/routing at Schiphol. Airlines have multiple sources of revenues and were not dependent on the operational revenue stream. Hence, although the aim was to be profitable, it was assumed that minimising the costs was also acceptable.
5. The financial framework was designed in such a way that it redistributes the cost based on the Shapley Value analysis and was able to minimise the cost of the airlines in any specific time horizon.
6. Since, in every time instance the data set were different with different value of delay and different airlines, it was not possible to consolidate the Shapley Value or the Financial Analysis over the entire range, however, a representative analysis was done which was recreated over each instance.
7. The nature of the coalition and the stability was analysed through a concept called Core. In this research, it can be concluded that the core in non-empty due to the convex nature of the game but the uniqueness of the core cannot be established owing to the dimensional constraints and large data set.

12.3 Research Question: Sub Questions

In this section, the sub-questions from the research question were revisited and were answered based on the analysis conducted –

1. **How the current system in place was not sustainable and what were the problems?**
   The FCFS has been studied to be a non optimal algorithm in terms of scheduling in airport owing to a lot of factors like safety requirement and multiple objectives of the multiple actor system. And after running this experiment, it can be said that FCFS was indeed the worst case scenario. The lack of any optimisation algorithm in FCFS makes it non-optimal and the proposed algorithm performs better than FCFS in all the test instances.

2. **What was the impact due to the centralised (global) control system employed in the Terminal Control Area on the operational efficiency?**
   The global control system was in a way mandatory due to the hierarchical nature of operations with ATC being the absolute authority on the scheduling and routing matter. However, the use of the proposed algorithm reduces the overall delay and improves the performance of the airport as a whole. The global control system makes it possible for the algorithm to operate on a macro scale and take decision accordingly. However, due to the global control system, the individual performance of the airlines cannot be ascertained or taken into account while rendering decisions. This affects the airlines since their input was not taken into account and the decisions impact was borne by them owing to their objective being non-aligned with ATC's objective. Hence, it was important to undertake a fairness analysis subsequent to evaluating the algorithm.
3. **What was the effect on delay of the operations of the airport and financial implications of same?**
   The cost of operation, as it was, was huge in the aviation sector and on top of that, delay causes a lot of losses for the airlines. Also, if the delay involves en-route delay, the financial implication was huge for the airlines. Also, due to the intertwined nature of operation, a single delay has a cascading effect throughout the whole system because it affects the resources like gate/slot allocation and transfer passenger leading to even more loss. Hence mitigating and minimising delay was one of the primary objectives of ATC and airlines although to different degrees. And given a delay, minimising the delay was the primary objective.
4. **What was the hierarchical representation of the stakeholders in context of the said algorithm?**
   Although this was a multi actor system, a clear hierarchical relationship exists between the stakeholders and it was different based on the scoping of the point of view, For example, at a strategic level, ATC has no role to play but at an operational level, ATC was at the top if the hierarchical representation. This was a given situation and cannot be changed and this causes problems because there was an inherent difference in the objective of the ATC with that of the airlines. Hence, the primary function was to solve the problem from the point of view of ATC and then modify the algorithm to ensure fairness amongst the airlines.
5. **How much fairness can be incorporated into the decision making process by using the proposed algorithm?**
   Fairness, as explained before, refers to the fair distribution of the decision from ATC, pertaining to routing and scheduling. Now, as it was established that the objective of ATC and the airlines were not totally aligned, a framework of financial compensation was proposed to mitigate the impact of the decisions. Although the decisions in it were within comparable range of the payment, there were some airlines that were paying too much or too little, and this has been addressed through a financial framework. Hence, the system cannot be designed to be completely fair due to the constraints and the hierarchical relationship between the stakeholders, but a sense of fairness can be introduced by analysing the system through game theory concepts and then compensating the airlines.

12.4 Recommendations

Based on the above analysis and conclusions, the following recommendation can be proposed in view of the project with respect to routing and scheduling operations at Schiphol –

1. From an operational point of view, the proposed algorithm can be tested and implemented at Schiphol ATC in real life situations.
2. The interests and objectives of KLM are of critical importance and should always be considered while taking any decision.
3. To ensure fairness, the financial framework should be initiated in a transparent manner, following which; the other airlines can be attracted to participate in the system to adopt the proposed algorithm.
4. The flow of information is of paramount importance and while dealing with situations analogous to cooperative games, such as the current scenario, it assumes even more importance. Hence, at least between ATC and the various airlines, the flow of information should be bi-directional and complete. This would ensure attractiveness of the grand coalition.
5. The overall model, operational, financial and game theoretic, was practical and can be implemented and has shown improved performance from the current scenario. However, further studies, in the same vein, needs to be carried out at a macro level and the results need to be consolidated with the output of this project before implementation and testing measures can be taken.

Chapter 13. Future Scope of Research

The present project focussed on the routing and scheduling aspect of the airport operations from an operational point of view, having a time horizon of few hours. Also, the algorithm was focussed on minimising the delay for the whole system by taking decisions on the individual delays of aircraft of different airlines. Since, the aircraft was traced from the time it enters the TCA till it reaches gates, the complete journey was taken into account while taking decisions. However, an important addition would be to take into account the aircraft which make multiple trips between locations and take into account the complete life cycle of the trip of each aircraft. This would result in also extending the analysis the tactical aspects of the scheduling, with increased time horizon of few days.

A further addition that can be explored was the impact of holding circle in the algorithm. A holding circle represents a stack where aircraft can be asked to manoeuvre if they cannot be allowed to land due to some eventuality at the airport. The introduction of the holding circle was expected to at least maintain the same operational efficiency as the current situation because this will provide more flexibility to the decision maker while trying to schedule or route an aircraft and that flexibility, in theory, should translate to improved performance in the form of system optimal.

Also, it would be more realistic if taxi time and corresponding gates and slot allocation were included in the problem formulation in a dynamic manner. The dynamic nature of the taxi ways was represented in the choice of taxiway depending on the usage of runway. Also can be included were the de-icing spots, other mechanical maintenance and fuelling and the impact of these activities can be taken into account in the algorithm. The gates and slot allocation were done at a strategic level and hence were not included in this research, but in order to be as practical as possible, gates and slots van be categorised depending on airlines and origin-destination pair.

From the point of view of the algorithm, the quantification of the savings or performance improvements was still not studied yet. The savings do not follow any specific trend and seem to depend on the initial situation of the test instance, depending on the delay values initially and number of aircraft and potential conflicts. So, it will be very beneficial to know what kind of scenario can result in what amount of savings.

The output was used to conduct an analysis using game theoretic approaches. However, prior to that, since this was a Multi Actor System, this scenario can be analysed from the point of view of a Principal Agent Problem. This was possible because, essentially all the airlines (principal) entrust the ATC to make the operational decision with respect to routing and scheduling. There exists an information asymmetry between the airlines and ATC and an inherent uncertainty due to the nature of operations. And since, the Schiphol group and the airlines have strategic agreements with contract between them, yet the operational output was the prerogative of ATC. So, it was important to examine the contractual agreements between the airlines and Schiphol group and also the understanding with ATC keeping in view the cooperative game analysis that has been conducted in this research.

Another aspect of the cooperative games analysis was the analysis of core and convexity. Although this has been explored in this research and conclusions have been drawn with respect to the presence of the core and non-uniqueness of the core owing to the convexity of the game, the data set was not exhaustive and there might be instances where the core was empty leading to instability. Hence, it will be interesting to study the core of such a coalition within the Schiphol and airlines framework. Mechanism Design can be used to design a game which promotes stability and coalitional nature of the operation.

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